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DIAGNOSTIC ANALYSIS OF IRRIGATION SYSTEMS

VOLUME 2: EVALUATION TECHNIQUES

Water Management Synthesis Project

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DIAGNOSTIC ANALYSIS OF IRRIGATION SYSTEMS

VOLUME 2: EVALUATION TECHNIQUES

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WATER MANAGEMENT SYNTHESIS PROJECT

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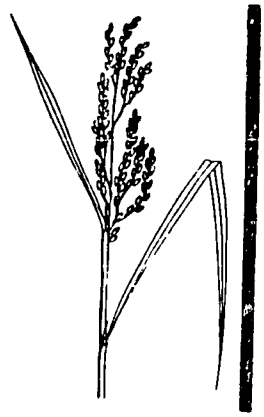


PREFACE

Procedures, scientific and otherwise, normally are explained in terms of concepts and methods. You need to understand where you are going, why you are going, and how to get there.

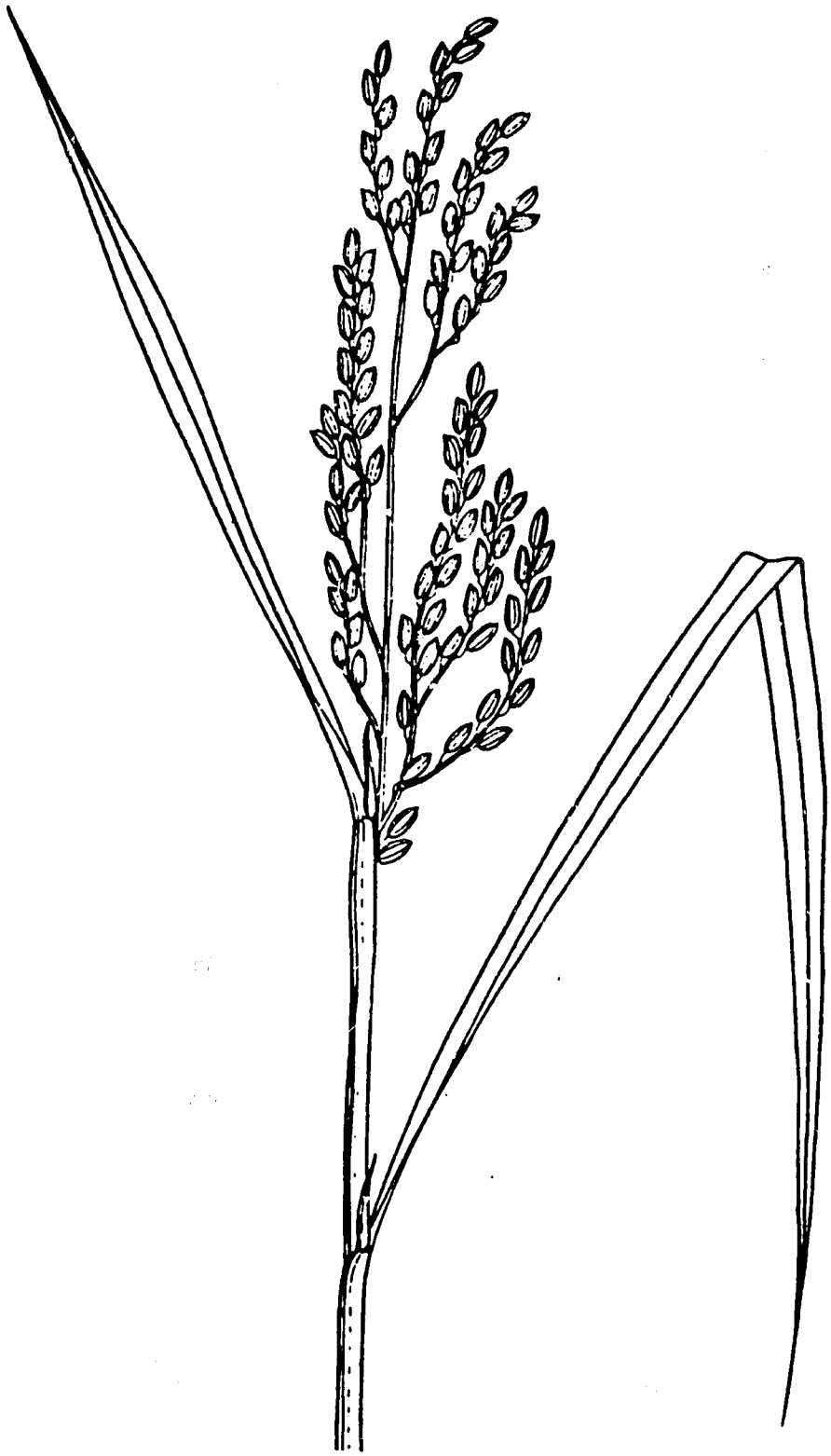
Volume 1 of DIAGNOSTIC ANALYSIS OF IRRIGATION SYSTEMS examined the conceptual framework of that specific investigative procedure. The framework is structured so as to incorporate interdisciplinary teamwork, farmer involvement, field-level data collection, and a system perspective. The methodology essential to implement the procedure also was outlined. Upon reading Volume 1, a workshop participant or an individual reader would possess a solid understanding of Diagnostic Analysis.

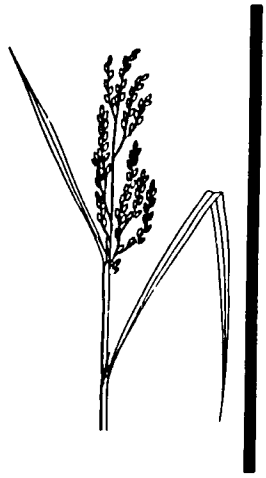
Volume 2 is intended to expand that understanding--particularly the "how" of investigation. Indeed, the draft version of this present volume was entitled the "How-To-Do-It Series". That original volume was the result of extensive professional involvement and labor in Pakistan and Egypt. The primary focus was, and continues to be, the improvement of disciplinary skills. As such, the articles are grouped now into disciplinary sections, an arrangement which also makes field use of the manual easier.

Despite such disciplinary grouping, however, there is nothing to stop the agronomist from venturing into the economics section thereby becoming more familiar with another area of expertise. Particular articles also may be located under one discipline, but applicable to others. For example, the article dealing with sampling techniques is located in the sociology section, but is of use to economists and agronomists as well.

If this manual, therefore, is approached as a companion to Volume 1, an inseparable companion, it can only strengthen the interdisciplinary process while improving disciplinary skills. You then will understand where you are going, surely why you are going, and above all, how to get there!

SOCIOLOGY





FIELD DATA COLLECTION*

by M. Lowdermilk, R. Laitos,
and J. Wilkins-Wells

INTRODUCTION

Data collection is one of the most important steps in the early phases of any project. It is then that a team must define a problem and begin to search for solutions. An interdisciplinary team's aim is to study the interrelated system of irrigation, crops, soils, marketing, and social relationships. Because these factors influence each other, they are of equal importance to the engineer, agronomist, economist and sociologist.

The social scientists' understanding of economic conditions and social relationships enables the engineers and agronomists to determine the type of physical technology most acceptable and beneficial to the farmer. A watercourse may be technically efficient with concrete-lined channels and an optimal route. However, it may not be beneficial to the farmer if the high price of cement makes construction costs too great. It also may not be acceptable, for example, if the channel runs through property belonging to opposing kinship groups who refuse cooperation in repairing or cleaning it.

Accurate information collected by an interviewer helps the project team know which technology will be most useful to the farmers. Inaccurate or incomplete information may cause the wrong technology to be used which may harm rather than help farmers and their families. The interviewer has direct contact with a large number of farmers. The goodwill he or she creates can contribute greatly to a project when the team or government attempts to implement new technology in the villages.

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* Modified from an article in The Problem Identification Handbook. (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100. Fort Collins, CO.

Interviewing requires skill. Interviewers must understand completely the meaning of the questions they asks. They must also understand enough about the subjects to know if the answers are reasonable. They must understand the farmer so as to gain his cooperation. Developing these skills requires a great deal of training: the work is hard. However, there are rewards. Interviewers can gain a better understanding of other people and learn much about the problems of farmers. They also may form lasting friendships with the people in the area where they work.

The work done during a Diagnostic Analysis will involve primarily the use of two separate, but related, data collection techniques: qualitative field studies and quantitative survey questionnaires. The techniques of the field study include interviewing one or more key informants. These procedures are most useful in gathering qualitative data on formal status positions, roles, and rules of behavior. Survey questionnaires, on the other hand, are best for gathering quantitative data on the distribution of certain population traits.

FIELD STUDIES

An excellent method for gathering certain types of data is the more informal, non-structured interview which helps to describe a particular social setting. These interviews are qualitative in nature, meaning that they are not concerned with numbers, but with the actual social processes in a rural village or irrigation system. These studies emphasize systematic observation and informal interviewing that provides much in-depth knowledge about the farmer's social setting. These interviews take place in the local rural area and offer an opportunity to examine a farmer's environment in very rich detail.

What is Studied?

Although any number of possible issues can be examined by using this unstructured interview approach, there are four primary areas of study:

1. Life Histories - A participant in Diagnostic Analysis may study the social experience and duties of the individual as a community member. This might involve questioning a farmer about his role as the head of a farming family.

2. Cultural Patterns - One could also study the attitudes and values of a culture. For example, how does the village culture deal with the issue of tenancy? What values are placed on land ownership?

3. Community Organizations - Such organizations may or may not have written rules and/or an organizational charter. The investigator may study the rights and duties associated with different roles (coop leader, irrigation association official) in order to understand the structure of relations between people. Another area of study might be the rules of behavior associated with various positions and roles, in order to understand the dynamics of social interaction. Finally, the participant might study the social patterns that occur in different social settings. For instance, how are social arrangements different in an area of high tenancy compared to an area of low tenancy?

4. Behavior Patterns - What patterns of behavior occur over and over again, either in the village or the irrigation community? Is it common and proper for a large landholder to take more water than smaller farmers? Does this pattern of behavior occur at all times? When does it not occur?

All these major areas of qualitative field studies deal with some aspect of social relationships. Examining the history, rules, and consequences of tenure and land use in a particular area, for instance, might be done with the use of these more unstructured interviews.

How Are These Issues Studied?

Before beginning the actual unstructured interview, there are some preliminary issues that need to be considered. Properly dealing with these issues will help to ensure the quality of the field studies.

1. Before entering the field, the participants in the Diagnostic Analysis should participate in developing guidelines for possible issues and problems to ask about. Variables and concepts should be clearly defined before the informal interviewing begins. For example, the participants may wish to expand their investigation of water distribution, system maintenance, conflict management--topics mentioned in Volume I of this manual.

2. The farmers, officials, or organizations to be studied should be clearly defined and carefully selected as representing the general population. The

specific observations and interviews needed should be decided upon before entering the field.

3. Some preliminary planning is always necessary, including defining the objectives and time table for the study. A field reconnaissance should be carried out, in which the Diagnostic Analysis participant looks for significant variables and decides what kind of questions would be useful for the sample survey techniques.

4. Some attempt should be made to seek a variety of contacts in the group or community being studied, to check with leadership groups, and to enter the community with an unbiased attitude towards any party. Both farmers and officials should be informed as to what the investigator is doing; the investigator should be honest and consistent.

5. The ideas expressed by the interviewer need to be culturally relevant to the person being interviewed. For instance, "water use efficiency" may be defined one way by the interviewer, and another by the local farmer.

Once these issues have been addressed, the open-ended interviewing can begin. The questions asked should be formulated so as to examine the issues and perceptions that facilitate an understanding farmer behavior.

Perhaps the most relevant people to interview are key informants. Any member of a group under study who provides information to the Diagnostic Analysis participant is called an informant. A key informant, however, is an individual who is selected deliberately to provide detailed information on various special topics or areas of knowledge. Such people as village leaders, local elected officials, and/or the staff of local irrigation organizations can be used as key informants. These same people also can help the investigator to gain the trust of the local community.

Key informants are useful in several ways. They can help the participant develop a local perspective of the social organization of irrigation. A group of key informants can be selected and interviewed to gain an in-depth picture of a particular issue, such as the structure and function of the local irrigation organization. Key informants can be used to provide background information, or to investigate problem areas in the community.

Finally, an investigator also can aim for an equal number of key informants, as well as comparable role representation, in each of the community sectors studied. As each

key informant is interviewed he or she should be asked about other important people in the area who could provide valuable data for the Diagnostic Analysis.

The choice of key informants does not involve a random sample from the farmers and officials under study. Rather, the researcher is selectively sampling specialized knowledge. The successful use of key informants greatly depends on the use of proper interviewing techniques and field diaries as discussed in later chapters.

Advantages/Disadvantages of Qualitative Field Studies

There are a number of advantages to using relatively unstructured interviews of key informants to collect certain data.

1. Qualitative field studies put the Diagnostic Analysis participant in close touch with the phenomenon under study.

2. Such studies provide much rich, detailed information about the village or irrigation system under study.

3. These interviews and observations have the potential to reveal patterns of farmer behavior that a structured questionnaire might not discover.

4. The investigator studies irrigation behavior in its social setting. The participant is not removed from the farmer's world, but comes into close contact with that setting and resulting behavior.

All of the above factors make qualitative interviews a valuable tool for a Diagnostic Analysis of an irrigation system. These same types of studies, however, also have certain disadvantages.

1. If a participant is conducting these studies in the field, he or she likely affects the farmers' behavior and responses. Simply by being in the field, the participant's presence alters the behavior of the farmer.

2. The investigator takes interview notes from his/her own perspective. The biases each interviewer takes into the field unintentionally can alter later interruption.

3. The overall design of such studies often can be very unsystematic; later, the participant may have trouble making sense out of recorded observations.

4. The unintended selection of community elites as key informants may result in an elite bias in the data.

A second, and somewhat different type of data gathering technique is the survey questionnaire.

DEVELOPMENT OF THE SURVEY QUESTIONNAIRE

The structured questionnaire is the most frequently used instrument for collecting socio-economic data. Understanding its design and purpose helps project personnel make the best use of it. Most socio-economic surveys are designed to obtain information from a single structured interview. The single interview reduces the cost of obtaining data, both in terms of money and time. Information not asked for or not recorded during the first interview usually is lost, therefore, it is essential that the questionnaire be designed as carefully as possible before interviewing ever begins. It is far less costly to spend additional time designing the questionnaire than to return for a second interview to obtain important missing informaton.

DEFINITION

A questionnaire is a written form with 1) a set of questions to be answered by a respondent, and 2) instructions for the interviewer on how to ask the questions and record the answers. The questions are organized so the answers can be easily tabulated and statistically analyzed.

The questionnaire usually contains open-ended questions that require the respondents to give their opinions and closed-ended questions that contain predetermined answer categories into which the respondents' answers are placed. Other questions directed to the interviewer ask for objective and subjective observations. There also may be requests for information about the interview, such as identity of interviewer, location of the interview, date, and time.

DESIGNING THE QUESTIONNAIRE

The person most responsible for the questionnaire is the social scientist. He or she should have extensive training and experience designing questionnaire formats that are used easily by the interviewers and data analysis personnel. The questions also need to be formulated so as to be easily understood by the farmers and key informants.

All team members, however, should be involved in determining the topics to be covered in the questionnaire and should be encouraged to submit questions. Team members can provide technical background and insights related to their disciplines.

People familiar with computers should be consulted if the data are to be mechanically tabulated and analyzed. They may suggest format designs that reduce tabulation error or increase flexibility for cross tabulation of data.

The host country's workshop coordinator should receive a draft of the questionnaire to ensure that the project's personnel and sponsor are in agreement. The final draft of a questionnaire should be reviewed and approved by all team members.

WHO USES THE QUESTIONNAIRE?

1. An interviewer uses the questionnaire to obtain information. An interviewer must understand the questions (know the correct interpretation) and be able to follow the instructions.

2. A field supervisor or training officer is responsible for seeing that the interviewer completes the required number of interviews and for ensuring that each of these interviews is of high quality. He/she also must edit the questionnaires for accuracy and completeness, and may be required to do some of the preliminary tabulations.

3. Data processing personnel transfer the data from the questionnaire to the computer. These people must be familiar with many computer applications.

4. The data analyst uses the statistical information to write a report reflecting the conditions of the survey area.

Often, all four of these roles will be assumed by the same individual.

A PROFESSIONAL CREED

A creed expressing the general attitudes the interviewer should have in regards to his/her job and the farmers should be kept in mind at all times. The creed should reflect the cultural and professional emphasis for the specific region and project. Following is an example of a creed that may provide general guidelines.

- I come as a guest to the village and into the house of the farmer. I will accept hospitality graciously, but never demand it. I will pay all debts and in no way take unfair advantage of my position.

- I shall respect the farmer, his family and all villagers. I will never be discourteous when I am with them. I will respect the opinion of others, no matter what that opinion is.

- At all times my personal conduct will reflect respect for religious, social and family traditions. Whenever invited and appropriate, I will participate in religious and social celebrations. I will follow village customs. I will wear appropriate clothing. I will treat villagers with proper courtesy and respect: I will speak with the villagers as equals.

- Because my work will be of service to the people of the area and my nation, I will fulfill my responsibilities to the best of my ability. This will be done with honesty and goodwill to reflect honor on myself and on those with whom I work. I will work always in such a manner that when I leave, researchers who follow me will be welcomed in the village because the people will know that we have come to help.

CONTENT OF THE QUESTIONNAIRE

The questionnaire should require the following information at the beginning of the interview: 1) name of interviewer; 2) name of the respondent(s); 3) location of interview; 4) date of interview; and, 5) time of interview.

Introduction

A short paragraph written in the local language should be provided at the top of the questionnaire to be read by the interviewer as a basic introduction to the interview. The paragraph should include: 1) what the interview is about and how the information will be used; 2) how the respondent was chosen; 3) that names will not be associated with answers; and 4) who is

sponsoring the survey. The interviewer should be prepared to spend time expanding on the introduction and answering any questions the respondent may have.

Questions: Nature and Sequence

Questions should be short and to the point. Ideally, they should be written in the language of the country and, as much as possible, in the local dialect. Time constraints, however, may make this impossible. It is useful to have a person from the local area read the questions and suggest changes to make them more understandable. Questions should use local units of measurements and weights. Farmers or respondent may become uninterested or uncooperative if they have trouble understanding the questions. They also may become defensive if they think the questions are unreasonable or if the answer is obvious. For example, if an interviewer is standing near the farmer's electric irrigation pump, one does not need to ask how the farmer pumps his water! Many questions can be answered by observation.

Closed-ended questions provide the respondent with a set of alternative answers to choose from or provide categories into which the interviewer can fit the answer. For example, how many hectares of land do you own: 1) none; 2) one to two; 3) three to five; 4) six or more.

A major advantage of closed-ended questions is that the interviewer can easily and accurately record answers. If the question is ambiguous, the interviewer immediately sees it does not fit a category and can clear up any misunderstanding. In addition, it is easy to hand tabulate data in the field for preliminary reports.

The biggest disadvantage of closed-ended questions is that they force answers into predetermined categories thereby losing some of the richness and variation that can provide insight into areas being explored. As a result, the categories themselves must be carefully designed. Categories usually are based on the designer's experience and knowledge of the subject areas, and on the pretest responses. When the survey is done in an area in which little is known about the socio-economic variables, it is easy to miss important information by using inappropriate categories. Experience shows multiple choice questions are not easily understood in some cases. Multiple choice questions also may bias the respondent's answer in a certain direction so as to distort replies.

The open-ended question usually asks for the farmer's opinions. For example, the interviewer may ask, "Do you think it is fair for the government to charge the farmer directly for the amount of water he uses?" "Why?" Open-ended questions encourage the farmer to share his opinion.

An important advantage of such questions is that the respondent has the opportunity to provide an answer from his own perspective. The cultural perspectives of the project team may be entirely different from those of the farmer whom they interview. The farmer may have a different rationality set from what was expected by the project team.

The open-ended question, however, is more demanding for respondent, interviewer, and analyst. A "What is your opinion about..." may bias the respondent to an answer that he thinks will satisfy the interviewer. The interviewer is expected to distinguish between relevant and irrelevant answers and probe vague or ambigious answers. If data are used for statistical purposes (rather than for case studies), answers must be coded. Coding open-ended questions requires careful interpretation of replies: errors reduce reliability.

The order in which questions are asked can add to the quality of the answers as well as increase the respondent's cooperation. Most surveys require several different types of information that can be thought of as information blocks. Questions should be ordered so one block of information is obtained before going on to another. Questions should progress from the general to the specific. If events involve some chronological sequence, questions should follow the chronological order.

An exception to the above is the sequence of sensitive questions. Such questions may differ within different cultures, but usually include most dealing with family and income. The most sensitive questions should be asked at the end after the interviewer has gained the trust of the respondent and the respondent is more at ease.

Well-trained and experienced interviewers may be able to disregard the question order on the interview form. If the interviewer guides discussion toward the questionnaire topics, the farmer may provide much information without being asked for it directly. The natural flow of conversation puts the farmer at ease and helps insure his cooperation.

LENGTH OF THE QUESTIONNAIRE

A long questionnaire is tiring for both the interviewer and the respondent. It may cause the farmer to become restless or give incomplete answers. The interviewer, on the other hand, may hurry through the questions without giving adequate explanations and become less alert to answers that should be challenged. The questionnaire should be limited so that the interview lasts an hour or less. If the survey requires more than an hour, it may be necessary to make a second appointment with the farmer.

The 8-1/2 x 11-inch paper size, e.g. the size of this page, usually is easier to handle than larger sizes. Paper quality should be good as questionnaires are handled a great deal. Lost or torn pages occur more frequently with low grade paper. If there are subsamples within the survey, the questionnaires may be color coded.

SURVEY PRETEST

What Is a Pretest?

The survey pretest is much like the first test flight of a new airplane. It is the research team's opportunity to try out on a limited scale the questionnaire, interviewing, sampling, tabulation, and logistics before doing the actual survey. The pretest should be carried out under the same field conditions as anticipated for the main study. In a Diagnostic Analysis study, the field reconnaissance is often used as the pretest.

Purpose of the Pretest

Most socio-economic surveys are designed to be carried out over a short period of time and involves single contact with each respondent. Once the survey interviewing is begun, major problems may be costly in terms of money and the quality and quantity of information.

The purpose of the pretest is to discover and correct problems before the full-scale survey begins. The survey design at this point is not finished, but it should have progressed to nearly a complete stage. Discussion with informants, interview training, and small-scale trials for each category should be complete. Results will show where modifications still need to be made. If serious faults are revealed and major changes are necessary, a second pretest is conducted following revisions.

The number of pretest interviews should be large enough that each category has an adequate review. Following is a more detailed review of specific areas of pretesting.

Questionnaire Pretest

1. There may be possible problems with the questions.

   a. The question may be vague or unclear.

   b. The question may be too long making it difficult for the farmer to follow.

   c. The farmer may not understand some of the words because the dialect of his village is different.

2. Measuring devices may be necessary to obtain better estimates. The farmer may have difficulty accurately estimating crop yields, the amount of feed given to animals, and so forth.

3. Memory aids may be necessary to help the farmer with certain questions. Such aids include records he has kept or information previously obtained from the reconnaissance survey.

4. Change in the sequence of the questions may increase the farmer's willingness to give answers or improve the quality of his answers.

5. Sensitive questions may need to be worded or positioned differently in the questionnaire. In some cases, they may need to be deleted.

Interviewing Pretest

1. The interviewer will become familiar with using the questionnaire.

2. The interviewer can report problems back to the field supervisor or training officer.

3. Field supervisors have an opportunity to evaluate the interviewer's training, honesty, and enthusiasm.

Sampling Pretest

1. The pretest can provide important sampling information concerning

   a. Population size,

   b. Geographic dispersion,

   c. Settlement patterns, and

   d. Suitability of stratification classifications

2. Adequacy and accuracy of maps and sampling lists can be checked.

Tabulation Pretest

1. Frequency tabulations may indicate data consistency problems or a need for a change in closed-ended question categories. This is especially evident by examining the "other" category in these questions

2. Coding and tabulating open-ended questions may make it possible to change these questions to closed-ended questions.

3. Further training of the interviewer may be indicated if the tabulator has difficulty understanding the responses or the interviewer's handwriting.

4. Pretest tabulations should indicate significant differences in responses among different sample groups which may affect how the questions are worded.

Operations and Logistics Pretest

1. Pretest can provide a realistic estimate of the average number of questionnaires per day that can be completed.

2. The training officer can determine the amount of supervision necessary to maintain quality control.

3. Realistic deadlines can be set from the above information.

4. The pretest period is a good time to listen to interviewers' complaints caused by the stress of living and traveling in strange surroundings.

CONCLUSION

Whether the participant in the Diagnostic Analysis uses a qualitative, unstructured field study, or a more quantitative, structured survey questionnaire, there are some general rules to follow. These rules help to ensure that the data are both valid and reliable.

1. Cross-check the data gathered from key informants with other key informants.

2. Use different strategies of collecting and analyzing data. For instance, try both a qualitative and quantitative approach to the data.

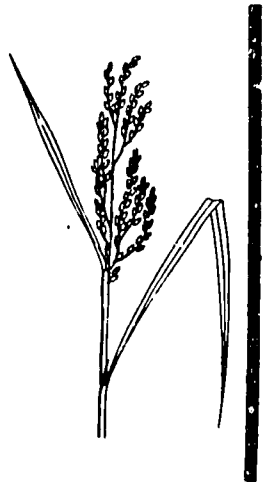
3. Use different times, persons, and social situations to provide several accounts of the same event.

4. Use community members to verify the meanings of important concepts. For instance, does your meaning of "system maintenance" have the same meaning as it does to the farmer at the tail of a watercourse?

5. Use personal observation whenever possible to verify interview data.

6. Use interdisciplinary research teams to evaluate interpretations.

Although in this article we have divided the data collection techniques into two general catagories, the best overall strategy is to combine the methods to take advantage of the strengths of each approach. Though more time-consuming, such an approach most likely will produce a better and more accurate final product.



FIELD DIARIES*

by J. Layton and M. Lowdermilk

Field diaries are used to record the researcher's observations and thoughts during the research process. A field diary provides an organized method of observation which supplements formal measures of the research design. For a field diary to serve a useful purpose, it must meet four major objectives.

OBJECTIVES FOR THE FIELD DIARY

1. A field diary should help the investigator understand the physical and social setting. The diary can be used to describe the situation so that the participants can view the setting from a proper perspective. For instance, before starting a research program a researcher must be aware of the social and physical situation of the rural area. Aspects of the situation that can help place the research program in its proper perspective include such factors as average age and level of education of the population to be studied, the degree of complexity in the society, the degree and type of stratification and the values and beliefs of the population. The physical environment of the population to be studied also can reveal many things about the population. Writing down observations and impressions of the social and physical

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* Modified from an article in The Problem Identification Handbook, (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100. Fort Collins, CO.

environment sensitizes the researcher to the boundaries of the research activity.

2. A field diary should describe the research process: who, what, why, where, when, and how. Who refers to the sample being surveyed. If the sample includes specific persons, the diary can be a record of the relationship between the researcher and the people studied. Questions can be explored such as: What effect does the researcher have on the people and how does that influence the answers that they give him? Is the researcher an outsider, a member of the group, a leader, or someone else?

The what question concerns the information gathered. Does the surveyed information create conflict, make people suspicious, or is it perceived by the farmers and officials to be of help?

The questions of why, where, when, and how are procedural questions. When a researcher begins to interpret information surveyed about a selected group of people, for example, farmers, the information has greater meaning when the researcher can interpret that data from a particular perspective. The diary helps the researcher recall various influences that were present when the information was obtained.

3. A field diary should be able to evaluate the research activity. The researcher can record successes and failures, unique events, problems, and other conditions that shape the form of the research activity. Such information helps the researcher evaluate how the project is proceeding.

4. A field diary should sensitize the researcher to conditions affecting the project. Recording observations and beliefs enables a researcher to pick up clues about how the project is progressing. The researcher then can begin action to modify an activity and thus, feel closer to the project and its workings.

PROCEDURE FOR WRITING A FIELD DIARY

In writing the field diary, there is no special format. Three general considerations, however, should be addressed: schedule, administrative support provided for writing a diary, and the method of recording. Field diaries should be written daily in chronological order so information is not forgotten or changed because of forgetfulness. Various administrative incentives help motivate a researcher to keep a diary. Forms containing a checklist of what to consider when writing a diary can be printed. Information for diaries can be directly written into notebooks or recorded on tapes which are then transcribed. The

critical concern is that a diary is written on a regular schedule according to a systematic outline.

CONTENT OF THE FIELD DIARY: OBSERVATION

Diary content should be organized under two general categories: observations and impressions. Observations include the more formal descriptions of the physical setting, the demographic setting, and the organizational setting of an area. The physical setting includes climate, geographic area, resources, and so forth. Demographic setting includes descriptions of the concentration of people, movement of people, and general characteristics of the people (e.g., age, sex ratio, fertility). Organizational setting includes a description of the different social levels in the social system, the communication network, and the degree of complexity in the system. These observations place the research project in the perspective of the researcher.

Within the situation, units of analysis are observed such as, individuals, small groups, clans, families, tribes, villages and so on. Observations can be made of situations and interactions. Observation of interactions include that between team members, between the team and pertinent governmental agencies, and between the team and the studied population.

Observation also should focus on the research process itself. This involves evaluation of how the research is being implemented; how thinking about the problem is progressing; and, how data collection and analysis are being conducted. This again includes observation of personnel interaction.

CONTENT OF THE FIELD DIARY: IMPRESSIONS

The second general category in a field diary is the more subjective impressions of the recorder. Impressions are important in that they provide a perspective for the researcher to evaluate the observations. Thus, impressions should be given on all observed aspects of the research process: individual opinions, concerns, and general comments on various conditions of the research project. As a result of this exercise, new ideas may emerge and a better understanding of the dynamics of the research process may occur.

In conclusion, field diaries are instruments by which personal observations and impressions are recorded in an organized manner. Diaries should be written daily. The diaries are personal and subjective: they supplement the formal method of the reseach process. Field diaries can make the research process more complete and thus more responsive to its stated goals and objectives.

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FIELD INTERVIEW TECHNIQUES*

by M. Lowdermilk, J. Layton and W. Smith

OBJECTIVE

The objective of a field-level interview is to obtain information that reflects the farmer's actual socio-economic conditions. The farmer's "social web", that is, family group, community affiliations, and organizations is part of that desired information.

RESPONSIBILITY

The primary responsibility of the interviewer is: 1) interview all the assigned respondents; 2) record all responses accurately, but be alert for answers that may not be fully correct (The interviewer then needs to ask for further explanation of the answer, for example, "Do you mean.." or "Does this include all..?"); and 3) obtain all data required by the questionnaire. You also must understand how the data will be used so you can report questionnaire design problems to the supervisor early in the data collection process.

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* Modified from an article in The Problem Identification Handbook. (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100. Fort Collins, CO.

GUIDELINES

Good interviewing is a combination of carefully following instructions and using good personal judgment. The following section contains instructions to use as guidelines rather than as unbreakable rules. Although the instructions should be followed whenever possible, each interview situation is different, so the interviewer's technique must be flexible.

1. Meet with key opinion leaders and authorities in the village before interviewing. Explain who is sponsoring the survey and how the information will be used. In some cases, village leaders may wish to be interviewed to show the farmers that they approve of the survey thereby adding status to those chosen to be interviewed.

2. Be sensitive to the traditions and customs of the village. Interviewers often will work among farmers whose lifestyle and customs differ from their own. Interviewers can do several things to minimize these differences and gain greater acceptance. Wear appropriate informal work clothes when interviewing farmers. When speaking to farmers treat them as equals, not as an officer might treat one of his subordinates. Try to use the language dialect of the village in which you are interviewing. Carefully follow all local customs with regard to religious observances. Although a village generally may be receptive to the interviewer, political events may occur that temporarily make the interviewer unwelcome. Announcements by the government or other countries may make farmers unwilling to give interviews for a few days.

3. Take time to explain the purpose of the interview. Farmers often are suspicious of strangers. They may be afraid an interviewer will be responsible for increasing their taxes or will discover illegal activities in which they are involved. Before beginning the questions, explain how the farmer was chosen and why the study is being done. Answer honestly all the questions the farmer may have. Assure him that the data will be kept confidential, that reports will refer only to summaries of numbers, and that no one will be able to trace answers to a specific respondent. Then be sure to keep these promises.

4. Be thoroughly familiar with the questionnaire. Complete familiarity with the questionnaire helps determine the relevancy of an answer and helps you interpret questions for the respondent. When answering a question, a farmer may continue his discussion and provide answers to other questions without being asked. These answers should be noted in the appropriate places on the questionnaire.

5. Be sure to have adequate directions for locating the farmer-respondent. Valuable time can be lost searching for a respondent. Village leaders are a good source of information about the location of a respondent's house or farm. They also may know if the respondent is likely to be at his fields. A guide who lives in the area may be hired. He may not only know the farm of the respondent, but also where he most likely can be found. If the guide is well liked in the village, he may be useful in introducing the interviewer to the respondent.

6. Interview the family member best able to answer the questions. The head of the household often is an uncertain term when extended families are involved. The oldest male member of the family may be the head in terms of social status, but have little decision-making power or knowledge of farm operations. Crop and irrigation data may be known only by a person who works in the field. Marketing, price or cost data may have to come from a different person. Older family members may be best qualified to answer questions about sociological relationships.

7. Put the farmer at ease and gain his confidence. Offers of cigarettes to adults and candy to children help to gain the farmer's cooperation. Walking with the farmer through his fields and discussing farm topics show him you have a sincere interest in his work. At the same time, you can make observations that relate to information required by the questionnaire.

8. Whenever it is appropriate, make actual counts or take actual measurements. Livestock may be counted and storage areas measured. Field areas may be estimated by counting the steps required to walk around the field. Amounts of livestock feed fed daily may be weighed.

9. Interview the farmer in private if possible. The presence of other persons, especially other farmers, may cause the respondent to give answers he wants his neighbors to hear rather than true answers. Interview the farmer in his fields to ensure a private interview. However, if others are around, do not make the farmer or others persons uncomfortable by insisting the two of you be left alone. Use your best judgment.

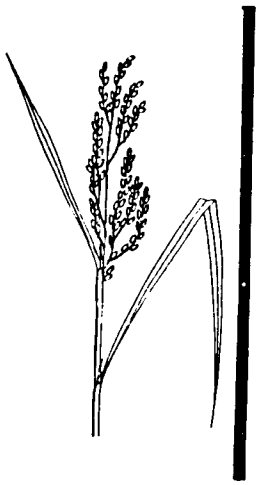
10. Think critically about the information you receive. The farmer may misinterpret a question, an answer may not be complete, or an answer may not be consistent with other answers or with what you observed on the farm. Use your best judgment in rephrasing the question or probing for a better answer. Do not confront the respondent with the suspicion that he is not answering honestly. Note inconsistencies on the margin of the

questionnaire and finish the interview. It is better to lose one piece of information than to have the respondent become angry and stop the interview before it is finished.

11. Ask to complete the questionnaire at a later time if the farmer wishes to stop the interview before it is complete. Farmers may not have time to complete the questionnaire during the first interview. In that case, make an appointment to complete it at another time, but as soon as possible. The questionnaire must be completed, even if it requires a second visit.

12. At the end of the interview check to see that all questions are answered. At this time, you may discuss any inconsistencies you may have noted; however, avoid antagonizing the respondent. Write comments you may have about the interview that may be useful to those who tabulate and analyze the data.

13. Thank the respondent for his cooperation. It is important that the interview be concluded on a note of good will. Other farmers will ask the respondent about the interview. Their cooperation may depend on the attitude of the respondents already interviewed. In addition, you may need to return to obtain further information or clarify an answer.



SAMPLING

by J. Wilkins-Wells
and R. Laitos

INTRODUCTION

Perhaps the first question to ask when considering sampling is why do we do sampling in the first place? Why is sampling stressed so much not only in the social sciences, but in agronomy and engineering as well?

Very often, people involved in Diagnostic Analysis studies need to study some specific population: a group of farmers within a command area, rice plants in a paddy field, or tubewells in an improvement project. By using correct sampling procedures, we do not have to study every farmer, every rice plant, or every tubewell. Instead, we can accurately study the farmers, rice plants, and tubewells by choosing only a limited number of them for study. Sampling is easier and less time consuming because fewer units need to be examined.

It is generally acknowledged that sampling is the best way to make generalized statements about population characteristics without entering into the costly and time-consuming task of surveying a whole population. Sampling also can provide greater accuracy than large-scale population surveys. The logistics of sampling are more manageable; better quality data is provided; and follow-up research is easier.

As mentioned previously, sampling is based on the assumption that you can select and examine a small section of the larger population that accurately reflects all the important characteristics of that population. What we discover about the sample also should be true for the population. However, this is known as a probability statement for with sampling, there is always

a small chance of being wrong. You abandon certainty and replace it with probability, but you also know the chances of being wrong.

Sampling involves selecting or randomly choosing a set of units from a larger population or subpopulation for statistical purposes (Figure 1).

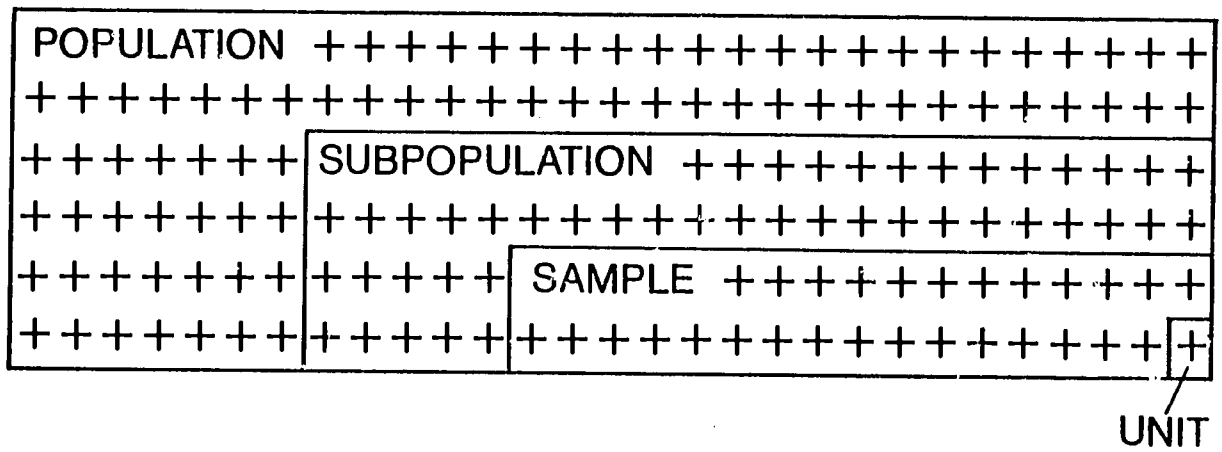


Figure 1. Diagram of the Sampling Process

For example, a population would include all the farmers who use water from one particular irrigation system. The subpopulation would include all the farmers within one particular command area. The sample would include all the farmers selected or randomly choosen from the population and subpopulation to be interviewed. An individual unit is simply one particular farmer within the sample.

In other words, a population is simply a specified collection of things to be surveyed: farms, income levels, soil or plant features, irrigation command areas, kinship groups, people, or simply a collection of numbers. A population is whatever the researcher wishes it to be. A subpopulation is a special category within a population. A unit is the individual object drawn from a population or subpopulation. It is the basic unit of analysis.

There are two important scientific and theoretical goals to sampling. The first is to maximize the ability to generalize findings. The goal is to have the values of the sample match the values of the population as closely as possible. For instance, if the mean landholding size of the population is one hectare, a proper sample also would show a mean landholding size of approximately one hectare. The second goal is to maximize the opportunity for new insights by guaranteeing that the sample chosen truly represents the variation found in the population. A scientifically useful sample is representative of the population. For example, if the plant height in the population in a selected field ranges from 20 to 50 centimeters, then a correct sample also should contain plants from 20 to 50 centimeters.

The individual units chosen also must be quantified in some way, that is, be given a number so that statistical methods can be utilized (See the subsequent article on reliability and validity measurement checks.)

PROCEDURES FOR SELECTING A SAMPLE

Certain rules and procedures must be followed if sampling is to have any scientific value. The following brief discussion will cover the most important rules and procedures needed when selecting a sample from within a population. From this presentation, the reader should achieve a basic understanding of how to organize methods of sampling.

Various sampling rules and procedures must be followed to control research bias and statistical error. In establishing a specific sampling design, one must ask the following general questions:

1. What resources are available for the study?

2. How much does the researcher already know about the population?

3. How acccessible is the population?

4. How does the researcher want to generalize the results of the sample findings?

APPROPRIATE SAMPLING PROCEDURES

Certain sampling rules can guide the researcher in choosing the appropriate sampling procedures.

- Define the Population. A clear definition of the population is needed along with a concise definition of the sample units. What do we want to generalize from the sample to the whole population? It is important initially to make some statements about the population under evaluation and the units being examined. If ones does not have an adequate understanding of the population in advance, it is difficult to select an appropriate sampling procedure. This also allows future researchers to replicate the sampling procedure and statistical analysis.

- Choose the Sampling Frame. If a Diagnostic Analysis participant wanted to study the behavior of irrigation officials in a particular area, a list of all those officials would have to be made. This is called a sampling frame. From this list, the participant would select a representative sample of officials using one of the methods outlined later in this article in Tables 2 or 3. A sample is only as accurate as the list of units from which it is drawn. All members of a population must have an equal chance of being selected. Potential omissions from the list must be identified. The reason for this is that sample survey findings are representative of a population to the degree the units include all the variability in the population.

- Select the Sample Size. The task of choosing the sample size, one of the most important aspects of a sample survey, varies greatly depending upon the selected sampling frame and procedure. Thirty units or values are usually considered the minimum for statistical purposes. Many researchers, however, advocate larger minimum numbers. There are four important points to remember when considering sample size:

  1. The greater the estimated variability or variance around a population mean, the larger the sample size needed. This is illustrated in the following diagram, where the larger variability displayed in (b) would require a larger sample size than (a).

$\bar{x}$ Estimates n More Accurately

$\bar{x}$ Estimates n Less Accurately

Population Mean -- n (Frequently Estimated)
Sample Mean -- $\bar{x}$

Any population element has an average (mean) frequency, and a spread (variance) around that average. It is helpful to note that if every unit in a population had the same value, then a sample of one would be sufficient. Conversely, a wide distribution spread of measurement values for a population of units would require a large sample. For instance, if all farmers in the selected population owned only one hectare of land, and landholding was the important variable studied, then only one farmer would need to be selected. Conversely, if a field contained many different heights of plants, then many plants (the units in this case) would have to be chosen.

2. The greater the heterogeneity (diversity) in a population of elements, the larger the sample size needed. However, large samples from populations of dissimilar units tend to increase the probability of sampling error--the degree of error between the known or unknown population values and the sample values; however, these large populations can be effectively sampled by more controlled procedures. Such procedures include developing special categories called sub-populations. For example, a population of farms could be broken down into joint versus individual operation, land holding size, tenure pattern, type of irrigation water source, cropping pattern, or head versus tail in the distribution of water.

3. The greater the number of categories in the population the larger the sample size needed. Although using categories reduces the diversity, and therefore reduces potential sampling error, each category must be represented in the overall sampling procedure--unless the population is redefined as simply a given category. To generalize from the sample to the population, a sample must contain the same variation that exists in the population defined. An acceptable rule is that sampling error is reduced by an increase in the sample size and a decrease in internal diversity of the units.

4. The greater the precision desired, the larger the sample size needed. For a sample to be truly meaningful, both its value and its probability of representing the population value need to be stated. The probability value represents the degree of precision with which the sample statistic estimates the population value.

   With a probability of .95, it is estimated that some sample value, such as farmer age, will occur within one standard deviation of the unknown farmer age in the population. A probability of .99 implies that this sample value will occur within two standard deviations of the unknown population value. These are confidence limits (intervals) for sample estimates of population values.

   For example, if the sample values (such as age) should not exceed a 1% or 4% difference from the population values, then to guarantee a probability of .95, the researcher would have to choose a population size of 9,604 or 600 as shown in Table 1.

Table 1. Simple Random Sample Size for Several Degrees of Precision

Tolerated Error %	Confidence Limits (intervals) 95 Samples in 100	99 Samples in 100
1	9,604	16,587
2	2,401	4,147
3	1,067	1,843
4	600	1,037
5	384	663
6	267	461
7	196	339

Source: Parten, Mildred. 1958. Surveys, polls, and samples. Harper and Row, NY.

- Reduce Sampling Error. There are several common sources of sampling error which cannot be corrected by increasing the sample size. Some of these are:

1. An incomplete population list and/or sampling frame;
2. Non-responses in a questionnaire sampling frame;
3. Non-coverage of units that should properly belong in the sample; and
4. Poor sampling distribution assumptions.

In such cases, sampling error is reduced by improving the quality of the sampling procedure.

- Reduce Non-Sampling Error. The major sources of non-sampling error include:

1. Non-randomized features in the overall sampling procedure;
2. Error in measurement;

3. Error in the assigning of numerical values to units sampled from the population; and

4. Data processing errors.

PROCEDURES (DESIGNS)

Tables 2 and 3 present a brief description of several sampling procedures or designs that are often used in Diagnostic Analysis studies. They are equally applicable to soil, crop, and water analysis. The main distinction between the various procedures involves the notions of probability and of chance selection of population units.

PROBABILITY VERSUS NON-PROBABILITY

The basic difference between probability (Table 2) and non-probability (Table 3) sampling is that, in the former, the probability of selecting each unit is both known and non-zero, whereas in the latter it is not. In probability sampling, it is expected that every unit chosen has a known, non-zero probability of being in the sample, yet it is not necessary that these probability values be equal. We can apply weighting procedures to those that are not.

Probability sampling allows one to utilize good statistical inference tests by avoiding conscious or unconscious biases in the selection of population members. Non-probability sampling does not have this facility despite having good samples. Probability sampling maximizes the ability to generalize the sample findings to the whole population.

Sampling procedures that do not involve chance selection are called non-probability designs. Non-probability sampling is generally less complicated and expensive, and is clearly adequate for exploratory studies and even theory construction. However, it often limits the researcher's ability to generalize from the sample to the population.

RANDOM SAMPLING

Random sampling refers to a selection process in which each unit of a population has an equal chance of being selected. There is random sampling with or without replacement. The most commonly used form of random sampling is that without replacement, often called "simple random sampling".

If the population size is relatively large and/or one has a small sample size, the effects of random sampling without replacement are very small. Each draw out of a sample frame increases the probability value of remaining population

Table 2. Types of Sampling Designs: Probability

Type of Sampling	Brief Description	Advantages	Disadvantages
A. Simple Random Sampling	Assign each population unit a unique number. Randomize, and select units with or without replacement.	1. Minimum knowledge of population characteristics needed. 2. Free of possible classification errors.	1. Does not make use of of knowledge of population possessed by researcher.
B. Systematic Random Sampling	Choose sampling ratio (proportion of units to be sampled from the population). Then, choose units from the randomized sampling frame in a specific order, i.e. every 10th unit.	1. Same results as simple random sampling, using smaller sampling frame.	1. Sampling may be biased by an unobserved periodicity in the population.
C. Stratified Random Sampling	Select a simple random sample from each defined category of the population. Maximize inter-category variation, and minimize intra-category variation.	1. Assures representation of all research categories in population. 2. Reduces sampling error.	1. Increases sampling bias derived from classification procedures.
D. Cluster (Area) Sampling	Sampling of groups or clusters, followed by the selection of units within each of the selected clusters. Maximize the number of clusters selected, and minimize the number of units within each cluster.	1. Good for very large populations and/or when sampling frame is difficult to consider.	1. Larger errors for comparable size than other probability samples.
E. Multi-Stage Cluster Sampling, Stratification	The successive random sampling of clusters and groups within clusters, with the addition of defining stratification variables for clusters. Maximize heterogeneous clusters.	1. Good for large populations. 2. Can handle several relevant stratification variables at same time. 3. Reduces variability of simple cluster sampling.	1. Sampling errors are cumulative in multi-stage cluster designs.

(Table 2. (continued)

Type of Sampling	Brief Description	Advantages	Disadvantages
F. Probability Proportionate to Size Sampling (PPS)	A two-stage sampling procedure, where clusters are given a chance of selection proportionate to their size, then followed by the same number of units being chosen from each cluster.	1. Reduces selection bias of most cluster (area) sampling designs.	
G. Disproportionate Sampling and Weighting	Giving units a disproportionately better chance of selection, or making sure that the units in the sampling frame are represented by the same proportions that exist in the overall population.	1. Allows manipulation of sampling frame for research purposes.	1. Weighting affects statistical inference tests considerably.

Table 3. Types of Sampling Designs: Non-Probability Sampling

Type of Sampling	Brief Description	Advantages	Disadvantages
A. Quota Sampling (Stratified)	Each category chosen for sampling is generally represented in the sampling list in the same proportion as exists in the entire population.	1. Guarantees inclusion of minority population groups in sampling frame.	1. Requires considerable knowledge of population trait distributions and/or proportions. 2. Can result in considerable sampling error.
B. Dimensional Sampling	Developing a research typology, then choosing randomly from each cell of the typology.	1. Frequently useful for developing research hypotheses.	1. No generalizability from sample to population.
C. Purposive (Judgemental) Sampling	Select units in the population which, on the basis of available information, can be judged to be representative of the total population; take a complete count or subsample of these units.	1. Good for exploratory studies on population.	1. Variability and bias cannot be controlled. 2. Requires considerable knowledge of population and/or units selected.
D. Snowball Sampling	Conducted in stages. The first stage involves selecting units (people) having requisite characteristics for research. The second stage involves selecting people recommended by first stage informants.	1. Good for sampling subcultures or particular networks, or when the distribution of population categories is not known.	1. No generalizability from sample to population.
E. Contrast Sampling	Sampling from the extreme values of a trait or variable in the population, or drawing samples from groups which contrast in the variables most important to research.		

members. However, as long as the sample remains small enough, the effect of these higher probability values for remaining population members is negligible unless the sample size is equal to or more than one-fifth of the population. If this is so, then there are correction formulas that can be used to estimate the appropriate standard error.

In the sampling designs presented in Tables 2 and 3, most are probabilistic, although a few popular non-probabilistic designs are described. Depending on the situation and the research problem at hand, the more effective samples will include a combination of these various types of sampling designs or procedures. Depending upon the overall goals of the research, it should always be remembered that both probabilistic and random sampling may or may not be warranted.

CONCLUSION

The size of the sample is of primary concern when selecting a sample plan. The population must be precisely defined to construct an appropriate sampling frame. In addition, the type of data required must be determined.

Previous studies on the selected population will need to be reviewed. Degrees of precision are established in advance. The relative efficiency of various sampling procedures then are evaluated in relation to how they apply to the problem, the data, and the available financial and human resources.

The form of data collection, having been determined, is pretested on the sampling frame. A regular sample survey follows the pretest and includes the final step of data intrepretation, that is, the ability to generalize.

For more in-depth descriptions of sampling please see the following references.

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RELIABILITY AND VALIDITY CHECKS: INTERVIEW DATA*

by M. Lowdermilk and J. Layton

When evaluating a questionnaire, the primary concern is whether the information obtained reflects what is truly occuring in the world. Two types of tests are used to determine how well an interview achieves what it is intended to achieve: reliability tests and validity tests.

Reliability is the consistency, stability, or dependability of a measuring instrument. Example: when two independent investigators use the same interview instrument and come to the same results, the reliability of the instrument is said to be good. Validity, on the other hand, is a test to see if a measure does in fact measure what it is supposed to measure. Example: in asking farmers to rank their farm problems in terms of importance, they may give the highest ranking to water because the interviewer is involved with water management. This results in a low degree of validity because the answer is based on the farmer's perception of what the interviewer can do for him.

Tests have been designed that evaluate reliability and validity. The outline which follows addresses these procedures.

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* Modified from an article in The Problem Identification Handbook. (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100. Fort Collins, CO.

1. Reliability Tests

   a. External Consistency Procedures

      - Test-Retest

      - Parallel Form

   b. Internal Consistency Procedures

      - Split-Half

2. Validity Tests

   a. Face Validity

   b. Content Validity

   c. Criterion Validity

RELIABILITY

As indicated, two procedures help determine the degree of reliability of a questionnaire: (a) external consistency procedures and (b) internal consistency procedures. External consistency procedures compare the cumulative test results against themselves to verify the reliability of a measure. Two examples of this procedure are the test-retest measure and the parallel form of the same test.

With test-retest, the researcher interviews a farmer for the first time after a predetermined time period, the interviewer (or another interviewer) returns to the same farmer and conducts the same interview. The purpose is to see if there is measurable agreement between the first and second tests. If there is, it can be inferred that the questions have a degree of reliability.

Table 1 presents an example of the test-retest measure of reliability. As the table indicates, the variables "Nitrogen Fertilizer Applied to One Crop" and "Nitrogen Fertilizer Applied to Second Crop" had a lower reliability than the other variables, based on the "r" correlation figure. The farmers retested, then, gave very similar figures for the other variables listed in Table 1, but not so similar figures for "Nitrogen Applied." A participant in Diagnostic Analysis would treat these two variables with a great deal of caution.

With the parallel form of the same test, a farmer's knowledge, for example, of watercourse management is measured during an interview; after a period of time, he again is

Table 1. Test Re-test Reliability of Selected Measures

Item	Number of Farmers Interviewed	Percent of Sample Retested	Pearson Product Moment Correlation "r"*
Total Acres Owned	75	19.3	.996
Acres Cultivated This Watercourse	76	19.6	.978
Cropping Intensity (Wet & Dry Seasons)	74	19.1	.814
Nitrogen Fertilizer Applied to One Crop	73	18.8	.680
Crop Yields (Acre)	69	17.8	.840
Trading Full Irrigation Turns (Wet & Dry Seasons)	74	19.1	.826
Nitrogen Fertilizer Applied to Second Crop	74	19.1	.686
Percent Increase in Yields	75	19.3	.926
Percent Increase in Acreage	72	18.6	.846

*A fuller discussion of Pearson's "r" as well as Spearman's rho immediately follows this article.

interviewed measuring the same knowledge, but using different questions. If there is a measurable agreement between the responses, a degree of reliability can be inferred for the surveys.

Several problems occur in determining reliability from the above two procedures. The major problem is that the first test affects the farmer's subsequent responses by exposing him to the points brought out by the questions. When the second test is administered, the farmer's awareness of the questions may cause him to change his answers. The interviewer should be sensitive to this problem when interpreting the results of such procedures.

The second major procedures measuring reliability are internal consistency procedures. Such procedures attempt to increase the reliability by seeing if respondents' answers to various questions are based on some pattern of agreement. In other words, if a number of questions are used to measure one variable, a respondent who answers low on one question should also answer low on other related questions. One technique to measure such agreement is the split-half technique.

The split-half technique uses a large number of equivalent questions. After the data is collected, the questions are divided into two halves and compared for their equivalence. For example, a researcher wishes to measure the degree of innovativeness of farmers based on their income, education, and so forth. To do this, a questionnaire is constructed that contains a list of innovations adopted in the region. The list then is presented to a respondent who checks the innovations he uses. In testing the reliability of the instrument, the list of innovations is divided into two equivalent parts (that is, both parts have an equal number of easy and difficult innovations). A reliable instrument would be one where a farmer who scores high on one set of innovations also scores high on another set of variables that measure the same degree of innovativeness.

In addition, two types of errors, random and non-random, can occur which affect the reliability of a questionnaire. Random errors are the most difficult to recognize as they lack any pattern. Non-random errors, on the other hand, occur consistently throughout the questionnaire and can be more easily detected and corrected by a supervisor.

There are three reasons why either type of error transpires: 1) the questionnaire is not pre-coded; 2) the interviewer incorrectly codes the responses onto the questionnaire; and/or 3) the data is inaccurately entered in the computer.

Reliability is a practically critical problem when open-ended questionnaires are converted into quantitative data. Those persons coding and/or entering the information

must be instructed and supervised carefully to insure consistency of coding responses. A check should be made of the process after a few questions have been coded to see if there is standardized unity. If errors are discovered such as, coders making individual decisions about answers, they must be corrected and the responsible persons once again must be instructed according to the defined procedures.

VALIDITY

There are three types of validity tests: (a) face validity, (b) content validity, and (c) criterion validity.

The procedure that is least objective and perhaps most subject to error is face validity. One simply looks at the concept to be measured and makes an assumption based on observation. For example, measuring a farmer's wealth by counting the amount of equipment he has on his farm would be a measure having face validity.

With content validity, the question becomes: is the substance or content of the measure representative of the content of the property being measured? For example, if a questionnaire measuring a farmer's degree of wealth only asks questions regarding the number of items in his house while neglecting the ownership of farm equipment, the measure would not have high content validity. A measure with a high degree of content validity includes all aspects of a concept it is to measure.

Criterion validity is measured by comparing the researcher's test with another test known to measure the concept under study. For example, if a researcher measures and compares results of a test with a previously used and recognized measure that also was used and the results are equivalent, then it can be said that a high degree of criterion validity is present.

EVALUATION OF MEASURING DEVICE

Evaluations concerning validity and reliability are used to determine if any biases occurred in the data gathering. The following questions should be asked when constructing a measuring device (such as a questionnaire) to determine the degree of validity and reliability.

1. Does the form of the questionnaire introduce any bias?

   - Is the questionnaire too long? A respondent may become tired toward the end of a long questionnaire and provide poorly thought out answers.

   - Are the sensitive questions placed in an appropriate position within the questionnaire? Inappropriate placement may cause the respondent not to answer truthfully.

   - Do the questions actually extract the information desired, either directly or indirectly?

   - Do questions parallel other questions so as to see if the answers given are consistent?

2. Does the cultural aspect of the measuring instrument lead to patterned biases?

   - Are the questions appropriately worded so as not to offend anyone?

   - Is the phrasing inappropriate?

   - What bias emerges from an open-ended questionnaire versus a closed-ended one?

3. What mechanical factors may emerge to create a patterned bias?

   - What is the reading and writing abilities of the respondent?

   - What is the time schedule for each interview? If time is too short, the interviewer may hurry to complete his assignment and negatively affect the quality of the answers.

4. What environmental factors impede the validity and reliability of the measure?

   - Is the personal interaction between the respondent and the interviewer appropriate? The following questions, among others, need to be addressed: Does the interviewer ask questions in a leading manner; does the socio-economic (class) difference between the two parties affect the questions; does the ethnic difference or similarity affect the interview?

   - Do the questions call for a respondent to depend on his or her memory and if so, over what period of time?

   - What are the physical facilities in which the interview is conducted? Is the atmosphere comfortable, hostile, or friendly?

5. Does the interpretation of the data lead to patterned biases occurring?

To ensure a proper degree of reliability and validity these questions must be considered when preparing the instruments and gathering data. Every effort should be made to alleviate conditions brought out by these questions that interfere with proper reliability and validity.

AUXILIARY INFORMATION:
RELIABILITY MEASUREMENT

When using reliability measurements, two possible statistics to employ are Pearson's "r" or Spearman's "rho". Both of these are correlation coefficients, which examine how a change in one variable is related to the change in another variable.

Pearson's "r"

Pearson's "r" is a measure of association that indicates the strength and direction of a linear relationship between two variables. This measure of association ranges from +1 to 0 to -1. An r = +1.0 indicates that as variable "x" increases, variable "y" also increases in a straight line. An r = -1.0 indicates that as variable "x" increases, variable "y" decreases in a straight line. This is referred to as statistical dependence. If there is no relationship at all between an increase in variable "x" and variable "y", there is statistical independence and r = 0. Interval level data is required for Pearson's "r". This correlation coefficient is calculated by the formula:

$$r = \frac{\Sigma(X_i-\overline{X})\ (Y_i-\overline{Y})}{\left[\Sigma(X_i-\overline{X})^2\right]\ \left[\Sigma(Y_i-\overline{Y})^2\right]}$$

where X_i = ith observation of variable x

Y_i = ith observation of variable y

$\overline{X}$ = mean of variable x

$\overline{Y}$ = mean of variable y

Spearman's Rank-Order Correlation (rho)

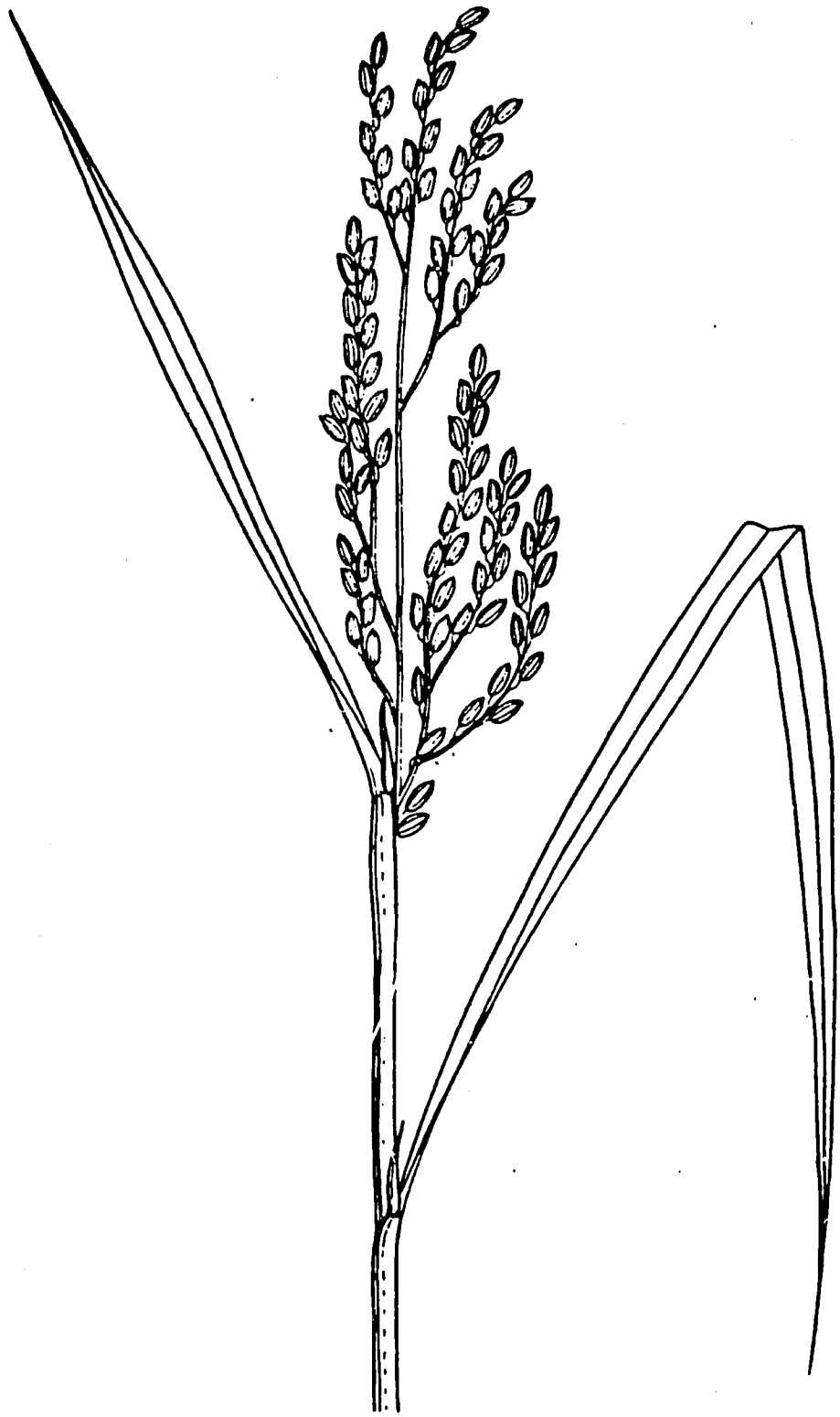
Spearman's rho is a measure of association used to determine whether two sets of rank-order data are related. To calculate the statistic rho, at least an ordinal level of measurement is required for both variables. The correlation coefficient for rho, however, can vary from -1 to 0 to +1. Complete statistical independence would be indicated by a rank-order correlation of 0, while complete inverse statistical dependence would be indicated by -1, and complete positive statistical dependence would be indicated by +1. Spearman's rho is calculated by the formula:

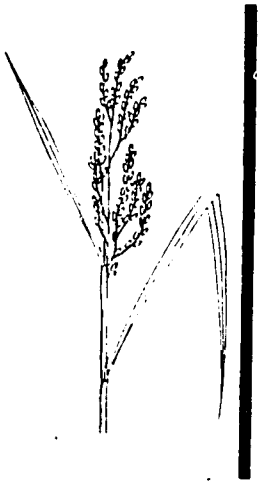
$$\text{rho} = 1 - \frac{6 \Sigma D^2}{N(N^2-1)}$$

where D = difference score between each X and Y pair

N = number of pairs of scores

ECONOMICS





FARM ENTERPRISE BUDGETING

by A. Madsen and
M. Haider

A farm enterprise budget is a systematic collection of relevant costs and returns associated with a specific crop, livestock, or other farm enterprise. Enterprise budgets do not remain the same from year to year. Continuous effort is required to keep input costs and product prices current and to accurately estimate production costs and potential revenue. Without current information, serious errors may be made in evaluating the economic consequences of available alternatives.

In some countries, public agencies assume responsibility for preparing enterprise budgets for major crop and livestock enterprises. Where this service is not available, producers or local organizations must prepare the budgets to the best of their ability.

Individual cost items are different for each enterprise budget: see Tables 1 and 2 which are budgets prepared by the Egypt Water Use Project teams for rice and wheat. The monetary unit is Egyptian pounds (LE). For example, the wheat budget identified seed costs and planting seeds by hand. The rice enterprise budget, on the other hand, identified costs for nursery plants pulling and transplanting. Cost items are different because there are various production input items and production operations that are unique to each crop. However, certain costs categories called variable costs and fixed costs, are common to all enterprise budgets.

Variable costs (or operating costs) are those that change with the production level during a given time period. As the production of rice increases, the farmer has to purchase more seed, use more labor, apply more water and fertilizer, and so forth. Thus, such costs vary with the rate at which they are used up in the production of crops or livestock. Variable costs are avoidable in that they need not incur when production is not undertaken.

The second cost category is fixed costs. Fixed costs also are referred to as ownership or overhead costs because it is often difficult to allocate some costs to specific products or enterprises. Fixed costs are costs not related to the level of production--they continue to incur whether or not production occurs. Such costs include depreciation, interest, taxes, and so forth. The crop enterprise budgets shown in Tables 1 and 2 have classified land rent and a management overhead charge as fixed costs.

To minimize economic losses, producers must receive returns sufficient to at least cover all variable costs and make some contribution to fixed costs in the short run. If variable costs are not covered, other things being equal, it is better not to produce the particular product.

Tables 3 and 4 provide information on labor and water use to help decision makers select enterprises and plan labor and water use. The information identifies labor and water requirements by month for each crop. After noting the crop mix, the total monthly requirements for labor and water can be estimated from the relevant tables. The next step is to estimate the amounts of labor and water available to the farm each month. By relating the input requirements and the input availability, it is possible to identify when there is surplus labor or water that can be used for other purposes or where there may be shortages of labor and water. If shortages occur in a particular month, the farmer must arrange to hire additional labor and to acquire additional water when possible. If financial or other constraints prevent farmers from obtaining the necessary inputs, different enterprise combinations must be considered. Although labor and water flow budgets are much simpler than cash flow budgets, they are important to the farm's overall success.

Enterprise budgets in Tables 1 and 2 can be used by individual producers as basing points for on-farm Diagnostic Analysis. When farm costs, production, or returns seem to be out of line with those of enterprise budgets, in-depth analysis of management and production practices can be made to identify where problems may exist. Such analysis involves consulting with engineers to evaluate water application and drainage practices, and with agronomists to consider the adequacy of cultivation, seeding rates, fertilization. Sociologists also can help determine why certain practices are followed that may reduce production or family income.

Table 1. An Example of Cost and Return Per Feddan* of Rice Production: Abu Raia, Egypt, 1980

Item	Unit	Number of Units	Price or Cost/Unit	Total Income or Cost
INCOME				
Rice Grain Sold to Government	Kg	900.00	0.075	67.50
Rice Grain Consumed/Marketed	Kg†	900.00	0.085	76.50
Rice Straw	C.L.	3.50	1.400	4.90
Total Income				148.90
VARIABLE COSTS				
Purchased Inputs:				
Seed	Kaila‡	6.00	1.080	6.48
Ammonium Sulfate, 20.6% N	Kg	141.00	0.048	6.77
Ammonium Nitrate, 33.5% N	Kg	5.00	0.074	0.37
Urea, 46.0% N	Kg	12.00	0.108	1.30
Super Treble, 42.0% P	Kg	14.00	0.089	1.25
Production Practices:				
Plowing	Feddan	1.00	5.400	5.40
Seeding	Man Hr.	1.00	0.300	0.30
Rice Puddling	Man Hr.	3.00	0.300	0.90
	Cow Hr.	3.00	0.080	0.24
Transplanting				
Pull and Transport	Man Hr.	20.00	0.300	6.00
Planting	Woman Hr.§	40.00	0.200	8.00
Weeding	B&G Hr.	24.00	0.050	3.60
Chemical Fert. App.	Man Hr.	6.00	0.300	1.80
Organic Fert. Transport	D.L.	50.00	0.050	2.50
Irrigation				
Water Lifting	Cow Hr.	58.00	0.080	4.64
	B&G Hr.	58.00	0.150	8.70
Water Application	Man Hr.	29.00	0.300	8.70
Ditch Maintenance	Man Hr.	12.00	0.300	3.60
Harvesting and Transportation				
Harvesting	Man Hr.	35.00	0.300	10.50
Threshing	Mach. Hr.	3.00	3.000	9.00
Winnowing‖	Kaila	7.50	0.850	6.38
Bundling	Man Hr.	8.00	0.300	2.40
Loading	Man Hr.	10.00	0.300	3.00

Table 1. (continued)

Item	Unit	Number of Units	Price or Cost/Unit	Total Income or Cost
Harvesting & Trans., cont.				
Transporting	C.L.	10.00	0.500	5.00
Taxes, Marketing and Weighing	Ton	1.80	0.68	1.22
Total Variable Costs				108.65
Return Over Variable Costs				40.25
FIXED COSTS				
Sakia (waterwheel)	Hour	58.00	0.110	6.38
Land Rent	Month	6.00	6.000	36.00
Land Tax	Month	6.00	0.830	5.00
Management	Month	6.00	1.000	6.00
Total Fixed Costs				53.38
Grand Total				162.03
Return Above all Costs				(13.13)

Source: EWUP Farm Management Survey, Farm Records, Staff Paper No. 21. and Abu Raia Cooperative.

*Feddan = .42 hectare.

†C.L. = Camel Load.

‡One Kaila of rice - 10 kg.

§B&G Hr. = Boy and girl hour.

||Paid in Kind at the rate of half kaila per ardab (150 kg), or 5 kg for every 120 kg of rice processed.

Table 2. An Example Cost and Return Per Feddan of Wheat Production: Abu Raia, Egypt, 1980

Item	Unit	Number of Units	Price or Cost/Unit	Total Income or Cost
INCOME				
Wheat Grain	Ardab	7.70	11.100	85.47
Wheat Straw	C.L.	5.00	9.600	48.00
Total Income				133.47
VARIABLE COSTS				
Purchased Inputs:				
Seed	Kaila	6.10	0.910	5.55
Ammonium Nitrate, 33.5% N	Kg	60.00	0.074	4.44
Urea, 46.0% N	Kg	33.00	0.108	3.56
Super Phosphate, 15.5% P	Kg	5.00	0.046	0.23
Super Treble, 42.0% P	Kg	8.00	0.089	0.71
Production Practices:				
Plowing	Feddan	1.00	5.400	5.40
Smoothing	Feddan	1.00	2.200	2.20
Seeding	Man Hr.	3.00	0.300	0.90
Weeding	B&G Hr.	12.00	0.150	1.80
Organic Fert. Transport.	D.L.*	100.00	0.050	5.00
Chemical Fert. App.	Man Hr.	4.00	0.300	1.20
Organic Fert. App.	Man Hr.	4.00	0.300	1.20
Irrigation				
Water Lifting	Cow Hr.	20.00	0.080	1.60
	B&G Hr.	20.00	0.150	3.00
Water Application	Man Hr.	20.00	0.300	6.00
Ditch Maintenance	Man Hr.	12.00	0.300	3.60
Harvesting and Transportation:				
Harvesting	M&W Hr.	36.00	0.250	9.00
Threshing	Mach. Hr.	3.00	3.000	9.00
Winnowing †	Kaila	7.70	0.930	7.12
Loading	Man Hr.	8.00	0.300	2.40
Transporting	C.L.	8.00	0.500	4.00
Total Variable Costs				77.91
Return Over Variable Costs				55.56

Table 2. (continued)

Item	Unit	Number of Units	Price or Cost/Unit	Total Income or Cost
FIXED COSTS				
Sakia	Hour	20.00	0.110	2.20
Land Rent	Month	6.00	6.000	36.00
Land Tax	Month	6.00	0.830	4.98
Management Charge	Month	6.00	1.000	6.00
Total Fixed Costs				49.18
Grand Total Costs				127.09
Return Above All Costs				6.38

Source: EWUP Farm Management Survey, Farm Records, Staff Paper No. 21, and Abu Raia Cooperative.

*D.L. = Donkey Load.
†Paid in kind at the rate of one kaila per ardab (150 kg) of wheat processed.

Table 3. Monthly Labor and Water Requirements Per Feddan of Rice: Abu Raia, Egypt, 1980

Month	Labor Requirements in Hours			Water Requirements
	Man	Woman	Boy/Girl	M^3
May	21		18	732*
Jun	42	40	31	2,188†
Jul	22		16	1,762
Aug	12		12	1,378
Sep	5		5	534
Oct	53			
Season	155	40	82	6,594

Source: EWUP Farm Management Survey and Farm Records.

* Water applied in the rice nursery.
† Includes the irrigation for rice transplanting.

Table 4. Monthly Labor and Water Requirements Per Faddan of Wheat: Abu Raia, Egypt, 1980

Month	Labor Requirements in Hours			Water Requirements
	Man	Woman	Boy/Girl	M^3
Nov.	22		3	410
Dec	3		3	334
Jan	2		14	205
Feb	11		7	755
Mar	5		5	529
Apr				
May	26	18		
Season	69	18	32	2,233

Source: EWUP Farm Management Survey and Farm Records.

PREPARING A CASH FLOW BUDGET

by A. Madsen

Preparation of a cash flow budget, whether formal or informal, is critical to decision-making on farms. A budget that shows the sources, amounts and timing of cash income and expenses is especially relevant to decisions concerning investments for irrigation systems. Partial budgets may show the economic benefits from improvements in water application or drainage, but do not show the ability to pay off debts that may be incurred to make the improvements.

A cash flow budget may consists of two tasks. The first is to identify the actual cash flow during the previous year. This involves documenting monthly income and expenditures for each of the last 12 months. The information may be prepared from farm records or from the farmer's best estimate. The second, and more difficult, task is to project next year's cash flow. The estimate may be guided by historical results and crop and livestock plans for the future. For major investments, such as land leveling, installing lined ditches and irrigation water pumps, or land purchases, it is necessary to pay off loans over time periods of more than one year. Therefore, this requires projecting expenditures and incomes for longer time periods to better estimate the ability to repay investments.

The following worksheets provide a step-by-step procedure to construct the cash flow budget. The entries are mostly self-explanatory, but every area of the world and every farm has its own particular cash flow characteristics. The forms may have to be adjusted to meet the conditions of individual producers.

To illustrate the use of the worksheets for monthly cash planning, a hypothetical example of an Indian farm is presented. The 2 hectare case farm is assumed to produce paddy and wheat. The monetary unit is rupees (Rs).

CASH FARM RECEIPTS

Worksheet 1A, "Estimation of Cash Farm Receipts: Crop and Other Income", indicates that paddy was sold in November. Note that only one fourth of the paddy is sold; the rest is kept for family consumption. All wheat produced is used in family consumption.

For Worksheet 1B, "Estimation of Cash Farm Receipts: Livestock Products and Livestock Sales", it is assumed the farm has two cows which are used as draft animals and for milk production. Only one cow is shown to produce milk during June through November which provides time for each cow to be dry for a period and produce a calf. It is assumed that one calf is sold each year in September and the other may die or is butchered for the family. The totals in the last column of Worksheet 1B are included in the final column of Worksheet 1A.

Because only two crops are produced, it is not necessary to use Supplemental Worksheet 1, "Estimation of Receipts from Crop Sales", to complete Worksheet 1A. However, Supplemental Worksheet 1 is included to show the type of information it provides.

CASH FARM EXPENSES

Worksheets 2A through 2E and Worksheet 3 are used to estimate cash farm expenses. All expenses should be recorded when they are expected to be incurred. The expense categories commonly are used in farm records. Interest expenses are not included in this series of worksheets because it is difficult to separate the principal payment and interest in future debt payments. Debt payments including interest expenses are entered in Worksheet 6 and Supplemental Worksheet 3. To project future costs, estimate the inflation or deflation for each category and then make further adjustment according to individual circumstances for a particular farm. For example, labor wage rates and the amount of labor used may increase. Therefore, the expected cost of labor would be larger than the simple adjustment for wage rates.

Labor, feed and livestock purchase cash farm expenses are estimated on Worksheet 2A. It is assumed that the cows are fed farm produced feed and some purchased feed. One animal was purchased in September in this example. The labor expenses are distributed among the months in which labor must be

hired as shown in the first columns. Worksheet 2B, "Estimation of Cash Farm Expenses: Machinery", contains entries for custom work. No custom work was hired in the example. The farm has no machinery repairs or fuel expenses.

Worksheet 2C, "Estimation of Cash Farm Expenses: Crops", identified cost estimates for fertilizer, seeds, sprays and land rent. It is assumed the farm does not rent. The estimated change in fertilizer costs reflects the expected ten percent price increase of this input.

"Estimation of Cash Farm Expenses: Real Estate Expenses" identified in Worksheet 2D are not substantial because the farm does not have buildings. Property taxes are not large.

Worksheet 2E, "Estimation of Cash Farm Expenses: Utility, Marketing, Misc.", identifies farm expenses for utilities. This hypothetical farm does not have any utility expenses or marketing expenses, but water charges are shown in the miscellaneous column.

Worksheet 3, "Summary of Cash Farm Expenses" pulls together all farm expenses identified to this point. The worksheets from which the monthly data are taken are identified with parentheses at the top of each column. The row and column data can be summed to check accuracy.

Worksheet 4, "Capital Purchases Planned", provides for detailed itemization of expected capital purchases. The hypothetical farm does not anticipate such expenditures during the coming year.

The preparation of Worksheet 5, "Cash Inflow and Outflow for Next Year: Including Non-farm; Excluding Credit", is a critical step in arriving at potential cash flow for a farm. The "Cash Farm Receipts" in Column 1 are taken from the last column of Worksheet 1A. The "Net Non-farm Cash Income" in this case is assumed to be zero. The sources of information for other columns are identified within parentheses. Care must be taken in calculating Column 8, "Cash Inflow Minus Cash Outflow." Negative results should be enclosed by parentheses. Family expenses must be estimated for each month and entered in Column 6. Families frequently find it difficult to estimate expenses, so Supplemental Worksheet 2, "Family Living Expenses", is provided to act as a guide in preparing the estimate of monthly family expenditures.

Worksheet 6, "Projected Cash Flow Budget", is the end product provided by preparing the previous information. It is a guide for the use of short-term credit and for decision-making in assuming long-term debt. The manager must evaluate

constantly the ability of the farm and family to service debt. Following is a column by column explanation of Worksheet 6.

- Cash inflow less outflow excluding credit transactions (Column 1): The numbers in this column are the difference between cash inflow and cash outflow on Worksheet 5, Column 8.

- "Scheduled Debt Payments" (Column 2): Listed on this column is the principal and interest the business is required to pay each month. Supplemental Worksheet 3 can be used to project debt payments for next year.

- "Capital Purchase Loans" (Column 3): For many capital purchases, the farm manager knows in advance that he will borrow all or part of the money from a bank, a government agency, machinery dealer, or other source. When this is the case, the amount of the loan is included in this column. When he starts making payments on the loan (probably the following month), the amount of the payment (principal and interest) is included in Column 2, "Scheduled Debt Payment" (Supplemental Worksheet 3 also can be used).

- "Uncommitted Cash Flow" (Column 4): This is the money projected to be left over or that must be obtained after the cash inflow-outflow, debt payments and new capital loans are considered. If figures in the column are positive, money is available: 1) to pay back short-term borrowings or make additional payments on longer term debt, or 2) to add to the family's ready cash fund. (Family living expenses have been accounted for already.) If these data are negative, the deficit must be covered: 1) from reductions in the family's ready cash fund, or 2) by short-term borrowing from a bank, individual, or some other source, and/or by charging feed, fertilizer or other bills.

- "New Short-term Debt" (Column 5): This column is used to record new short-term debt which is projected to be required to cover a negative uncommitted cash flow.

- "Additional Debt Payments" (Column 6): These are payments of interest and principal on short-term debt and additional principal payments on longer term debt. (It is assumed that interest paid on longer-term debt is covered in the scheduled debt payments).

- "Cash Flow This Month" (Column 7): This is the projected change in the family ready cash fund for the month.

• "Cash Flow Balance" (Column 8): Note that the farm ended the past year (or started this year) with Rs 400 in the family ready cash fund. The column is the running balance of cash on hand. Remember that transactions occur daily, not monthly, and that a significant balance may be required to meet day-to-day fluctuations. The August balance of Rs 75 may be too low and additional borrowing required.

In parentheses at the top of each column the sequence of adding and subtracting is identified as follows:

Cash Inflow Less Outflow Excluding Credit

- Scheduled Debt Payments

+ Capital Purchase Loans

= Uncommitted Cash Flow

+ New Short-Term Debt

- Additional Debt Payments

= Cash Flow: This Month

+ Balance from Last Month

= Cash Flow: Balance

Good short-term credit management is indicated if at least one of the columns, "New Short-Term Debt" or "Additional Debt Payments," is zero for each month. Short-term credit should be managed to maintain a somewhat constant cash flow balance without paying back money and then turning around and reborrowing it immediately. One rule of thumb is to repay short-term debt whenever the money will not be reborrowed for at least two months; otherwise, the money could be left in the family ready cash account to cover the cash flow deficit in the following month.

REFERENCES

Milligan, R.A., S.F. Smith, and E.L. LaDue. 1976. Monthly cash flow planning. Department of Agricultural Economics, Cornell University, AE Ext. 76-2, Ithaca, NY.

WORKSHEET 1A. ESTIMATION OF CASH FARM RECEIPTS: CROP AND OTHER INCOME

Farm Identification: 2 Hectare Farm

Month	Crop	Crop Sales: This Year Quantity	Crop Sales: This Year Price	Crop Sales: This Year Value	Crop Sales: Next Year Quantity	Crop Sales: Next Year Price	Crop Sales: Next Year Value	Other Farm Income† This Year	Other Farm Income† Next Year	Cash Farm Operating Receipts‡
Jan										Rs 100
Feb										Rs 100
Mar										Rs 100
May										Rs 100
Jun										Rs 100
Jul								Rs 55	Rs 55	Rs 105
Aug										Rs 50
Sep										Rs 1250
Oct										Rs 50
Nov	Paddy	1.5 T	Rs 1500	Rs 2250	1.5	Rs 1500	Rs 2250			Rs 2300
Dec										Rs 50
TOTAL				Rs 2250				Rs 55	Rs 55	Rs 4405

* From Supplemental Worksheet No. 1--Estimation of Receipts from Crop Sales.

† Includes income from work performed for others, rental of land, water, draft animals, or machinery to others and the sales of used machinery of equipment. Do not include income from livestock or livestock products.

‡ Value of next year's crop sales plus other farm income next year plus total expected receipts for livestock products (from Worksheet 1B).

NOTE: Although 2 hectares of wheat and 2 hectares of paddy are grown only 25% of the paddy is sold. Also, none of the wheat/paddy straw is sold.

WORKSHEET 1B. ESTIMATION OF CASH FARM RECEIPTS: LIVESTOCK PRODUCTS AND LIVESTOCK SALES

Farm Identification: 2 Hectare Farm

	Livestock Products Sales: Milk & Eggs							Receipts Livestock Sales		
Month (Produced)	Number of Cows	Production Per Cow	Total Production	Price Per ℓ*	Receipts This Year	Month (Received)	Expected Receipts Next Year	This Year	Next Year	Total Receipts From Livestock Products & Livestock Next Year
Dec	2	60 ℓ	120 ℓ	Rs 0.8	Rs 100	Jan	Rs 100			Rs 100
Jan	2	60 ℓ	120 ℓ	Rs 0.8	Rs 100	Feb	Rs 100			Rs 100
Feb	2	60 ℓ	120 ℓ	Rs 0.8	Rs 100	Mar	Rs 100			Rs 100
Mar	2	60 ℓ	120 ℓ	Rs 0.8	Rs 100	Apr	Rs 100			Rs 100
Apr	2	60 ℓ	120 ℓ	Rs 0.8	Rs 100	May	Rs 100			Rs 100
May	2	60 ℓ	120 ℓ	Rs 0.8	Rs 100	Jun	Rs 100			Rs 100
Jun	1	60 ℓ	60 ℓ	Rs 0.8	Rs 50	Jul	Rs 50			Rs 50
Jul	1	60 ℓ	60 ℓ	Rs 0.8	Rs 50	Aug	Rs 50			Rs 50
Aug	1	60 ℓ	60 ℓ	Rs 0.8	Rs 50	Sep	Rs 50	Rs 1200	Rs 1200	Rs 1250
Sep	1	60 ℓ	60 ℓ	Rs 0.8	Rs 50	Oct	Rs 50			Rs 50
Oct	1	60 ℓ	60 ℓ	Rs 0.8	Rs 50	Nov	Rs 50			Rs 50
Nov	1	60 ℓ	60 ℓ	Rs 0.8	Rs 50	Dec	Rs 50			Rs 50
TOTAL			1080 ℓ		Rs 900		Rs 900	Rs 1200	Rs 1200	Rs 2100

* ℓ = liter(s).

WORKSHEET 2A. ESTIMATION OF CASH FARM EXPENSES: LABOR AND FEED AND LIVESTOCK PURCHASE

Farm Identification: 2 Hectare Farm

Month	Labor Percent Change 0		Feed Purchase Percent Change 0		Livestock Purchase* Percent Change 0	
	This Year Rs	Next Year Rs	This Year Rs	Next Year Rs	This Year Rs	Next Year Rs
Jan			15	15		
Feb			15	15		
Mar			15	15		
Apr			15	15		
May			15	15		
Jun			15	15		
Jul	15	15	15	15		
Aug			15	15		
Sep			15	15		
Oct			15	15		
Nov	10	10	15	15		
Dec			15	15	900	900
TOTAL	25	25	180	180	900	900

* Livestock purchased for feeding - growing and later resale should be included here.
Livestock purchased for draft or herd expansion should be included as capital items in Worksheet 4.

WORKSHEET 2B. ESTIMATION OF CASH FARM EXPENSES: MACHINERY

Farm Identification: 2 Hectare Farm

Month	Custom Work Hired Percent Change ___		Repairs Percent Change___		Fuel Percent Change___		Total Machinery Expense
	This Year Rs	Next Year Rs	This Year Rs	Next Year Rs	This Year Rs	Next Year Rs	Next Year Rs
Jan	Not Applicable This Farm		Not Applicable This Farm		Not Applicable This Farm		
Feb							
Mar							
Apr							
May							
Jun							
Jul							
Aug							
Sep							
Oct							
Nov							
Dec							
TOTAL							

WORKSHEET 2C. ESTIMATION OF CASH FARM EXPENSES: CROPS

Farm Identification: 2 Hectare Farm

Month	Lime and Fertilizer Percent Change 10		Seeds and Sprays Percent Change 0		Crop Expense Next Year Rs	Land Rent Percent Change ___	
	This Year Rs	Next Year Rs	This Year Rs	Next Year Rs		This Year Rs	Next Year Rs
Jan						Not Appli. This Farm	
Feb							
Mar							
Apr							
May							
Jun	314	345	80	80	425		
Jul							
Aug							
Sep							
Oct							
Nov	157	172	300	300	472		
Dec							
TOTAL	471	517	380	380	897		

WORKSHEET 2D. ESTIMATION OF CASH FARM EXPENSES: REAL ESTATE EXPENSES

Farm Identification: 2 Hectare Farm

Month	Land & Building Expenses (Repairs, etc.) Percent Change 0		Property Taxes Percent Change ___	
	This Year Rs	Next Year Rs	This Year Rs	Next Year Rs
Jan	Not Applicable to This Farm			
Feb				
Mar				
Apr			8	8
May				
Jun				
Jul				
Aug				
Sep				
Oct				
Nov				
Dec				
TOTAL			Rs 8	Rs 8

WORKSHEET 2E. ESTIMATION OF CASH FARM EXPENSES: UTILITIES, MARKETING, MISC.

Farm Identification: 2 Hectare Farm

Month	Utilities Percent Change ___ This Year Rs	Utilities Next Year Rs	Marketing (Transportation, etc.) Percent Change ___ This Year Rs	Marketing Next Year Rs	Miscellaneous Percent Change 0 (Water Charges) This Year Rs	Miscellaneous Next Year Rs
Jan	Not Applicable to This Far		Not Applicable to This Farm			
Feb						
Mar						
Apr						
May					152	152
Jun						
Jul						
Aug						
Sep						
Oct						
Nov						
Dec						
TOTAL					212	212
					Rs 364	Rs 364

WORKSHEET 3. SUMMARY OF CASH FARM EXPENSES

Farm Identification: 2 Hectare Farm

Month	Labor (2A)	Feed (2A)	Livestock (2A)	Machine (2B)	Crop (2C)	Rent (2C)	Land Building (2D)	Taxes (2D)	Utilities (2E)	Marketing (2E)	Misc. (2E)	Total
Jan		15										15
Feb		15										15
Mar		15										15
Apr		15						8			152	175
May		15										15
Jun		15			425							440
Jul	15	15										30
Aug		15										15
Sep		15										15
Oct		15										15
Nov	10	15	900		472							1397
Dec		15									212	227
TOTAL	25	180	900		897			8			364	2374

WORKSHEET 4. CAPITAL PURCHASES PLANNED

Month	Land & Building		Machinery		Draft and Producing Livestock*		Total Capital Purchases
	Item	Cost†	Item	Cost‡	Item	Cost	
Jan							
Feb	No capital purchases are anticipated this year.						
Mar							
Apr							
May							
Jun							
Jul							
Aug							
Sep							
Oct							
Nov							
Dec							
TOTAL							

* Capital purchases of livestock include all livestock purchases for planned expansion. Replacement purchases are livestock expenses and should be entered in Worksheet 2A.
† Cost is monthly payment on loans.
‡ Cost is cost after trade-in is deducted.

WORKSHEET 5. CASH INFLOW AND OUTFLOW FOR NEXT YEAR: INCLUDING NONFARM, EXCLUDING CREDIT

Month	Cash Farm Receipts (From Worksheet 1A) (1)	Net Non-Farm Cash Income* (2)	Total Cash Inflow Ex. Borrowing (3)	Cash Farm Expenses (From Worksheet 3) (4)	Capital Purchases (From Worksheet 4) (5)	Family Living Expense† (6)	Total Outflow (Ex. Principal Payments) (7)	Cash Inflow (Col. 3) - Cash Outflow (Col. 7) (8)
Jan	100	None	100	15	None	70	85	15
Feb	100		100	15		70	85	15
Mar	100		100	15		70	85	15
Apr	100		100	175		70	245	(145)
May	100		100	15		70	85	15
Jun	100		100	440		70	510	(410)
Jul	105		105	30		70	100	5
Aug	50		50	15		70	85	(35)
Sep	1250		1250	15		70	85	1165
Oct	50		50	15		170	185	(135)
Nov	2300		2300	1397		70	1467	833
Dec	50		50	227		70	297	(247)
TOTAL	4405		4405	2374		940	3314	1091

* All non-farm receipts minus non-farm business expenses. Family living expenses are included in Column 6.
† Supplemental Worksheet 2 is provided to assist in calculating family living expenses.

WORKSHEET 6. PROJECTED CASH FLOW BUDGET

Month	Cash Inflow Less Outflow Excluding Farm Credit Transactions (Worksheet 5) (1)	Scheduled Debt Payments: Principal and Interest* (-) (2)	Capital Purchase Loans (+) (3)	Uncommitted Cash Flow (± Sum) (4)	New Short Term Debt (+) (5)	Additional Debt Payments (-) (6)	Cash Flow: This Month (+ Sum) (7)	Cash Flow: Balance Rs 400 (8)
Jan	15			15			15	415
Feb	15			15			15	430
Mar	15			15			15	445
Apr	(145)			(145)			(145)	300
May	15			15			15	315
Jun	(410)			(410)	200		(210)	105
Jul	5			5			5	110
Aug	(35)			(35)			(35)	75
Sep	1165			1165		206†	959	1034
Oct	(135)			(135)			(135)	899
Nov	833			833			833	1732
Dec	(247)			(247)			(247)	1485
TOTAL	1091			1091	200	206		

* Supplemental Worksheet 3 is provided to assist in projecting monthly debt payments.
† Rs 200 x 11% interest x 3 month ≈ Rs 6.

SUPPLEMENTAL WORKSHEET 1. ESTIMATION OF RECEIPTS FROM CROP SALES

Production				Sales			
Crop	Hectares	Yield	Total Production	Month	Quantity	Expected Price	Value
	Not Necessary for This Farm.						

SUPPLEMENTAL WORKSHEET 2. FAMILY LIVING EXPENSES

Farm Identification: 2 Hectare Farm

Month	Food	Clothing	Dwelling & Household Expense	Property & Income Taxes	Utility & Transport. Expense	Payment into Savings & Non-Farm Investments	Other Family Expenses	Credit Payments	Total Family Living Expense
Jan	50	—	15	None	None	None	5	None	70
Feb	50	—	15	—	—	—	5	—	70
Mar	50	—	15	—	—	—	5	—	70
Apr	50	—	15	—	—	—	5	—	70
May	50	—	15	—	—	—	5	—	70
Jun	50	—	15	—	—	—	5	—	70
Jul	50	—	15	—	—	—	5	—	70
Aug	50	—	15	—	—	—	5	—	70
Sep	50	—	15	—	—	—	5	—	70
Oct	50	100	15	—	—	—	5	—	170
Nov	50	—	15	—	—	—	5	—	70
Dec	50	—	15	—	—	—	5	—	70
TOTAL	600	100	180	—	—	—	60	—	940

SUPPLEMENTAL WORKSHEET 3. SCHEDULED DEBT PAYMENTS

Farm Identification: 2 Hectare Farm

	Debt Payments - Principal and Interest*							
Month	_____	_____	_____	_____	_____	_____	_____	Total Scheduled Debt Payments
Jan	_____	_____	_____	_____	_____	_____	_____	_____
Feb	_____	_____	_____	_____	_____	_____	_____	_____
Mar	_____	_____	_____	_____	_____	_____	_____	_____
Apr	_____	_____	_____	_____	_____	_____	_____	_____
May	_____	_____	_____	_____	_____	_____	_____	_____
Jun	_____	_____	_____	_____	_____	_____	_____	_____
Jul	_____	_____	_____	_____	_____	_____	_____	_____
Aug	_____	_____	_____	_____	_____	_____	_____	_____
Sep	_____	_____	_____	_____	_____	_____	_____	_____
Oct	_____	_____	_____	_____	_____	_____	_____	_____
Nov	_____	_____	_____	_____	_____	_____	_____	_____
Dec	_____	_____	_____	_____	_____	_____	_____	_____
TOTAL	_____	_____	_____	_____	_____	_____	_____	_____

* Include all scheduled payments: Real estate loans, liens on livestock and equipment, payments to machinery dealers, etc. Be certain to include payments on loans that will be added during the year.

PARTIAL BUDGETS

by A. Madsen

Farmers often face choices between two alternatives. Such choices may involve such questions as: Should I purchase a new diesel water pump or continue with the animal powered irrigation wheel? Should I line irrigation ditches or maintain ditches in the traditional manner? Should I produce corn rather than rice? These types of questions can be evaluated using partial budgeting procedures.

Partial budgeting is an organized method for appraising the effect a proposed change may have on the net returns of the farm. The four main steps in constructing a partial budget are:

1. State the change contemplated;

2. List a) key information required to estimate the impact of the potential change and b) the assumptions made;

3. Make the economic analysis to estimate the net effect of the changes on income; and

4. List all considerations or factors on which placing a monetary value is difficult.

The typical partial budget consists of seven key parts (see the attached "Partial Budget Form" for basic format):

- Part I is a listing of additional costs that will be incurred if a new enterprise or factor is introduced. For example, identify and add all costs that will increase if the decision is made to introduce a new diesel powered irrigation pump. Fixed costs include an allowance for depreciation, interest on borrowed funds, taxes, shelter, and so forth. Variable costs include fuel, oil, grease, repairs, and labor. The hypothetical example, which follows this article, uses American dollars, and shows the added costs to be $2,000 during the expected useful life of the pump.

- Part II identifies the reduced receipts--returns that no longer will be received after the change. In our example, returns may not be reduced because the farmer would still be able to maintain the previous level of production and combination of products with the new means of lifting water. Thus, total reduced returns are zero in Exhibit 1. If a certain crop or product can no longer be produced after the diesel pump is installed, the sacrificed income is the value of the product not produced.

- Part III of the partial budget is a summation of the estimate of total additional costs from Part I and the reduced returns from Part II. In Exhibit 1 this value is $2,000.

- Part IV is a listing of all additional returns expected if the new enterprise or factor is introduced. In our example, it is the total value of additional crops or livestock produced from the availability of more irrigation water and more timely application because of the diesel pump. In the example, increased yields or higher value crops are assumed to increase returns by $1,650 during the pump's useful life.

- Part V consists of estimates of all costs eliminated if the old enterprise or factor is replaced. In our example, when the animal powered water wheel is replaced, a reduction in the number of draft animals to feed and irrigation wheel repairs, and perhaps in irrigation labor requirements would occur. In the example these cost savings equal $1,020.

- Part VI contains the total of the gains--additional returns (Part VI) plus reduced costs (Part V). In the example these gains are $670 over the useful life of the pump.

- Part VII shows the net change in income from the potential introduction of the new enterprise or production input. The change is calculated by subtracting Part III (the negative impacts) from Part VI (total gains). If Part VII shows income can be significantly increased through the proposed change, action can be taken to make changes considered. If Part VII indicates income will be reduced or there will be little positive impact, the farmer can see the risk in making the change before action is taken. It is best to identify potential benefits or costs before money or labor is committed to an unprofitable project. In the example, there was benefit ($670) from introducing the irrigation pump. But before a final decision is made, the producer should make a "sensitivity analysis" of the proposed change by testing various levels of crop yields, prices, or costs to see the effect on net changes in farm income. Non-monetary considerations also should be carefully examined before the final decision is made.

CAUTION: Partial budgeting is only as accurate as the data used. A positive net change implies it may be wise to proceed with the alternate plan. A negative amount implies it would not be profitable to proceed with the change. Erroneous data lead to serious mistakes.

REFERENCES

Budgeting a change. University of Nebraska, Neb Guide, G77-333. Lincoln, NE.

Partial budgeting in farm management. Ohio State University, Extension Facts, No. 142. Columbus, OH.

PARTIAL BUDGET FORM

STEP 1. Proposed Change: _____

STEP 2. Key Information and Assumptions: 1. _____

2. _____

3. _____

STEP 3. Economic Analysis:

ITEMS THAT REDUCE NET INCOME

Part I. Added Costs:

_____	$ _____
_____	_____
_____	_____
_____	_____
_____	_____
Total Added Costs	$ _____

Part II. Reduced Returns:

_____	$ _____
_____	_____
_____	_____
_____	_____
_____	_____
Total Reduced Returns	$ _____

Part III. Total Added Costs and Reduced Returns $ _____

ITEMS THAT INCREASE NET INCOME

Part IV. Added Returns:

_____	$ _____
_____	_____
_____	_____
_____	_____
_____	_____
Total Added Returns	$ _____

Part V. Reduced Costs:

_____	$ _____
_____	_____
_____	_____
_____	_____
_____	_____
Total Reduced Costs	$ _____

Part VI. Total Added Returns and Reduced Costs $ _____

Part VII. Net Change in Farm Income (Part VI minus Part III): $ _____

STEP 4. Non-monetary Consideration:

_____

PARTIAL BUDGET FORM

STEP 1. Proposed Change: Replace animal powered waterwheel with a diesel powered water pump.

STEP 2. Key Information and Assumptions:

1. More irrigation water will be made available.
2. Fuel costs will increase at about the same rate as the past 5 years.
3. Crop prices be about the same as the past 5 years.

STEP 3. Economic Analysis:

ITEMS THAT REDUCE NET INCOME

Part I. Added Costs:

Variable costs: fuel, grease, repairs, oil, etc.	$ 1500
Fixed costs: interest on loan, depreciation, taxes, etc.	500
Total Added Costs	$ 2000

Part II. Reduced Returns:

All crops & livestock produced when waterwheel was used can be produced using a diesel pump (Milk & meat may be reduced if animals used for power are sold)	$ 0.0
Total Reduced Returns	$ 0.0

Part III. Total Added Costs and Reduced Returns $ 2000

ITEMS THAT INCREASE NET INCOME

Part IV. Added Returns:

Maize (better yield)	$ 400
Forage (better yeild)	150
Rice (better yield)	300
Tomatoes (increased acreage)	800
Total Added Returns	$ 1650

Part V. Reduced Costs:

Draft animal feed	$ 500
Waterwheel repair	100
Labor	420
Total Reduced Costs	$ 1020

Part VI. Total Added Returns and Reduced Costs $ 2670

Part VII. Net Change in Farm Income (Part VI minus Part III): $ 670

STEP 4. Non-monetary Consideration:

Diesel pump repair parts may be difficult to obtain. Farmers are more familiar with animals than with machinery.

DISCOUNTING

by A. Madsen

CONCEPT EXPLAINED

When farmers evaluate the potential payoff of investments such as land leveling, a water drainage system, or lining canals and ditches, they want the investments to eventually pay for themselves. As a consequence, the time value of money must be considered--both the cost and income aspects of an investment must be weighed over time.

If money is borrowed to finance a project and repayment made at different periods through time, certain questions arise. What is the present value of the future payments? What is the present value of the future income that will be earned during the useful life of the investment item?

An associated problem is evaluting the net results of two alternative investment possibilities, i.e., ditch lining versus installing a drainage system. Project alternatives may have different earnings each period, different amounts of time during which the investment is useful in producing farm income, and different loan repayment arrangements which complicate efforts to make comparisons. Discounting is an economic tool which facilitates comparing investment alternatives when future income or costs are a factor.

Using an Egyptian farmer as an example, the basic concept to consider when understanding income is that a pound received today is worth more than a pound received one or more

years from now. The income received today can be invested for future profit or loaned to earn interest. Thus, income received in the future must be discounted by some factor to estimate the comparability between having a pound now versus a similar amount in the future. If the farmer must pay 20 percent interest to borrow funds to purchase seed, fertilizer, and other inputs, the borrowing cost becomes burdensome. In view of this cost, 1 Egyptian pound (LE) available one year from now is worth only .83 LE compared to 1 LE today. The discount formula for this future value is:

$$PV = \frac{1.0 \text{ LE}}{1.0 + r} \quad \text{where}$$

PV = present value of the future income

r = the discount rate (the same as the interest rate of 20 percent in this case).

$$\text{Thus, } \frac{1.0 \text{ LE}}{1.0 + .20} = .83 \text{ LE}$$

Present Value of a Fixed Income for Indefinite Future Time

If a farmer expects to earn the same amount each year from an investment for the foreseeable future, the present value of each 1 LE annual income is 1/r. If the discount rate (r) is 20 percent, each pound per year has a present value (pv) of 5 LE (1/.20) = 5 LE. If a farmer invested in a drainage system that increased the value of crop production 100 LE each year indefinitely into the future, the present value of this income stream is 100 LE/.20 = 500 LE. Farmers should compare this present value to the cost of the drainage system. Other things being equal, if present value of the investment exceeds the present value of the income stream, the investment should not be made.

Present Value of a Different Income Amount Each Period

Frequently, the expected earnings from investments in land, machinery, equipment, or capital improvements vary from period to period. The discounting formula for this situation becomes:

$$PV = \frac{LE_1}{(1+r)^1} + \frac{LE_2}{(1+r)^2} + \frac{LE_3}{(1+r)^3} + \ldots \frac{LE_n}{(1+r)^n}$$

where LE_i (i = 1 to n) represents amounts earned during Period 1 through n.

For example, assume that an Egyptian farmer invests in a water pump which he expects to increase crop production valued at the equivalent of:

50 LE the 1st year

200 LE the 2nd year

100 LE the 3rd year

75 LE the 4th year

At the end of the fourth year, the pump will be sold for 150 LE. So the farmer can determine how much he should consider paying for the pump, discount the annual returns as follows, assuming a discount rate of 20 percent:

$$PV = \frac{50\ LE}{(1+.20)^1} + \frac{200\ LE}{(1+.20)^2} + \frac{100\ LE}{(1+.20)^3} + \frac{75\ LE}{(1+.20)^4} + \frac{150\ LE\ salvage}{(1+.20)^4}$$

The present values of the income each year are summed to obtain the total present value of the pump.

$$PV = 41.67 + 138.89 + 51.87 + 36.23 + 72.46 = 353.12$$

In this example, the farmer should not pay more than 353 LE for the pump.

<u>The Present Value of Alternative Investments</u>

Assume that farmers in a one <u>sakia</u> (waterwheel) command area decided to pool their money to improve the irrigation system. They can raise up to 10,000 LE for investment. The group must choose between purchasing a large pump or lining the main feeder ditches. It will cost 9500 LE for a pump. The yearly increase in net value of the command area's crop production is:

4000 LE the 1st year

3000 LE the 2nd year

2000 LE the 3rd year

1500 LE the 4th year

1000 LE the 5th year

900 LE the 6th year

After the sixth year, the used pump will be sold for 2500 LE. The present value of the investment, assuming a discount rate of 20 percent, would be:

$$PV = \frac{4000\ LE}{(1+.20)^1} + \frac{3000\ LE}{(1.2)^2} + \frac{2000\ LE}{(1.2)^3} + \frac{1500\ LE}{(1.2)^4} + \frac{1000\ LE}{(1.2)^5}$$

$$+ \frac{900\ LE}{(1.2)^6} + \frac{2500\ LE\ salvage}{(1.2)^6} = 12,565\ LE$$

The second investment considered is lining the main feeder ditches at a cost of 9700 LE. This ditch improvement is expected to increase net crop returns 2000 LE per year for the next 11 years.

The present value of lining the ditches is the sum of each year's discount value, i.e., years 1 through 11:

$$PV = \frac{2000\ LE}{(1+.20)^1} + \frac{2000\ LE}{(1.2)^2} + \cdots + \frac{2000\ LE}{(1.2)^{11}} = 8653.59$$

To eliminate such laborious computations, tables were constructed to include conversion factors by which the expected costs or returns can be multiplied to obtain the present value. Use of these tables is explained in the section below entitled "Using Discount Tables".

In comparing the present value of the two investment alternatives, it can be seen that the pump is the better investment because it yields the highest returns above investment cost (3045 LE for the pump versus a loss of 1046 LE for ditch lining).

Discounting Future Costs

A concept parallel to discounting future income to estimate present value of an income stream is discounting future costs to estimate a present value of the future costs. Using the previous rationale, it can be seen that paying a bill one year from now is cheaper than paying now. Delayed payment allows the investor to deposit his money in a bank and earn interest or to invest in a profit-making enterprise for one year before making the payment.

The procedure for estimating present value of a series of future payments (costs) is the same as the procedure for estimating present value of future incomes. To obtain a true picture of net benefits from investments that have payments and incomes over time, both costs and returns should be discounted. The discounted costs must be subtracted from the discounted benefits to arrive at the net benefit figure. For example, if the discounted cost of an investment is 1200 LE and the discounted income is 1500 LE, the net benefit from the investment is 300 LE or 1500 LE minus 1200 LE.

Using Discount Tables

Using discount tables saves time and simplifies calculating present values of future returns or costs. Table 1 can be used when the same amount of money is received each time period (an annuity), as was assumed in our example for lining feeder ditches, or when payments are the same each period. To use Table 1, identify the applicable discount rate at the top of the page and go down the appropriate column to the number of years or periods considered. For example, assume a discount rate of 15 percent and a 5-year period of earnings. The conversion factor is 3.353. This factor was derived by summing

$$\frac{1}{(1+.15)^1} + \frac{1}{(1+.15)^2} + \frac{1}{(1+.15)^3} + \frac{1}{(1+.15)^4} + \frac{1}{(1+.15)^5}$$

If 100 LE is received each year, the present value of the investment is 100 LE x 3.353 = 335.30 LE.

If a different amount of income is received each year, the discount rate conversion factor for each individual year must be taken from Table 2 and multiplied by the income received that year. The multiplied totals then are summed. For example, assume a discount rate of 12 percent and returns of 50 LE the first year, 100 LE the second year, and 150 LE the third year. The 12 percent rate column is identified at the top of the table and conversion factors for each year noted. The computations are as follows:

$$50 \text{ LE} \times .89 \text{ or } (1/1+.12)^1 = 44.50 \text{ LE}$$

$$100 \text{ LE} \times .80 \text{ or } (1/1+.12)^2 = 80.00 \text{ LE}$$

$$150 \text{ LE} \times .71 \text{ or } (1/1+.12)^3 = 106.50 \text{ LE}$$

Present value of three years income 231.00 LE

It was previously demonstrated that the investment has a salvage value, the relevant income should be considered in the year the item is sold and the relevant conversion factor selected from Table 2.

Table 1. Present Value of a Uniform Income Each Period

n*	8%	9%	10%	11%	12%	13%	14%	15%	16%
1	.926	.915	.909	.901	.893	.885	.887	.870	.862
2	1.783	1.759	1.736	1.713	1.690	1.668	1.647	1.626	1.605
3	2.577	2.531	2.487	2.444	2.402	2.361	2.322	2.283	2.246
4	3.312	3.240	3.170	3.102	3.037	2.974	2.914	2.855	2.798
5	3.993	3.890	3.791	3.696	3.605	3.517	3.433	3.353	3.274
6	4.623	4.486	4.355	4.231	4.111	3.998	3.889	3.784	3.685
7	5.206	5.033	4.868	4.712	4.564	4.423	4.288	4.160	4.039
8	5.747	5.535	5.335	5.146	4.968	4.799	4.639	4.487	4.344
9	6.247	5.995	5.759	5.537	5.328	5.132	4.946	4.772	4.607
10	6.710	6.418	6.145	5.889	5.650	5.426	5.216	5.019	4.833
11	7.139	6.805	6.495	6.207	5.938	5.687	5.453	5.234	5.029
12	7.536	7.161	6.814	6.492	6.194	5.918	5.600	5.421	5.197
13	7.904	7.487	7.103	6.750	6.424	6.122	5.842	5.583	5.342
14	8.244	7.786	7.367	6.982	6.628	6.302	6.002	5.724	5.468
15	8.559	8.060	7.606	7.191	6.811	6.462	6.142	5.847	5.575
16	8.851	8.313	7.824	7.379	6.974	6.604	6.265	5.954	5.668
17	9.122	8.544	8.022	7.549	7.120	6.729	6.373	6.047	5.749
18	9.372	8.756	9.201	7.702	7.250	6.840	6.467	6.128	5.818
19	0.604	8.950	8.365	7.839	7.366	6.938	6.550	6.198	5.877
20	9.818	8.129	8.514	7.963	7.469	7.025	6.623	6.259	5.929
24	10.529	9.707	8.985	8.348	7.784	7.283	6.835	6.434	6.073
25	10.675	9.823	9.077	8.422	7.843	7.330	6.873	6.464	6.097
30	11.258	10.274	0.427	8.694	8.005	7.496	7.001	6.566	6.177
36	11.717	10.612	0.677	8.879	8.192	7.598	7.079	6.623	6.22[illegible]
40	11.925	10.757	9.779	8.951	8.244	7.634	7.105	6.642	6.233
48	12.189	10.934	9.897	9.030	8.297	7.671	7.130	6.659	6.245
50	12.233	10.962	9.915	9.042	8.304	7.675	7.133	6.661	6.246
60	12.377	11.048	9.967	9.074	8.324	7.687	7.140	6.665	6.249

* Years or periods.

Table 1. (continued)

n*	17%	18%	19%	20%	21%	22%	23%	24%	25%
1	.855	.848	.840	.833	.826	.820	.813	.806	.800
2	1.585	1.566	1.547	1.528	1.509	1.492	1.474	1.457	1.440
3	2.210	1.174	1.140	2.106	2.074	2.042	2.011	1.981	1.952
4	2.743	2.690	2.639	2.589	2.540	2.494	2.448	2.404	2.362
5	3.100	3.127	3.058	2.991	2.926	2.864	2.803	2.745	2.689
6	3.589	3.498	3.410	3.326	3.245	3.167	3.092	3.020	2.951
7	3.922	3.812	3.706	3.605	3.508	3.416	3.327	3.242	3.161
8	4.207	4.078	3.954	3.837	3.726	3.619	3.518	3.421	3.329
9	4.451	4.303	4.163	4.031	3.905	3.786	3.673	3.566	3.463
10	4.659	4.494	4.339	4.192	4.054	3.923	3.799	3.682	3.571
11	4.836	4.656	4.487	4.327	4.177	4.035	3.901	3.776	3.656
12	4.988	4.793	4.611	4.439	4.278	4.127	3.985	3.851	3.725
13	5.188	4.910	4.715	4.533	4.362	4.203	4.053	3.912	3.780
14	5.229	5.008	4.802	4.611	4.432	4.265	4.108	3.962	3.824
15	5.324	5.092	4.876	4.675	4.489	4.315	4.153	4.001	3.859
16	5.405	5.162	4.938	4.730	4.536	4.357	4.189	4.033	3.887
17	5.475	5.222	4.990	4.775	4.576	4.391	4.219	4.059	3.910
18	5.534	5.273	5.033	4.812	4.608	4.419	4.243	4.080	3.928
19	5.584	5.316	5.070	4.843	4.635	4.442	4.263	4.097	3.942
20	5.628	5.353	5.101	4.870	4.657	4.460	4.279	4.110	3.954
24	5.746	5.451	5.182	4.937	4.713	4.507	4.318	4.143	3.981
25	5.766	5.467	5.195	4.948	4.721	4.514	4.323	4.147	3.985
30	5.829	5.517	5.235	4.979	4.746	4.534	4.339	4.160	3.995
36	5.862	5.541	5.253	4.993	4.757	4.542	4.345	4.165	3.999
40	5.871	5.548	5.258	4.997	4.760	4.544	4.347	4.166	3.999
48	5.879	5.554	5.262	4.999	4.761	4.545	4.348	4.167	4.000
50	5.880	5.554	5.262	4.999	4.762	4.545	4.348	4.167	4.000
60	5.882	5.555	5.263	5.000	4.762	4.545	4.348	4.167	4.000

* Years or periods.

Table 2. Present Value of 1.00 LE In A Specific Period

n*	8%	9%	10%	11%	12%	13%	14%	15%	16%
1	.926	.917	.909	.901	.893	.885	.877	.870	.862
2	.857	.842	.826	.812	.797	.783	.769	.756	.743
3	.794	.772	.751	.731	.712	.693	.675	.658	.641
4	.735	.708	.683	.659	.636	.613	.592	.572	.552
5	.681	.650	.621	.593	.567	.543	.519	.497	.476
6	.630	.596	.564	.535	.507	.480	.456	.432	.410
7	.583	.547	.513	.482	.452	.425	.400	.376	.354
8	.540	.502	.467	.434	.404	.376	.351	.327	.305
9	.500	.460	.424	.391	.361	.333	.308	.284	.263
10	.463	.422	.386	.352	.322	.295	.270	.247	.227
11	.429	.388	.350	.317	.287	.265	.237	.215	.195
12	.397	.356	.319	.286	.257	.231	.208	.187	.168
13	.368	.326	.290	.258	.229	.204	.182	.163	.145
14	.340	.299	.263	.232	.205	.181	.160	.141	.125
15	.315	.275	.239	.209	.183	.160	.140	.123	.108
16	.292	.252	.219	.188	.163	.141	.123	.107	.093
17	.270	.231	.198	.170	.146	.125	.108	.093	.080
18	.250	.212	.180	.153	.130	.111	.095	.081	.069
19	.232	.194	.164	.138	.116	.098	.083	.070	.060
20	.215	.178	.149	.124	.104	.087	.073	.061	.051
24	.158	.126	.102	.082	.066	.053	.043	.035	.028
25	.146	.116	.092	.074	.059	.047	.038	.030	.024
30	.099	.075	.057	.044	.033	.026	.020	.015	.012
36	.063	.045	.032	.023	.017	.012	.009	.007	.005
40	.046	.032	.022	.015	.011	.008	.005	.004	.003
48	.025	.016	.010	.007	.004	.003	.002	.001	.001
50	.021	.013	.009	.005	.004	.002	.001	.001	.001
60	.010	.006	.003	.002	.001	.001	.000	.000	.000

* Years or periods.

Table 2. (continued)

n*	17%	18%	19%	20%	21%	22%	23%	24%	25%
1	.855	.847	.840	.833	.826	.820	.813	.806	.800
2	.731	.718	.706	.694	.683	.672	.661	.650	.640
3	.624	.609	.593	.579	.564	.551	.537	.524	.512
4	.534	.516	.499	.482	.467	.451	.437	.423	.410
5	.456	.437	.419	.408	.386	.370	.355	.341	.328
6	.390	.370	.352	.335	.319	.303	.289	.275	.262
7	.333	.314	.296	.279	.263	.249	.235	.222	.210
8	.285	.266	.249	.233	.218	.204	.191	.179	.168
9	.243	.225	.209	.194	.180	.167	.155	.144	.134
10	.208	.191	.176	.162	.149	.137	.126	.116	.107
11	.178	.162	.148	.135	.123	.112	.103	.094	.086
12	.152	.137	.124	.112	.102	.092	.083	.076	.069
13	.130	.116	.104	.093	.084	.075	.086	.061	.055
14	.111	.099	.088	.078	.069	.062	.055	.049	.044
15	.095	.084	.074	.065	.057	.051	.045	.040	.035
16	.081	.071	.062	.054	.047	.042	.036	.032	.028
17	.069	.060	.052	.045	.039	.034	.030	.026	.023
18	.059	.051	.044	.038	.032	.028	.024	.021	.018
19	.051	.043	.037	.031	.027	.023	.020	.017	.014
20	.043	.037	.031	.026	.022	.019	.016	.014	.012
24	.023	.019	.015	.013	.010	.008	.007	.006	.005
25	.020	.016	.013	.011	.009	.007	.006	.005	.004
30	.009	.007	.005	.004	.003	.003	.002	.002	.001
36	.004	.003	.002	.001	.001	.001	.001	.000	.000
40	.002	.001	.001	.001	.000	.000	.000	.000	.000
48	.001	.000	.000	.000	.000	.000	.000	.000	.000
50	.000	.000	.000	.000	.000	.000	.000	.000	.000
60	.000	.000	.000	.000	.000	.000	.000	.000	.000

* Years or periods.

THE PRODUCTION FUNCTION AND FARM PROFIT MAXIMIZATION

by A. Madsen

FACTORS INPUTS AND PRODUCT OUTPUTS

The physical relationships between the application of different levels of the factors of production (inputs) and associated product output levels are concepts generally understood by most producers. Producers in arid regions, for example, may not have detailed measures of production response to variable inputs, but they understand that if water is not applied, crops will be lost. They also recognize that as additional increments of water are correctly applied, total crop yield increases until a point is reached when total production actually decreases as overwatering occurs. Similar input-output relationships can be evaluated for inputs such as fertilizer, labor, pesticides, seed, etc. (It should be emphasized that the response to selected inputs is related to the present level of production and the kind of farming practices used.)

In the following diagram, a hypothetical production function or total product (TP) curve with associated average product (AP) and marginal product (MP) curves and three stages of production are shown. The total product (TP) curve represents the total amount of lucerne produced with the application of different amounts of water. The average product (AP) curve is the total production at each water application level averaged over all irrigations (TP ÷ the number of irrigations) or product output per irrigation. The marginal product (MP) curve represents the additional quantity of lucerne is produced by adding each additional irrigation (change in total product ÷ the change in number of irrigations). For example, Table 1 following this article shows that with five irrigations, the farmer produces 28.0 units of lucerne and by adding the sixth irrigation 28.5 units will

be produced (Table 1, Columns 1 and 2). The added lucerne production is 0.5 units (28.5 - 28.0) and the added irrigation is 1 (6-5). Therefore, MP is .5/1 or .5 units.

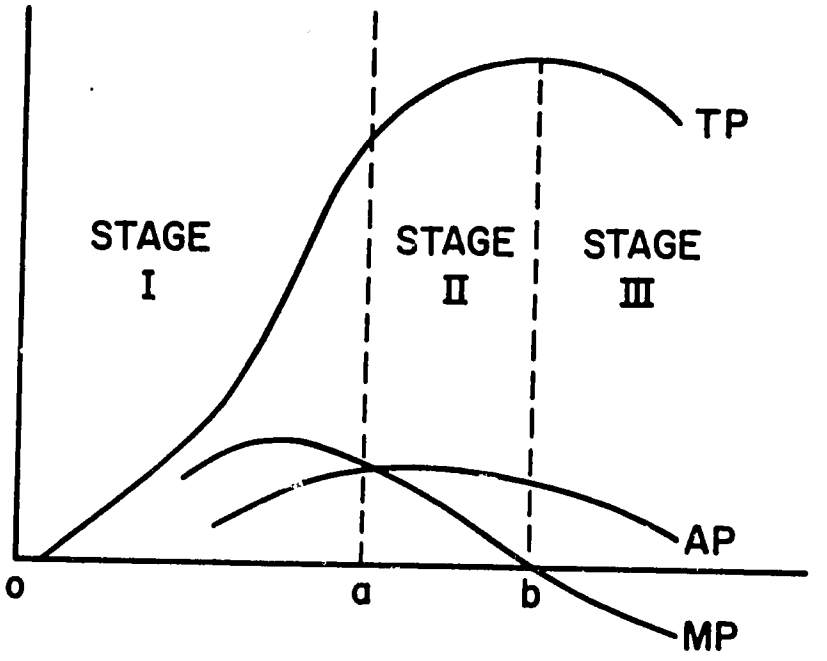


Figure 1. Hypothetical Production Function for a Single Input (Water) and a Single Output (Lucerne)

Three stages of the production are evident:

In Stage 1, the marginal product (the increase in total lucerne production from the last additional application of water) is higher than the average lucerne production (total product divided by total inputs). All other things equal, it is not rational to produce in Stage 1 because the output from the last unit of input is higher than the average production of all inputs. The average product of all inputs will be increased as long as the marginal product is higher than the average product. In Table 1, note that the marginal product exceeds the average product of lucerne up to the second irrigation.

Stage II begins where AP = MP (at point "a") in Figure 1 and at about the second irrigation in Table 1. At this point in the lucerne production function for the input water, the average production of lucerne is at its highest level. Stage II is considered the rational stage of production and extends to the point where total production of lucerne is maximized. The maximum is where the marginal product is zero (the last increment

Table 1. Basic Input-Output Data and Related Costs and Returns for the Production of Lucerne with an Alternative Number of Irrigations*

Physical Input-Output Data				Economic Data											
				Total Costs			Average Costs			Marginal Costs		Returns			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Units of Water Applied (Input)	Units of Lucerne (Total Product)	Marginal Product of Water Per Unit	Average Product of Water Per Unit Col. 2 ÷ Col. 1	Water Cost (Variable Cost) Col. 1 x Rs 40	All Other Costs (Fixed Costs)†	Total Cost Col. 5 + Col. 6	Average Variable Cost Col. 5 ÷ Col. 2	Average Fixed Cost Col. 6 ÷ Col. 2	Average Total Cost Col. 8 ÷ Col. 9	Cost per Unit of Add'l Input (MFC) Col. 5 ÷ Col. 1‡§	Cost per Unit of Add'l Output (MC) Col. 11 ÷ Col. 3	Total Return (TR) Col. 2 x Rs 2	Net Returns (Profit) Col. 13 - Col. 7	Marginal Return Per Unit of Input (MVP) Col. 3 x Rs 2	Marginal Return Per Unit of Output (MR) Col. 15 ÷ Col. 3
Irrigation Unit/Ha				Rupees											
0	0.0		0.0	0	400	400	-	-	-			0	-400		
1	8.0	8.0	8.00	40	400	440	5.00	50.00	55.00	40	5.00	1600	1160	1600	200
2	18.0	10.0	9.00	80	400	480	4.44	22.22	26.66	40	4.00	3600	3120	2000	200
3	24.0	6.0	8.00	120	400	520	5.00	16.67	21.67	40	6.67	4800	4280	1200	200
4	27.0	3.0	6.75	160	400	560	5.92	14.81	20.73	40	13.33	5400	4860	600	200
5	28.0	1.0	5.60	200	400	600	7.14	14.29	21.43	40	40.00	5600	5000	200	200
6	28.5	0.5	4.75	240	400	640	8.42	14.04	22.46	40	80.00	5700	5060	100	200
7	28.8	0.3	4.11	280	400	680	9.72	13.89	23.61	40	133.33	5760	5080	60	200
8	29.0	0.2	3.62	320	400	720	11.03	13.79	24.82	40	200.00	5800	5080	40	200
9	29.1	0.1	3.23	360	400	760	12.37	13.75	26.12	40	400.00	5820	5060	20	200
10	29.1	0.0	2.91	400	400	800	13.75	13.75	27.50	40	undef.	5820	5020	0	200
11	29.0	-0.1	2.64	440	400	840	15.17	13.79	28.96	40	-400.00	5800	4960	20	200

* The data do not represent actual output, costs and returns for lucerne production.

† Fixed costs per hectare are assumed to be Rs 400.

‡ Difference between successive total products divided by differences between successive total input units.

§ Each unit of variable input costs Rs 40.

of water added does not produce additional lucerne). This point is reached at irrigation number ten as indicated in Column 2, Table 1 or at point "b" on the diagram.

Stage III is an irrational level of water application because the total production of lucerne is decreased and the production response to the last irrigation of water applied is negative. (Note the results of the tenth irrigation presented in Column 2, Table 1.)

Agronomists and engineers must provide the coefficients for production response at different levels of input application. Farmers do not have the expertise or income to experiment with different crops and variable inputs. They have general information from historical events but not the detail information that may be desirable.

In the absence of specific production function data, farmers or researchers can recognize whether or not a particular farm is producing within a range of acceptable results. This evaluation may be based on community-wide averages with regard to yields, input use, net returns, capital availability, and so forth. Such data provide a first approximation of the potential range for improvement of the farm operation.

Farmers must decide within their own family goals the amount of water (or other inputs) to apply. If survival is the only objective and inputs are "free", the maximization of basic food production per hectare may be a rational decision.

COST AND RETURN CONSIDERATIONS

The physical input-output relationships identify the stage of production in which production should be conducted, but this stage can extend over a wide range of input levels. To identify the more exact level of input application, or level of output production (assuming the objective is profit maximization), it is necessary to establish the cost of factors of production and the prices of products produced. Table 1 again is an example to demonstrate the relationships between the production function and profit maximization from the point of view of adding inputs in incremental amounts or increasing production by incremental amounts.

Conversion of Farm Products to Monetary Values

From the hypothetical production function, we obtain the total amount of an established crop of lucerne that can be produced from increasing irrigations (Columns 1 and 2, Table 1). Again note the production response to water will vary according to the current level of application of other inputs. For each irrigation, the average product and marginal product or amounts of

lucerne produced have been calculated and identified in Columns 3 and 4. If each of the quantities in Columns 2, 3, and 4 are multiplied by the price per unit of lucerne (assumed to be Rs 200) the total returns or total value products are obtained and presented in Column 13. The marginal value product (MVP) or marginal returns are shown in Column 15.

Identifying Costs

Variable costs are costs that change as production increases or decreases. The variable cost equals the cost per hectare at applying different numbers of irrigations. In this example, it is assumed that it costs Rs 40 per irrigation to apply water to lucerne. (The variable costs are shown in Column 5, Table 1.) It is assumed only the amount of water is varied and all other inputs are fixed or do not vary with the level of lucerne production. Such fixed costs could be taxes, family labor, long-term debt payments, among others. The fixed costs are assumed to equal Rs 400 per hectare and are shown in Column 6. The total costs are the sum of the variable and fixed costs (Column 7).

Another critical cost factor needed to identify the level of inputs which maximize profits is marginal factor cost (MFC), which is the cost of each added input. If the cost of the last unit of input is the same as the cost of the first unit of input, the MFC remains constant as demonstrated in Column 11.

Deciding Upon the Most Profitable Level of Input

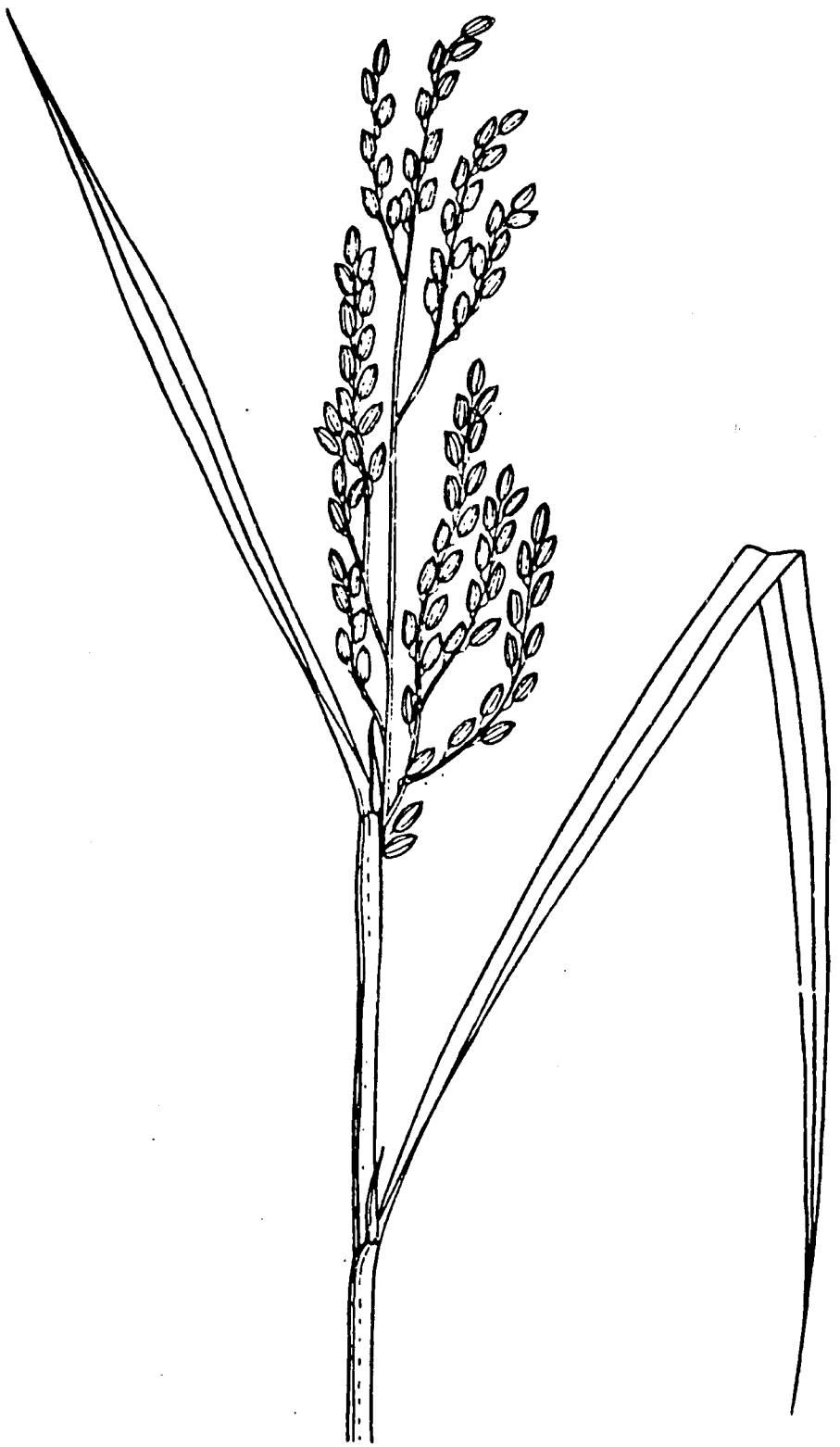
Through trial and error, one can find the most profitable level of input application namely, where Total Return (TR) less Total Cost (TC) = Profit is the greatest. The calculation can become laborious and time-consuming. A more direct way to identify the level of input application which maximizes profits is to apply inputs to the point where the marginal value product (MVP) shown in Column 15 is equal to the marginal factor cost (MFC) shown in Column 11. In our example, that occurs at eight irrigations which is proven by computing the net revenue (profit) for each irrigation. Table 1 shows the net return at the 7th and 8th irrigations are equal. The optimum point is between these two points. If additional irrigations are applied, profits will not be maximized.

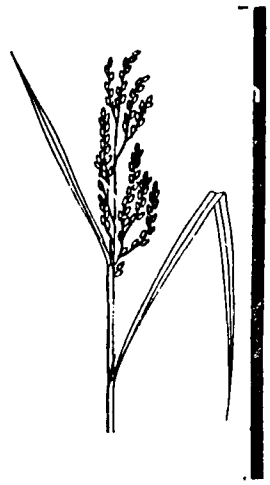
Deciding Upon the Most Profitable Level of Output

Frequently it is desirable to determine the most profitable level of crop or livestock production. The marginal principle again provides the most direct solution to the problem. In this case, however, the two elements required are marginal cost (MC) (the cost of producing an additional ton of lucerne) and marginal revenue (MR) or the price at which the addi-

tional unit of lucerne can be sold. To maximize profits, the producer will increase production to the point where MC = MR. In other words, the cost of producing the last unit of lucerne should equal the price at which the last unit of production can be sold. In the hypothetical example presented in Table 1, every unit (T) of lucerne sold by the farmer can be sold at Rs 200 (Column 16, Table 1). The marginal costs are calculated by dividing the cost of the last unit of input (each irrigation costs Rs 49 per hectare) by the marginal product (units of lucerne produced by the additional irrigation). The result is shown in Column 12, Table 1. In the example presented, the profits are maximized at an output of 29 units of lucerne per hectare. Note that this production level is the level of production achieved when the most profitable amount of water was applied (MFC = MVP). Thus, it matters not whether the analysis is done from the point of view of input application or from the point of view of product output. The solution is the same. The main factors affecting the level of production at which profits are maximized within Stage II of the production function are: 1) the production function itself, 2) the cost of the factors of production (inputs), and 3) the price of the output (product price).

AGRONOMY





CROP SURVEY METHODS*

by M. Lowdermilk

Crop survey methods, when related to command areas of farm irrigation systems, are designed to document, over an extended time, the crops cultivated in each farmer's field for each cropping season. Documentation becomes complex when three or more crops are cultivated in succession under intensive methods, or when more than one crop is cultivated in a single irrigation basin or farmer's field.

PROCEDURES:

1. Obtain or develop a precise map of the command area.

2. Choose the best time for a crop survey. If the survey is done during the transition of crops, invalid data may result because what appears to be fallow may be cultivated within a short period.

3. Measure the irrigation basins for each farm with tape measurements or by pacing the field boundaries. If the pacing method is used, each investigator must calibrate his pace in terms of feet and inches or meters and centimeters per pace.

4. Select a section of the command area. Station one person with a map near the center, use two people to take measurements and to call out the crop or crops in each unit as the party systematically moves down a command area.

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* Modified from an article in The Problem Identification Handbook. (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100. Fort Collins, CO.

5. Use codes for each crop such as W for wheat, F for fallow, and so forth.

6. If the map is of adequate scale and there are several crops in a given unit, record the crops in order of dominance, such as Ca = cabbage, To = tomatoes, W = wheat. If relay crops are used, note them as Co + berseem to show that berseem is interplanted in cotton (Co).

Return at the proper time in the crop cycle to record the next crop. If there are two distinct cropping seasons, for example, cotton (Co) followed by wheat, (W), it may be noted as Co/W. There is, however, sometimes a problem because farmers change the size of their irrigation basins and fields in relationship to the crops they cultivate at any given time. Also, farmers rent land from time to time.

CROP SURVEY DATA

Crop survey data provide records of cropping intensities, patterns, and rotations over time. The data should note intercropping patterns and the shift in field sizes in relation to crop selection.

SOIL TEXTURE DETERMINATIONS

by L. Nelson

Particle size distribution or soil texture undoubtedly is the most informative single property measured in an agricultural study. Soil texture is so important in directly influencing other soil properties that soil classification schemes include texture in the soil name. Simply knowing the soil texture allows one to predict many of the chemical and physical properties to be found in the field. One important example concerns the relationship between available water and soil texture (Table 1)--a relationship often used in evaluating irrigation methods.

Particle size analysis involves measuring the particle size distribution of a soil according to a set of standard procedures. Unfortunately, a number of classification systems dealing with particle size limits exist throughout the world. It is necessary, therefore, to specify the classification system used when reporting data. Two classification systems are shown in Tables 2 and 3. Three methods for particle size analysis in this section were developed for use with the USDA classification system: texture-by-feel analysis, particle size analysis by sieving, and soil texture by hydrometer method.

Soil texture-by-feel analysis is a simplified approach designed to supplement or, under certain conditions, replace laboratory testing methods. Particle size analysis by sieving is restricted to analysis of sand, gravel, or coarse texture soils. Particle size analysis by the hydrometer method may be used for any type of soil, but requires a well-equipped laboratory for large numbers of samples.

Table 1. Approximate Total Available Water (TAW) in mm cm^{-1} as a Function of Soil Texture

Textural Classification	TAW cm cm^{-1}
Very coarse sands	0.04 to 0.07
Coarse sands, fine sands, and loamy sands	0.07 to 0.10
Sandy loams and fine sandy loam	0.10 to 0.15
Very fine sandy loams, loams, and silt loams	0.12 to 0.19
Clay loams, silty clay loams, and sandy clay loam	0.15 to 0.21
Sandy clays, silty clays, and clays	0.13 to 0.21
Peat and mucks	0.17 to 0.25

Table 2. The U.S. Department of Agriculture Particle Size Classification

Function	Diameter, mm
Gravel	>2
Very coarse sand	2 - 1
Coarse sand	1 - 0.5
Medium Sand	0.5 - 0.25
Fine sand	0.25 - 0.1
Very fine sand	0.1 - 0.05
Silt	.05 - .002
Clay	<0.002

Table 3. The International Classification of Particle Size

Fraction	Diameter, mm
Gravel	>2
Coarse sand	2 - 0.2
Fine sand	0.2 - 0.02
Silt	0.02 - 0.002
Clay	<0.002

TEXTURE-BY-FEEL ANALYSIS

The flow diagram shown in Figure 1 provides step-by-step directions for determining the textural class of a soil sample.

PARTICLE SIZE ANALYSIS BY SIEVING

Equipment:

1. A balance or weighing device sensitive to 0.01 grams. The balance should be able to weigh at least 500 grams of material.

2. A set of standard sieves of size numbers 4, 10, 20, 40, 80, 100, 200 and a pan. The corresponding sieve openings are 4.75, 2.00, 0.850, 0.425, 0.180, 0.150 and 0.075 mm, respectively. The pan catches all material finer than a number 200 sieve. Sizes other than those listed can be used as long as they adequately cover the range of sizes.

3. A sieve shaker. The sieves can be shaken by hand or by a sieve shaker machine. Use a cover to prevent loss of material during shaking.

Method:

1. Air-dry a representative sample of the soil. Avoid separation of the soil during handling.

2. Carefully split or divide the soil sample to obtain an average sample weighing 300 to 500 grams. Use a sample splitter or divide the sample by hand on a paper or plastic sheet. Avoid losing small or large particles from the sample.

3. Weigh the sample to the nearest 0.01 gram.

4. Put the sample into the top of a stack of standard sieves. The coarsest mesh sieve should be on top and the pan for collecting the finest materials on the bottom.

5. Jar and shake the sieves vertically and horizontally until there is less than a one percent change in the weight of the material on a sieve during one minute of shaking. Overshaking can grind the material on the screens to powder. Do not rub the soil sample to make it go through the screens.

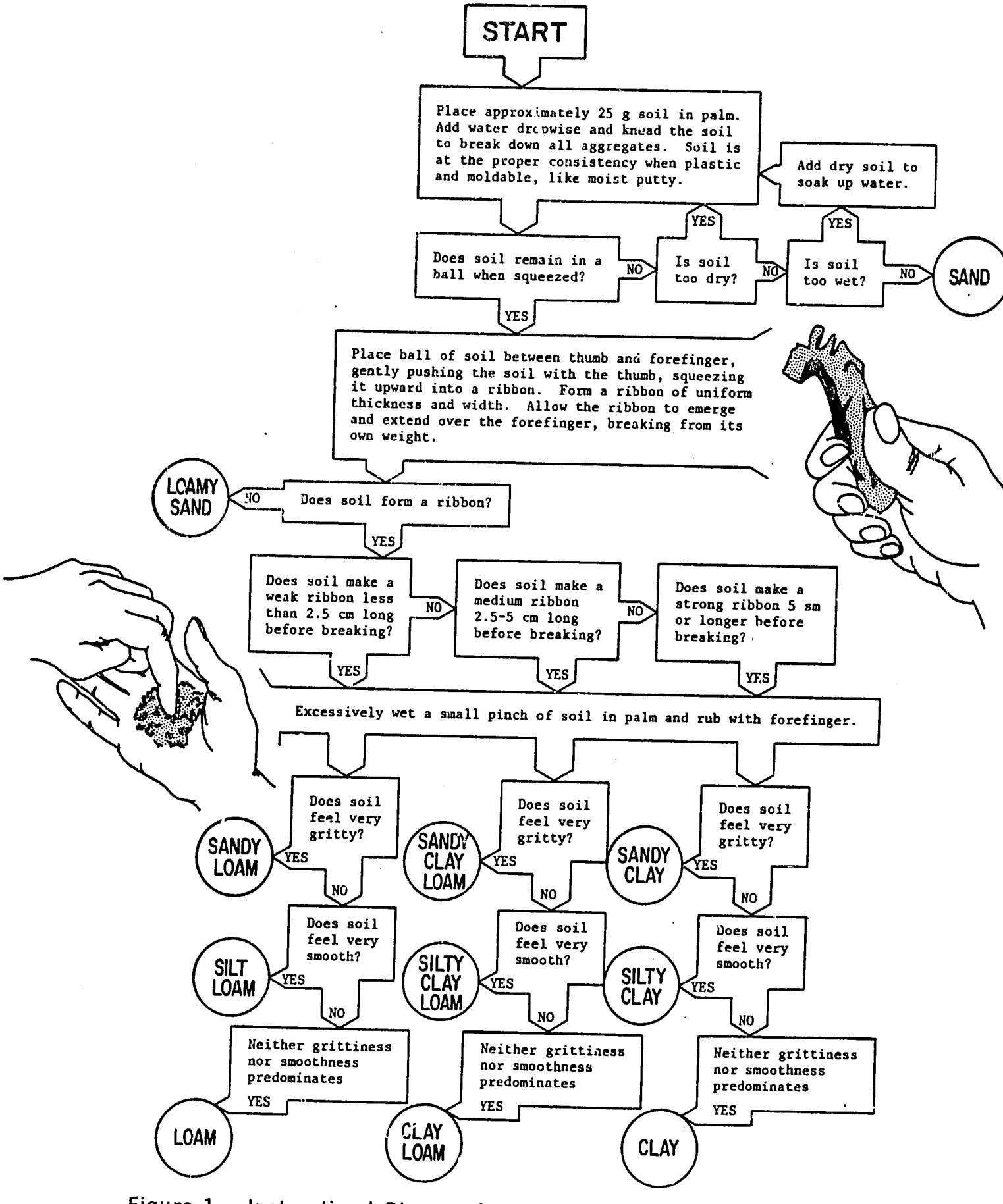

Figure 1. Instructional Diagram for Determining Soil Texture by Feel (Modified from Thien, S.J. 1979. Journal of Agronomic Education 8:54-55. Madison, WI)

6. When shaking is completed, weigh the amount of material retained on each screen. The sum of all the weights should be nearly equal to the weight of material placed in the sieves at the beginning.

7. Clean the sieves, especially the fine sieves, with a brush to avoid damage.

8. Determine the cumulative weight retained by adding the weights retained on each screen progressively. The results are tabulated as shown in the following example:

Sieve Number	Opening mm	Weight Retained	Cumulative Retained
4	4.75	0	0
10	2.00	0	0
20	0.850	9.10	9.10
40	0.425	16.95	26.05
80	0.180	23.40	49.45
100	0.150	17.30	66.75
200	0.075	3.90	70.65
Pan	--	1.32	71.97

Total	71.97
Original Weight	72.00
Loss	0.03 grams

9. Following this procedure, a table can be prepared for opening sizes and percent finer. An example follows:

Opening mm	Percent Finer
2.00	87
0.850	64
0.425	31
0.180	7
0.150	2
0.075	0

10. Plot data on semi-log paper with the vertical linear axis as percent finer and the horizontal logarithmic axis as particle size or sieve opening.

A very steep curve indicates a uniform material. A flatter curve indicates a graded material. The usual soil particle size distribution curve is an "S" shape.

SOIL TEXTURE BY THE HYDROMETER METHOD

The hydrometer method, most commonly used to determine the relative percentages of sand, silt, and clay, involves reading the density of the soil-water suspension at predetermined times with a hydrometer. The density of the suspension decreases as the larger, heavier soil particles settle out. The density of the solution at the predetermined times is proportional to the sand, silt, and clay remaining in suspension.

Equipment:

1. Hydrometer,
2. 1000 ml sedimentation cylinder,
3. Centigrade thermometer,
4. Dispersion cup mixer,
5. Dispersion cup,
6. Sodium hexametaphosphate solution (40 g/l buffered to pH 8-9 with sodium carbonate) or 5% Calgon solution,
7. Plunger for sedimentation cylinder,
8. 250 ml Erlenmeyer flask, and
9. Squeeze bottle.

Method:

1. Place 50 grams of air-dried, 2 mm sieved soil and 100 ml of 5% Calgon solution into a 250 ml Erlynmeyer flask. Stir and allow to soak overnight.

2. The next morning add 100 ml of 5% Calgon solution to a liter sedimentation cylinder and bring to volume with distilled water.

3. Transfer the sample from the flask to the dispersion cup. Be sure all of the sample from the flask is transferred. Place the dispersion cup in the mixer and mix for five minutes.

4. Transfer the sample from the dispersion cup to another sedimentation cylinder. Be sure all of the sample is transferred. Bring the sedimentation cylinder to volume with distilled water.

5. Allow both sedimentation cylinders to stand until their temperatures have equilibrated with air temperature.

6. Thoroughly mix the soil-water suspension in the cylinder with a plunger.

7. Begin timing when the plunger is removed from the sedimentation cylinder.

8. Carefully insert the hydrometer into the soil-water suspension and read after 40 seconds. The hydrometer should be inserted approximately 10 seconds before the reading is taken. Carefully remove the hydrometer from the cylinder. Take a temperature reading of the soil-water suspension. Do not leave the thermometer in the suspension.

9. Take a temperature and hydrometer reading of the Calgon solution.

10. Repeat steps 8 and 9 two hours after the starting time.

11. Correct the Calgon and soil-water suspension hydrometer readings for temperature by adding .11 for every degree over 20°C or subtracting .11 for every degree under 20°C (.2° for degrees F).

12. Subtract the corrected Calgon readings from all corrected soil suspension readings.

13. Use the final corrected values to make the following calculations:

a. 100 - 40 sec. reading = % sand

b. 40 sec. reading - 2 hours reading = % silt

c. 2 hours reading = % clay

14. Refer to Figure 2 to determine the soil textural class.

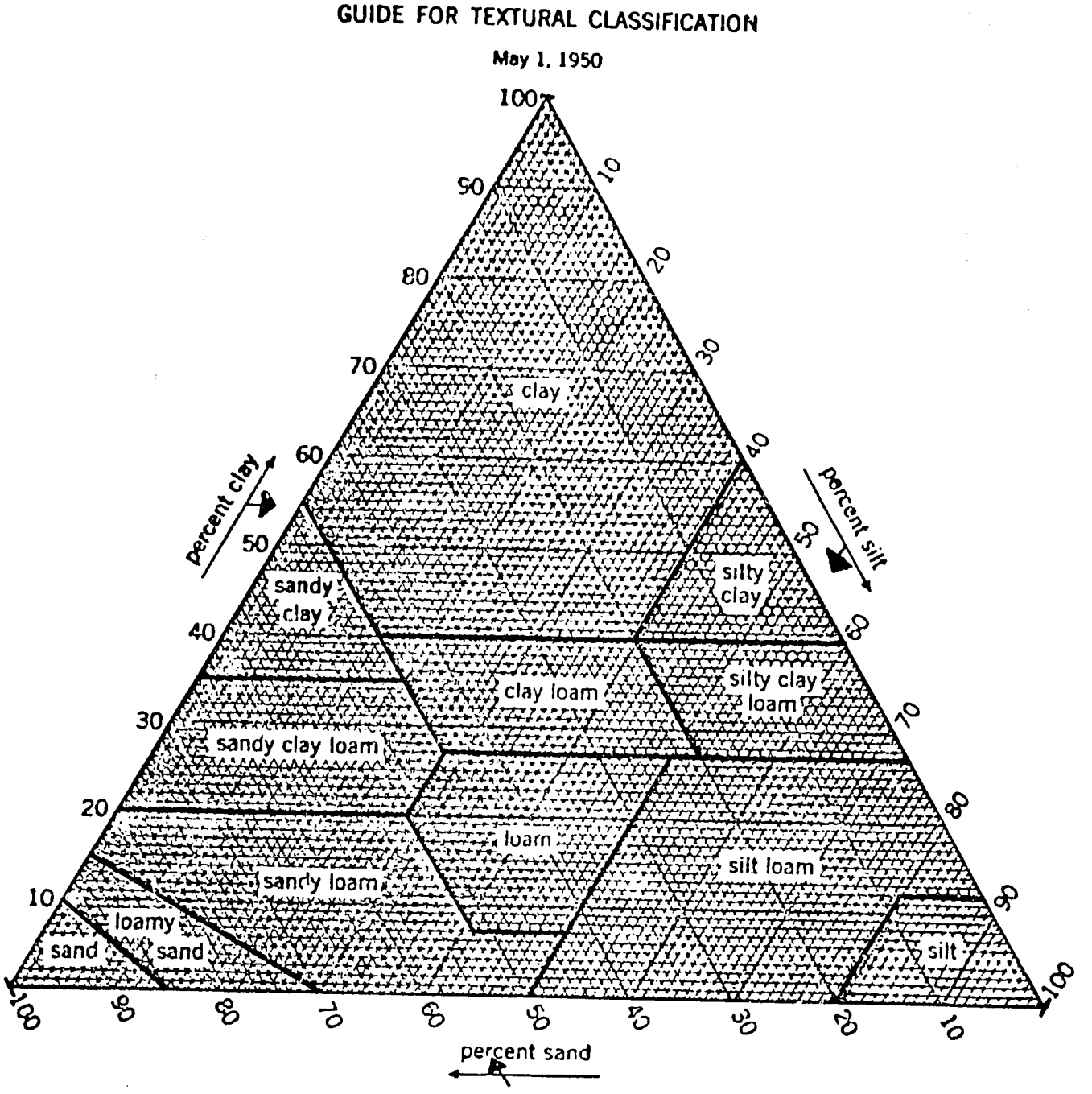

Figure 2. Textural Classification Guide, U.S. Department of Agriculture, Bureau of Plant Industry, Soils, and Agricultural Engineering. 1950.

SOIL MOISTURE SAMPLING*

by A. Early

The King Tube Sampler is a useful tool to the water management specialist. When properly constructed and correctly used, it provides volumetric samples of soil to calculate dry bulk density, soil moisture percentages, and plant food analyses. However, extremes in soil moisture percentages may limit density accuracy. In very dry soil, some of the sample often may be left at the bottom of the hole, and very wet soil will stick to the sides of the tube. In either case, lower-than-actual-density values may result.

A few precautions and suggestions were developed to assist in avoiding these pitfalls.

1. Clean and polish the tube regularly to be sure it is clean and free of rust. Cover with a light film of oil if tube is not used regularly.

2. Measure the inside diameter of the cutting edge of the tube and check the exterior depth calibrations above the cutting edge. Reject the tube if any of the measurements are not within 0.005 ft (.01 centimeter).

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* Modified from an article in The Problem Identification Handbook. (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100. Fort Collins, CO.

3. Select representative sites from the field to be sampled. Areas within the field which appear different from the "average" should be sampled separately.

4. Align the tube vertically and strike the tube vertically into the ground so the pointed edge of the hammer moves inside the tube in an up and down motion. Never swing the hammer as a driving device.

5. Place a straight edge on the ground next to the hole as a reference point to stop the sample tube at each depth graduation.

6. Remove the hammer from inside the tube and orient it horizontally (perpendicular to the tube), passing the hammer slot over the end of the tube. Rotate the hammer 90° in a horizontal plane and lift the tube slowly, vertically from the soil.

7. Place your left index finger over the cutting edge of the tube as it emerges from the surface of the soil to prevent sample spillage.

8. Invert the tube with top of tube over the container (a moisture can with tight fitting lid or a plastic bag) to keep the sample in proper moisture condition until weights are determined. Force the sample loose by pushing it loose with the index finger. A clean, polished tube, properly constructed, easily releases the sample into the container. Close the container immediately to prevent the loss of moisture. Do not allow unweighed sample to be exposed directly to the sun, especially samples collected in plastic bags.

9. Repeat steps 4 through 8 for as many different depth increments as needed.

10. Repeat steps 3 through 9 for at least two replicates in other representative sites of the field being sampled.

11. Weigh and record the weight of the wet sample in the field. Samples placed in plastic bags should be weighed immediately.

12. Dry the sample.

13. Reweigh the sample after predetermined drying time. (The sample is considered dry when no further weight changes occur.)

14. Make necessary calculations using the following procedures.

    a. Volume = $3.14\ (D/2)^2 H$.

    b. Water Weight = (wet weight of sample and container) - (dry weight of sample and container).

    c. Net dry weight of sample = dry weight (sample and container) - weight of container.

    d. Percent moisture by weight =

    $$\frac{\text{net weight of water}}{\text{dry weight of soil}} \times 100 .$$

    e. Field dry bulk density =

    $$\frac{\text{net dry weight of soil (gm)}}{\text{volume of sample (cc)}} .$$

    f. Percent moisture by volume = field dry bulk density x percent moisture by weight or

    $$\frac{\text{weight of water}}{\text{volume of sample}} \times 100 .$$

    g. Approximate available moisture (inches per foot) ASM = 12 x % MC Volume - Volume at wilting point where % MC-Vol. at the wilting point is to come from laboratory analysis of soil moisture characteristic.

SOIL MOISTURE DETERMINATION*

by A. Early

Water management proficiency requires technicians to learn 1) the water requirements of the plants to be grown, 2) how much of that water can be furnished from the soil's stored moisture, and 3) how much and how often water must be applied through irrigation. Soil moisture determination, therefore, is important as soon as soil samples are collected and prepared.

The sample must be protected against moisture loss from the time it is collected until the initial weight is recorded. Airtight metal or plastic containers provide such protection.

There are two types of moisture determination methods. The gravimetric (measurement by weight) determination involves determining weight differences at the time the sample is collected and after it is dried to measure the amount of the water in the soil. The touch and feel method is a field procedure used to make quick, practical estimates of moisture resources and requirements.

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* Modified from an article in The Problem Identification Handbook. (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100.

GRAVIMETRIC DETERMINATIONS

The Oven

The oven is used in the laboratory to determine soil moisture analyses. It provides an exact analytical measurement of the amount of moisture in the soil and, through combining the results from samples representing various segments of the soil profile, the water content of the field within the root zone of the crop to be produced can be calculated.

Standard procedure for use of the oven is:

1. Weigh and record weights of the air-tight containers and the soil they contain.

2. Open the containers and place them in the oven which is set at 105°C.

3. Dry for 24 hours.

4. Record dry weight.

5. Subtract dry weight from weight of the field-collected sample. The difference is water.

Because some soils dry more readily than others, this procedure may be repeated as necessary until the weight becomes constant.

The Sun Drying Method

Because ovens generally are not available to workers in the field, an alternate method was developed which uses solar energy for drying soil samples. In areas where the climate is warm and dry, results have been close to those obtained from oven-dried samples.

Plastic sheets or the same plastic bags in which the samples are stored are exposed to the sun after the sample is weighed. The procedure for sun-drying of samples is:

1. Determine weight of sheet or bag by weighing 100 of them and determining the average weight.

2. Spread the sample out and break any clods present to provide maximum exposure of soil to the sun.

3. Place the samples in a convenient, protected area where maximum exposure to the sun is available.

4. Exposure time:*

Time of Year	Sheet	Bag
Hot Season	3 hours	5 hours
Cool Season	4 hours	7 hours

These tabulated times assume the number of hours of bright sunshine. Drying cannot be done during cloudy or partly cloudy weather.

Overnight drying is not recommended because wind or storms can ruin samples quickly.

Specifications of drying sheets or bags:

Sheets

-- Sheets should be 2-to-6-mil. polyethelene plastic, 24-inches square.

-- Sheets need not be weighed if a special weighing dish is used.

Bags

-- If the same bag in which the sample is collected is used, larger bags are needed. 15" x 15" plastic bags are recommended so they may be folded to provide a two-inch rim around the exposed sample. Using bags provides somewhat more protection against spillage than use of sheets and requires fewer supplies and less handling.

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* These exposure times have been found to approach 1% of oven-dry weights in Pakistan, where the climate is warm and dry and the sun intensity is high.

THE TOUCH AND FEEL METHOD

The touch and feel method is not intended to replace field samplings and laboratory techniques. Rather, it is intended to enable the technician to develop a practical, quick estimate in the field when decisions about water use or irrigation planning are necessary.

A detailed explanation of the touch and feel method is presented in the previous article, "Soil Texture Determination" (L. Nelson). Figure 1 (page 18) of that article gives the step-by-step procedure for this method.

Once the basic textural group is determined, the samples in the field moisture condition is examined. Squeeze the sample into a ball about an inch in diameter. Test the ball for strength and compare its strength with the descriptions given in Table 1 representing the textural grade of the sample. Estimate the soil moisture deficiency in inches-per-foot of depth using the last column of the table.

Note: the chart assumes the average soil's available soil moisture, at field capacity, for the four textural classes to be:

Coarse - 0.7 inches per foot

Light - 1.3 inches per foot

Medium - 1.8 inches per foot

Fine - 2.0 inches per foot

These values can be divided by 12 and multiplied by 100 to convert to available moisture on a volume basis. The figure divided by the bulk density of the soil provides available moisture on a weight basis (which the gravimetric procedure provides).

Comparison of the Three Techniques

The three techniques discussed here are not designed to replace one another. They are each used in a manner to expedite the management program most efficiently.

Use of the oven provides the true analytical analyses of soil moisture availability. The other methods were developed to supplement, not replace, the oven. The accuracy of the sun drying method depends on the care with which the sample is handled, temperature, humidity and intensity of the sun. Its accuracy might not be dependable in cool or humid climates, but in warm, dry areas such as Pakistan, the results were found to be

Table 1. Soil Moisture Deficiency and Appearance Relationship Chart* (This chart indicates approximate relationship of soil moisture deficiency between field capacity and wilting point. For more accurate information the soil must be checked by drying samples.)

Moisture Deficiency (in/ft)	Soil Texture Classification: Coarse (loamy sand)	Sandy (sandy loam)	Medium (loam)	Fine (clay loam)	Moisture Deficiency (in/ft)
0.0	Leaves wet outline on hand when squeezed	Appears very dark, leaves wet outline on hand, makes a short ribbon	Appears very dark, leaves wet outline on hand, will ribbon out about one inch	Appears very dark, leaves slight moisture, on hand when squeezed, will ribbon out about two inches	0.0
0.2	Appears moist makes a weak ball	Quite dark color, makes a hard ball	Dark color, forms a plastic ball, slick when rubbed	Dark color, will slick and ribbons easily	0.2
0.4	Appear slightly moist sticks together	Fairly dark color, makes a good ball	Quite dark, forms a hard ball	Quite dark, will make thick ribbon, may slick when rubbed	0.4
0.6	Dry, loose, flows thru fingers. (wilting point)	Slightly dark color, makes a weak ball	Fairly dark, forms a good ball	Fairly dark, makes a good ball	0.6
0.8	Lightly colored by moisture, will not ball	Slightly dark, forms weak ball	Lightly colored, small clods crumble fairly easily	Will ball, small clods will flatten out rather than crumble	0.8
1.0		Very slight color due to moisture (wilting point)	Slight color due to moisture, small clods are hard (wilting point)	Some darkness due to unavailable moisture, clods are hard, cracked (wilting, point)	1.0
1.2					1.2
1.4					1.4
1.6					1.6
1.8					1.8
2.0					2.0

*From Merriam, J.L. 1960. Field method of approximating soil moisture for irrigation. Transactions of The American Society of Agricultural Engineers 3(1):31-32. St. Joseph, MI.

practical and accurate when samples were properly handled and protected.

The touch and feel method is not intended to replace gravimetric procedures. It was developed to make quick, practical field decisions. If the procedure is to be accurate and effective, the person using it should constantly calibrate his "feel" against gravimetric results.

PARTICLE DENSITY AND BULK DENSITY

by L. Nelson

Two methods are used to express soil weight: particle density and bulk density.

Particle density (specific density), a weight measurement concerned with soil solids, is defined by the equation:

$$D = \frac{Ws}{Vp}$$

where:

Dp = particle density (g/cc)

Ws = weight of oven (g) dried soil

Vp = volume of the particles (cc)

Although particle densities of soils may range from less than 2.40 g/cc in organic soils to greater than 2.75 g/cc in heavy mineral soils, most mineral soil particle densities are around 2.65 g/cc. While exact particle density of a mineral soil is relatively easy to determine in the laboratory, it is normally assumed to be 2.65 g/cc for most purposes. The small errors incurred by assuming this value have little effect on calculations which involve particle density.

Bulk density, which takes into account the entire soil, volume is defined by the equation:

$$Db = \frac{Ws}{Vb}$$

where:

Db = bulk density g/cc

Ws = oven dry weight of the soil

Vb = bulk volume of the soil

Thus, bulk density measurements take into account both solid particles and pore spaces of a soil. Bulk density values of clay, clay loam and silt loam soils normally range from 1.00 to 1.60 g/cc while sands and sandy loams may range from 1.20 to 1.80 g/cc. Very compact subsoils, regardless of texture, may have bulk densities as high as 2.00 g/cc or greater. Bulk densities vary within a field and often increase with depth.

Field and/or laboratory bulk density measurements are useful for pinpointing compacted soils which may restrict root growth of crops and impair plant-soil-water relationships. The extent and thickness of hardpans over a given area are determined easily with bulk density measurements. Even variations in management practices of farmers may be associated with changes in bulk densities. Bulk density data also can be used to calculate soil porosity which closely approximates the maximum percentage of water the soil will hold (saturation percentage)

$$P = 100 - \frac{Db}{Dp} \times 100$$

When average porosity of a soil is determined, estimates of water-holding capacities and irrigation requirements can be made from soil moisture determinations.

CORE METHODS FOR DETERMINING BULK DENSITY

A. Double Cylinder Sampler Method

Because larger samples are collected (fewer errors), the double cylinder apparatus is preferred to an open-sided probe for collecting bulk density samples. However, if a double cylinder apparatus is unavailable, the open-sided probe will suffice if extreme care is taken in obtaining the sample and if replications are increased.

Equipment:

1. Double cylinder sampler
2. Spatula or knife
3. Soil moisture cans (one/sample)
4. Shovel
5. Drying oven
6. Balance

Method:

The instrument is composed of a double-cylinder, connecting rod, and a sliding hammer. To obtain bulk density samples, drive or press the sampler into either a vertical or horizontal soil surface far enough to fill the sampler without compacting the soil. Then remove the sampler so the structure and packing of the soil are not disturbed. This may require the use of a shovel to loosen the soil and the sampler. After removal, separate the two cylinders from the sampler. The undisturbed soil is retained in the inner cylinder. Trim soil extending beyond the ends of the cylinder flush. The soil sample volume is the same as the volume of the sampler holder.

$$V = \pi r^2 h$$

where:

V = volume of the soil sample

π = 3.14

r = radius of the cylinder

h = height of the cylinder

Note: the cutting edge of the sampler normally has a slightly smaller diameter than the sample holder to reduce friction as the soil enters the inner cylinder. Therefore, use the diameter of the cutting head for volume calculations.

Once a satisfactory sample is collected, transfer the soil to a soil moisture can, dry in an oven at 105°C for 24 hours, and weigh. Then calculate the bulk density of the sample using the formula presented in the introduction of this section.

B. The Open-Sided Probe Core Method

Equipment:

1. Open-sided probe,
2. Spatula or knife,
3. Centimeter ruler,
4. Soil moisture cans,
5. Drying ovens, and
6. Balance.

Method:

The sampling procedure is somewhat similar to that of double cylinder method. Carefully press the open-sided probe vertically into the soil and withdraw the probe to avoid shearing of the exposed soil. Compaction of the soil sample is observed easily by comparing the depth the probe was inserted with the length of the soil sample. Discard compacted samples. The inside walls of the probe may be coated with a lightweight oil to reduce friction and compaction problems.

Once a satisfactory sample is collected, lay the probe on the ground with the exposed soil up. Then use a ruler to measure a predetermined length of the sample (> 10 cm). Carefully trim each end of the sample core with a spatula or knife, making sure the cuts are vertical. Remove excess soil from either side of the sample core and place the core in a soil moisture can. Then treat the known sample volume in a similar manner to that described in the double cylinder core method.

EXCAVATION METHOD FOR DETERMINING BULK DENSITY

Equipment:

1. 5 kg of standard size sand (sand particles passed through a Number 20 sieve and retained or a Number 60 sieve are recommended) or a rubber-balloon apparatus*
2. 1000 ml graduate cylinder,

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* The rubber balloon apparatus does not require a graduate cylinder or a template.

3. A template consisting of a thin, flat metal plate approximately 30 cm square, with a hole 10 to 12 cm in diameter,

4. Centimeter ruler,

5. Spoon (large),

6. Large metal soil containers,

7. Drying oven, and

8. Balance.

Method:

Lay the template on a previously leveled soil surface cleaned of loose soil. Excavate a hole 12 cm in diameter and approximately 12 cm deep. Place the excavated soil in a large soil can for later determination of oven-dry weight. Then fill the hole with sand to the bottom of the template. By using a graduated cylinder, the volume of sand used to fill the hole is known and bulk density may be calculated after oven-dry weights of the soil are determined.

The rubber-balloon apparatus follows a similar procedure except a balloon replaces the sand in the excavated hole and is attached to a specially designed water-filled cylinder. A valve is turned on to expand the balloon and fill the hole. Graduated readings on the cylinder permit easy volume determinations.

REFERENCES

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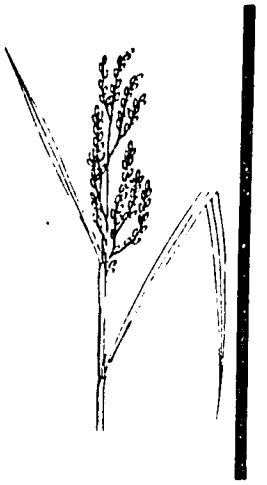

SOIL FERTILITY AND SALINITY ANALYSES SAMPLING*

by B. Stewart

The analyses of the soil sample provides a quick, practical way for the farmer and the field supervisor to obtain advanced information about the fields with which they will be working during the following production season. Cultural decisions can be made in advance, thus allowing for more efficient planning prior to when the soil is being prepared for planting.

If the tests are to be of value to the farmer, he must be able to associate each of them with a particular set of field conditions. Familiarity with the fields and with the situations that the tests represent will enable the farmer to formulate his production plan ahead of time. The manner in which the soil sample is collected and prepared, therefore, becomes very important. Rather precise techniques have been developed which, when followed, will provide accurate information about the fields under the conditions which the soil sample represents. It must be emphasized that samples that are not representative, or that are improperly handled are worthless.

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* Modified from an article in The Problem Identification Handbook. (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100. Fort Collins, CO.

Equipment:

The sample can be collected with the shovel or spade, normally used on the farm for other work (Figure 1). Soil sampling augers and tubes, however, simplify the collection. In Pakistan, the King Tube Sampler is widely used. Sampling equipment must be clean and free from rust to eliminate contamination. Clean, well-kept equipment also is easier to use. If micronutrient analyses are to be performed, stainless steel and plastic tubes and buckets are recommended to eliminate any possibility of introducing iron and zinc into the sample from the equipment.

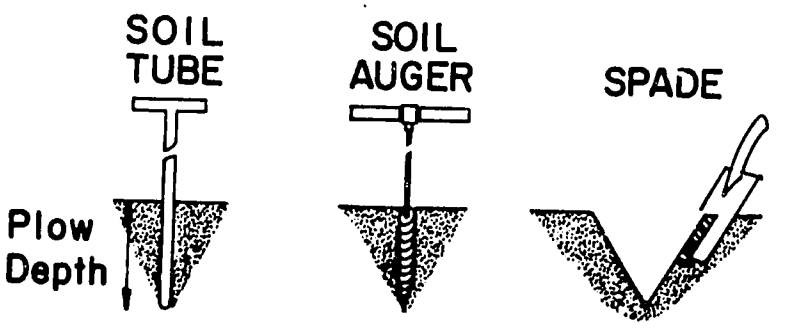

Figure 1. Possible Tools for Taking Samples to the Plow Depth

Method:

The field supervisor who is responsible for sampling procedures gradually will develop a routine which simplifies the sampling procedure and reduces the time involved. A rather definite procedure is followed:

1. The person who is sampling the field must become familiar with the various situations within the field and sample accordingly. Each sample must represent a specific field situation and condition, and be labeled, bagged, and packaged accordingly (Figure 2).

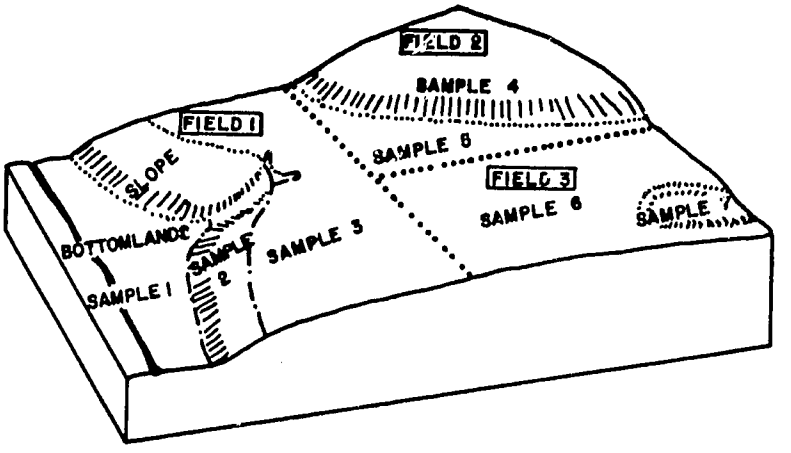

Figure 2. Illustration of How a Field Might be Divided So All Uniform Areas Are Represented

2. Using clean equipment, collect 10 to 20 cores from each selected ara. (If the spade is used, the "core" is a sample of the plow slice, 1 inch wide, from the center of the blade.) Most of the fertility elements are normally contained in the upper six inches of the soil, so sample to the depth of the "plow slice"--usually 6 to 8 inches. When necessary for salinity analyses, additional samples may be taken at intervals from the entire root zone.* If subsoil samples are to be taken, either for fertility or salinity analyses, collect a second sample from the same bore from the 6" to the 12" level, etc., until the desired depth is reached. Label and submit these samples separately.

3. Thoroughly mix the sample, breaking up any clods which might be present. Dry the sample (air dry, do no heat). Spread the sample upon a flat, clean surface and divide the sample into quarters until about a quart (about 1 liter volume) of soil remains for fertility analyses. Samples about twice this size should be collected for complete salinity analysis.

4. Package the sample in a strong, clean container.

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* For salinity analyses, subsoil samples are always required.

5. Be sure to fully identify each sample and record the information needed to identify it with the field situation from which it was collected.

6. Submit complete information to the laboratory. (Their information can only represent that which they are given.) Package the samples and deliver them to the laboratory with that information. Be sure that samples are protected against breakage and mixing on their way to the laboratory.

This completes the sampling process for one field condition. Repeat the process for each segment of the field which is to be sampled.

SOIL SALINITY DETERMINATION

by L. Nelson

The electrical conductivity, EC, of the soil solution is commonly used to indicate the salinity status of a soil. Electrical conductance is expressed in mhos and is the reciprocal of electrical resistance which is given in ohms. Electrical conductance is used to describe the salt concentration of soil solution because the conductance varies with salt content.

Most solutions have electrical conductivity much less than one mho. It is, therefore, customary to express electrical conductivity of soil solutions in millmhos/cm (mmhos/cm) and electrical conductivity of irrigation waters in micromhos/cm (umhos). One mhos/cm consists of 10^3mmhos/cm and 10^6umhos/cm.

Equipment:

1. Conductivity meter for electrical conductivity measurements,
2. Conductivity cell, pipet type, which consists of a pair of 1 cm square platinum electrodes separated by 1 cm. (The cell usually has a capacity of 2 ml.),
3. Extractor or vacuum system,
4. Balance,
5. Filtration flasks,
6. Buchner or Richards funnels,

7. Thermometer,

8. Mixing bowls or 500 ml beakers,

9. Spatula,

10. Distilled water,

11. Thermometer,

12. 100 ml graduated cylinder,

13. .01 N KC1 solution,

14. (2) 100 ml beakers, and

15. 50 ml beaker.

Procedure:

1. Weigh approximately 100 g of air-dried, sieved soil for a gravimetric soil moisture determination.

2. Weigh another sample, approximately 200 g of air-dried, sieved soil into a mixing bowl or beaker. Record weight of soil and weight of the soil plus mixing bowl.

3. Prepare the saturated paste by slowly adding distilled water to the soil sample while stirring with a spatula. At saturation, the soil paste glistens as it reflects light, flows slightly when the container is tipped, and slides freely and cleanly off the spatula. This is true for all soils except those with high clay content. Record the amount of water used to make the soil paste. Seal the bowl with a plastic wrapper and allow to stand for four or more hours.

4. Place a medium grade filter paper in the funnel of the Buchner funnel-vacuum flask assembly and dampen the filter paper with distilled water.

5. Spread the saturated paste over the filter paper and gently apply a vacuum. Terminate vacuum extraction after 15 to 20 ml of soil solution are collected.

6. Turn the conductivity meter on and allow it to warm up for 2 to 5 minutes.

7. Determine the cell constant with a 0.01 N KCl solution. Fill and empty the cell twice with the 0.01 KCl (a .01 N KC1 solution = 0.7456 g KCl dissolved in 1 liter of distilled water) solution to avoid contaminations from solutions previously used in the cell. Fill the cell a third time and follow the manufacturers instructions for balancing the bridge. Read the electrical conductivity and correct the reading with the temperature conversion factor f_1 (Table 1). Calculate the cell constant, k, as follows:

$$k = \frac{EC_{KC1\ 25°}}{1.4118 \text{ mmhos}}$$

where $EC_{KC1\ 25°}$ is the measured electrical conductivity of the 0.01N KC1 solution corrected to 25°C and 1.4118 mmhos is the known electrical conductivity of a .01 N KC1 solution at 25°C.

8. Fill and empty the cell twice with distilled water.

9. Fill and empty the cell twice with the soil solution (saturated paste extract).

10. Refill the cell with the soil solution and record the electrical conductivity reading.

11. Measure the temperature of the soil solution and record.

12. Repeat steps 8-11 for subsequent samples.

13. Turn off conductivity meter.

Table 1. Temperature Conversion Factors, f_t, for Converting Conductivity Data on Soil Solution Extracts to the Standard Temperature of 25°C

°C	f_t	°C	f_t	°C	f_t
3.0	1.709	22.0	1.064	29.0	0.925
4.0	1.660	22.2	1.060	29.2	0.921
5.0	1.613	22.4	1.055	29.4	0.918
6.0	1.569	22.6	1.051	29.6	0.914
7.0	1.528	22.8	1.047	29.8	0.911
8.0	1.488	23.0	1.043	30.0	0.907
9.0	1.448	23.2	1.038	30.2	0.904
10.0	1.411	23.4	1.034	30.4	0.901
11.0	1.375	23.6	1.029	30.6	0.897
12.0	1.341	23.8	1.025	30.8	0.894
13.0	1.309	24.0	1.020	31.0	0.890
14.0	1.277	24.2	1.016	31.2	0.887
15.0	1.247	24.4	1.012	31.4	0.884
16.0	1.218	24.6	1.008	31.6	0.880
17.0	1.189	24.8	1.004	31.8	0.877
18.0	1.163	25.0	1.000	32.0	0.873
18.2	1.157	25.2	0.996	32.2	0.870
18.4	1.152	25.4	0.992	32.4	0.867
18.6	1.147	25.6	0.988	32.6	0.864
18.8	1.142	25.8	0.983	32.8	0.861
19.0	1.136	26.0	0.979	33.0	0.858
19.2	1.131	26.2	0.975	34.0	0.843
19.4	1.127	26.4	0.971	35.0	0.829
19.6	1.122	26.6	0.967	36.0	0.815
19.8	1.117	26.8	0.964	37.0	0.801
20.0	1.112	27.0	0.960	38.0	0.788
20.2	1.107	27.2	0.956	39.0	0.775
20.4	1.102	27.4	0.953	40.0	0.763
20.6	1.097	27.6	0.950	41.0	0.750
20.8	1.092	27.8	0.947	42.0	0.739
21.0	1.087	28.0	0.943	43.0	0.727
21.2	1.082	28.2	0.940	44.0	0.716
21.4	1.078	28.4	0.936	45.0	0.705
21.6	1.073	28.6	0.932	46.0	0.694
21.8	1.068	28.8	0.929	47.0	0.683

Source: Richards, L.A. (Ed.). 1954. Diagnosis and improvement of saline and alkali soils. U.S. Department of Agriculture, Handbook 60. Washington, D.C.

14. Fill and empty the cell two or more times and store cell filled with distilled water.

Calculations:

Percent water in the air dry soil:

$$\% H_2O = \frac{(\text{air dry soil weight + tare - oven dry soil weight + tare})}{(\text{oven dry soil weight - tare})}$$

Percent water in saturated paste:

$$\% H_2O = \frac{(\text{grams water added}) + (\%, H_2O \text{ air dry soil})(\text{air dry soil weight})}{(\text{air dry soil weight}) - (\% H_2O \text{ air dry soil})(\text{air dry soil weight})}$$

Electrical conductivity of the soil solution:

$$EC = EC_R \times f_t \times k$$

COMMENTS

In areas where irrigation waters of low salinity are used, the concentration of soil solution extracts frequently range in electrical conductivity below 4 mmhos/cm. In these situations, little or no evidence of salt injury has been found and almost any crop adapted to the climatic conditions may be grown (Table 2). In areas where the soil solution extracts range in conductivity to 8 mmhos/cm, many of the more sensitive crop plants do not thrive, but such crops as cotton, alfalfa, sugar beets and cereals, including grain sorghums, may grow well and produce excellent crops.

Table 2. Crop Condition Related to the Electrical Conductivity of Soil Solution Extract From the Saturated Soil Paste (Richards, 1954)

Scale of Conductivity mmhos/cm			
0	4	8	16
All crops thrive no evidence of salt injury.	Sensitive crops do not thrive. Tolerant crops may do well.	Crop growth restricted, yield usually poor.	Only a few species survive.

MEASURING pH

by L. Nelson

The determination of the hydrogen ion activity or pH of a soil is a common measurement used to characterize soils. Although the amount of H^+ in soils is normally small ($10^{-3.5}$ to 10^{-12} moles/liter), the H^+activity is extremely important. The chemistry of the soil, both organic and inorganic, is so closely related to pH that no other single measurement conveys as much chemical information.

Field measurements of pH are either electrometric or colorimetric. Electrometric methods require use of a portable, battery-operated pH meter. Colorimetric methods use a series of indicators or a single indicator that change colors depending on the pH range found in the soil. Although colorimetric methods are not as precise as the electrometric methods, they are easily made in the field and therefore quite suitable for field surveys. Only within the specific ranges of pH 4.5 to 5.5 and pH-8-to-9 (borderline areas for problem soils) is it necessary to take samples to a laboratory for more precise electrometric determinations.

INTERPRETATION OF pH MEASUREMENTS

Interpretation of pH measurements requires an understanding of chemical dissociation of water and its dissociation constant.

$$H_2O \rightleftharpoons H^+ + OH^- \qquad 10^{-14}$$

and

$$(H^+)\ (OH^-) = 10^{-14}$$

In a closed system (no gas exchange), the hydrogen ion activity (H^+) and the hydroxyl ion activity (OH^-) are both 10^{-7} moles/liter. Examination of the equation reveals that (H^+) and (OH^+) can vary from 10^0 to 10^{-14} as long as they sum to 10^{-14}.

By convention, pH is defined as the negative log of the hydrogen ion activity and p OH as the negative log of the hydroxyl ion activity. The pH scale varies from 0 to 14. At a pH of 7, H^+ and OH^-activities are equal and the solution is said to be neutral. When the pH of a solution is less than 7, the solution is said to be acidic; that is, the activity of H is greater than the activity of OH . Conversely, when the pH of a solution is greater than 7, it is basic or alkaline and the activity of OH is greater than the activity of H . Terminology used to describe pH values for solutions is directly transferable to soils. Thus, a soil with a pH of 7 is a neutral soil, while soils with pH values less than 7 become more acidic and those with pH values greater than 7 become more alkaline.

It is important to realize that much information provided by pH measurements of soils is inferential. However, when the pH of a soil is combined with other chemical tests and field observations, the agronomist can be fairly certain the picture he presents of a given field will be confirmed by the more time-consuming, detailed research procedure involved in the solution phase of a project.

NUTRIENT AVAILABILITY

Because pH directly and indirectly affects the availability of minerals essential to plant growth, certain inferences about nutrient availability can be made from pH measurements. Figure 1 shows 1) the relative availability of some of the mineral nutrients as a function of pH and 2) that neutral and near neutral soils are capable of supplying nutrients at more favorable levels than soils falling in either acidic or alkaline pH ranges. It is important to realize, however, that other soil properties, determine the actual fertility of a given soil. They include the organic matter content, cation exchange capacity, the types of primary and secondary minerals in the sand, silt and clay fraction, and soil depth. In other words, improved availability of mineral nutrients, normally associated with pH ranges of 5.5 to 8, are unimportant if they are in low supply to begin with. The more acidic soils, usually associated with high rainfall areas, are generally deficient in major nutrients, while the more alkaline soils of the arid region often are incapable of supplying iron and zinc in quantities needed by some field crops. Furthermore, increased availability of iron and manganese in acid soils (pH < 5) and boron in strongly alkaline soils may cause toxicity problems in many field crops.

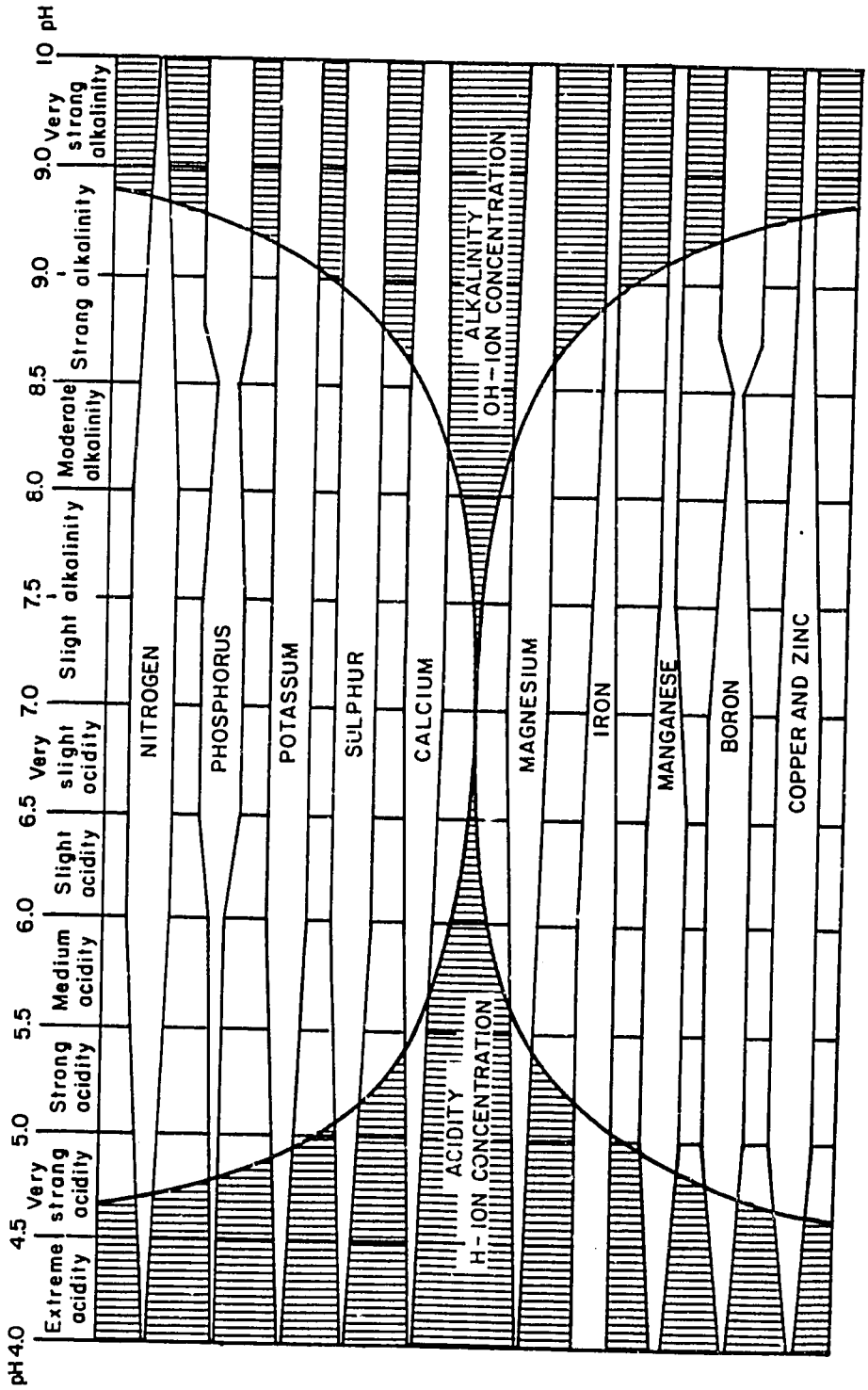

Figure 1. Chart of the General Relationships Between Soil pH and the Availability of Plant Nutrients (From Truog, E. (ed). 1951. Mineral nutrition of plants. University of Wisconson Press, Madison, WI)

CHEMICAL PROPERTIES

In addition to nutrient availability, soil pH determinations provide useful information about the chemical properties of a soil. Very acidic soils (pH < 5) contain significant amounts of exchangeable hydrogen and aluminum, have extremely low base saturation values and are unfavorable for the growth of field crops. Serious aluminum toxicity problems often are apparent in such soils. Extremely acidic soils, developed in coastal march areas, may be acid sulfate soils with very serious agricultural problems. Soils with pH values of 5 to 6 have sufficient exchangeable hydrogen to affect acid sensitive crops such as alfalfa. Soils with pH values varying from 6.5 to 8 are fully base saturated, with no exchangeable aluminum and are usually quite favorable for most field crops. Soils with pH values of 8 to 8.5 often possess free calcium carbonate with calcium and magnesium as the dominant exchange cations. When soil pH values exceed 8.5, exchangeable sodium percentages are greater than 15% and the soil is classified as either sodic or saline sodic, depending upon the amount of salts present in the soil profile. The agricultural productivity of a sodic, saline-sodic soil is seriously impaired by structural degradation associated with high sodium levels.

THE COLORIMETRIC METHOD FOR DETERMINING pH

Equipment:

1. Indicator solution(s),
2. Porcelain test plate specially designed with two indented compartments connected by a channel,
3. Standard color chart of the appropriate indicator(s), and
4. Glass rod or spatula.

Method:

A number of test kits are on the market that may contain a universal indicator or a series of indicators. Procedures differ only slightly between the two types of indicators.

1. A small representative sample of soil is placed in the upper compartment of the porcelain test plate and treated with a slight excess of the indicator solution. 2. After about one minute, the plate is tilted slightly so the solution runs down the channel into the second compartment. A glass rod or spatula can be used to draw the fluid down the channel. 3. The color of the solution then is compared with that given on the color

chart. Multiple indicator tests have color charts for each indicator. 4. If the pH should fall near the end of the color range for one indicator, repeat the test using another indicator that has an overlapping pH range.

THE ELECTROMETRIC METHOD FOR DETERMING pH

Equipment:

1. 2 standard buffer solutions,
2. 2 - 50 ml beakers,
3. 2 - 100 ml beakers,
4. Chem wipes or tissue paper,
5. 1 wash bottle, and
6. Saturated paste sample.*

Method:

Before using a pH meter, immerse the electrodes in distilled water for 5 to 10 minutes to reduce the potential of needle fluctuations when calibrating the pH meter. Where pH meters are used daily, store the electrodes in distilled water.

1. Turn the function selector to standby.

2. Lift the electrode out of the storage beaker and replace the storage beaker with a rinsing beaker (100 ml). Rinse the electrode with distilled water.

3. Remove the storage beaker and place a standard buffer solution (50 ml beaker) under the electrode. Place the electrode in the buffer solution and turn the selector switch to pH. The needle on the pH meter should read the pH value corresponding to that of the buffer solution. If it does not, adjust the needle to the pH of the buffer solution with the calibration knob. Turn the selector switch to standby. Lift the electrode from the buffer solution and rinse the electrodes with distilled water. Repeat the procedure with a second standard buffer solution to insure the instrument is functioning properly.

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* Saturated paste and sample may be replaced by 1:25 or 1:5 soil to water ratios, but the pH of the sample may be increased by as much as 1 pH unit upon dilution.

Turn the selector switch to standby, lift the electrode from the buffer solution and rinse the electrode with the wash bottle.

4. Remove the collector beaker and place the saturated paste sample under the electrode. Carefully lower the electrode into the saturated paste and turn the selector switch to pH.

5. After the meter has stabilized, record the pH reading on the sheet.

6. Turn the selector switch to standby, remove the electrode from the saturated paste and rinse the electrode off with the wash bottle, making sure all soil is removed.

7. Repeat steps 4, 5, and 6 for additional samples. After every 5 to 10 samples, the pH meter should be checked with one of the standard buffer solutions (Step 3) to avoid errors due to drift in the instrument.

8. Return the electrode to the storage beaker and turn selector switch to off.

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DETERMINING NUTRIENT DEFICIENCES

by L. Nelson

The sixteen elements essential for most higher plants are shown in Table 1. Three of the elements, carbon, hydrogen, and oxygen, constitute over 95% of the dry weight of plants and are obtained primarily from atmospheric gases and water. Although the remaining thirteen elements comprise less than 5% of the dry weight of plants, agricultural soils often are incapable of supplying one or more of the nutrients in the quantities needed for desirable crop yields.

Mineral nutrients that limit crop yields may be identified by foliar observation (visual diagnosis), chemical analysis of plants and soils, fertilizer trials, and the farmer's management records. Research projects dealing with soil fertility often use all four of the above methods to investigate disorders. However, survey projects concerned with the identification of production constraints within an agricultural area often are limited by time. As a result, less quantitative field testing procedures may be used to identify potential nutritional disorders. Data gathered from such a survey usually is adequate to identify nutrient deficiencies limiting crop yields.

As part of the survey, collect background information concerning soils, crop varieties, fertilizer requirements and on-going research from local, national and/or international research centers. During the survey, schedule interviews with farmers to obtain records of fertilizer inputs and to identify fertility-related problems encountered by the farmers. Whenever possible, encourage farmer participation in the field survey to benefit from the farmers' intimate knowledge of their fields and to improve the relationship between the farmer and project.

Table 1. Elements Essential for Most Higher Plants (Modified from Salisbury, F.B. and C. Ross. 1969. Plant physiology, Wadsworth Publishing, Belmont CA.)

Element	Chemical symbol	Form available to plants	Translocated between plant tissues	Concentration in dry tissue (%)
Molybdenum	MO	MoO_4	Yes	0.00001
Copper	Cu	Cu^+, Cu^{++}, $Cu(OH)^+$	No	0.0006
Zinc	Zn	Zn^{++}, $Zn(OH)_2$	No	0.0020
Manganese	Mn	Mn^{++}	No	0.0050
Iron	Fe	Fe^{+++}, Fe^{++}	No	0.010
Boron	B	$BO_3^=$, $B_4O_7^=$	No	0.002
Chlorine	Cl	Cl^-	Yes	0.010
Sulfur	S	$SO_4^=$	No	0.1
Phosphorus	P	$H_2PO_4^-$, $HPO_4^=$	Yes	0.2
Magnesium	Mg	Mg^{++}	Yes	0.2
Calcium	Ca	Ca^{++}	No	0.5
Potassium	K	K^+	Yes	1.0
Nitrogen	N	NO_3^-, NH_4^+	Yes	1.5
Oxygen	O	O_2, H_2O	Yes	45
Carbon	C	CO_2	Yes	45
Hydrogen	H	H_2O	Yes	6

PROBLEMS AND LIMITATIONS

Awareness of potential problems and limitations of visual diagnostic techniques is important when conducting a field survey. Problems with visual diagnostic technique are: 1) the expression of a particular mineral deficiency may differ from one type of crop to another; 2) the problem of identification of a deficiency becomes especially difficult, if not impossible, when multiple deficiencies are present; 3) disease and insect damage may induce nutritional disorders or the damage may be mistaken for a nutrient deficiency; 4) symptoms of toxicities, overirrigation or high watertables may be mistaken for a nutrient deficiency; 5) induced deficiencies may develop from abnormal changes in the environment or from management practices unrelated to soil fertility.

Because of such potential problems and limitations, visual diagnosis of a deficiency should be confirmed by other methods. Whenever possible, confirmation may be made by collecting plant and soil samples for laboratory analysis. If soil testing laboratories are not available, the research must rely on less quantitative methods for confirming a deficiency. Two such methods are described later in this section.

A general key to plant nutrient deficiency symptoms is outlined below. This key will not replace a good textbook dealing with nutrient deficiency symptoms of a particular crop. Neither chlorine nor molybdenum are included in the key because deficiencies of these micronutrients are relatively uncommon. In addition, a general description of common toxicity symptoms is included to reduce potential confusion of toxicity symptoms with deficiency symptoms.

GENERAL KEY TO PLANT-NUTRIENT DEFICIENCY SYMPTOMS

A. Older or lower leaves of plant mostly affected; effects localized or generalized.

1. Effects mostly generalized over whole plant; more or less drying or firing of lower leaves; plant light or dark green.

a. Plant light green; lower leaves yellow, drying to light brown color; stalks short and slender if element is deficient in later stages of growth....Nitrogen

b. Plant dark green, often developing red and purple colors; lower leaves sometimes yellow, drying to greenish brown or black color; stalks short and slender if element is deficient in later stages of growth....Phosphorus

2. Effects mostly localized; mottling or chlorosis with or without spots of dead tissue on lower leaves; little or no drying up of lower leaves. Lower leaves mottled or chlorotic (yellowed), with or without dead spots; leaf margins sometimes tucked or cupped upward or downward.

a. Mottled or chlorotic leaves typically, may redden, as with cotton; sometimes with dead spots; tips and margins turned or cupped upward; stalks slender....Magnesium

b. Mottled or chlorotic leaves with large or small spots of dead tissue; spots of dead tissue small, usually at tips and between veins, more marked at margins of leaves; stalks slender....Potassium

B. Newer or bud leaves affected; symptoms localized.

1. Terminal bud dies, following appearance of distortions at tips or bases of young leaves.

a. Young leaves of terminal bud at first typically hooked, finally dying back at tips and margins, so that later growth is characterized by a cutout appearance at these points; stalk finally dies at terminal bud....Calcium

b. Young leaves of terminal bud becoming light green at bases, with final breakdown here; in later growth, leaves become twisted; stalk finally dies back at terminal bud....Boron

2. Terminal bud commonly remains alive; wilting or chlorosis of younger of bud leaves with or without spots of dead tissue; veins light or dark green.

a. Young leaves permanently wilted (wither-tip effect) without spotting or marked chlorosis; twig or stalk just below tip and seedhead often unable to stand erect in later stages with shortage is acute....Copper

b. Young leaves not wilted; chlorosis present with or without spots of dead tissue scattered over the leaf.

   i. Spots of dead tissue scattered over the leaf, smallest veins tend to remain green, producing a checkered or reticulated effect....Manganese

   ii. Dead spots not commonly present; chlorosis may or may not involve veins, making them light or dark green in color.

      -- Spots generalized, rapidly enlarging, generally involving areas between veins and eventually involving secondary and even primary veins; in corn commonly broad yellowish to whitish band between mid-rib and leaf edge; leaves thick; stalks with shortened internoted; rosetting....Zinc

      -- Young leaves with veins and tissue between veins, light green in color....Sulfur

      -- Young leaves chlorotic, principal veins, typically green; stalks short and slender....Iron

FIELD TESTS USED TO CONFIRM NUTRIENT DEFICIENCIES

Tissue Testing

Tissue testing has some merit for confirming nutrient deficiencies identified by visual diagnostics. By using specific indicator chemicals, one can qualitatively estimate the amount of an element in plant sap. Results showing a high color intensity usually indicate a high content of the nutrient. Major problems associated with tissue testing are that the indicator test 1) varies from one part of the plant to another and

2) varies in each stage of the life cycle of the plant. Recent environmental conditions such as drought can change the test results by reducing utilization of nutrients by the plant. Detailed instructions are enclosed in the tissue test kit.

Fertilizer Evaluation: Granular

Nutrient deficiencies observed in the field often are confirmed with a series of short-termed fertility trials. Mark off two or three rows approximately 3 meters long or 1 meter square plots in the field. Then add a single element fertilizer into the soil of each plot. After one or two weeks, compare plants in the plots with the rest of the field. Improved growth and disappearance of deficiency symptoms in the fertilized treatment supports the original diagnosis.

Whenever field observations suggest more than one nutrient is deficient, similar plots may be constructed using various combinations of fertilizers to pinpoint each of the deficient nutrients.

Fertilizer Evaluation: Foliar

The application of fertilizer as foliar sprays often is preferable to soil applications because the plant response time may be shorter. In addition, mineral nutrients which are immobile in the plant (Table 1) are easily identified by spraying only a portion of selected plants. Absorption of the nutrient occurs within a few days and contrast between foliage sprayed with the fertilizer and foliage not sprayed is quite visible. However, foliar spray applications require a three- or four-day period without rainfall to be successful and must be applied carefully to avoid toxic symptoms from excessive additions of the nutrient. Approximate solution concentrations are listed below for several elements.

Nutrient solution concentrations for foliar sprays:

N 4% solution of Urea

P 0.3% solution of P

K 0.5% solution of K

Fe 2% solution of FeSO

Zn .5 to 1.5% solution of ZnSO

Mn .2 to 2% solution of MnSO with small amount of lime

Cu 0.5% solution of CuSO with small amount of lime

B 0.1 to 0.3% solution of H BO

GENERAL DESCRIPTION OF COMMON TOXICITY SYMPTOMS

Symptom	Description
1. Soil Salinity	Symptoms and effects vary widely with species. High salinity causes stunted plants commonly characterized by a deep bluish green color which results from an unusually heavy wax coating on the surfaces. The color may be very pronounced for sugar beets, crucifers, alfalfa, beans, clover and grasses. Cereals and milo may show a reddish color as the plants approach maturity. Salt accumulations in the leaves of many fruit trees cause a burning or necrosis (commonly called "tipburn") on the margins. Chloride (Cl^-) or sodium (Na^+) frequently is involved.
2. Chloride Injury	Chloride injury is described for woody and some other plants as an initial burning and necrosis of the leaf tips. As injury intensifies, burning progresses along the margins and may extend with greater severity into the interveinal area of the leaf.
3. Sodium Injury	May appear as a "spot burn" or necrotic interveinal areas midway between leaf margin and midrib. Such damage has been reported for avocado, raspberry, blackberry, grapefruit, and others. Excessive exchangeable sodium, commonly associated with soil salinity, may cause Ca deficiency. The symptoms are described in the general key to nutrient deficiencies.
4. Excessive Boron	Boron toxicity may occur on plants grown in irrigated soils where the irrigation water contains 1 ppm B or more. With many species, excessive B causes a tip or marginal burn or a general chlorosis of the

leaves. As the leaves mature, continued toxicity causes a dying of the leaf from the tip inward. Plants may show slight to medium toxicity symptoms without a depression in growth. With broadleaf plants, there is marginal necrosis and the leaf may be cupped because of restrictions in the growth of the margins.

5. Excessive Fertilizer

Excessive amounts of highly water soluble fertilizer used over time can cause salinity damage similar to that reported for saline soils. When fertilizer is placed too near the seed, damage or death may occur in the seedling stage. Where excessive fertilizer has been applied to a normally growing plant, the damage appears first as a wilting of leaf margins or the entire leaf, depending on the fertilizer rate. In a few days, the leaves dehydrate and dry with a marginal necrosis. With very high fertilizer rates, the plant may die.

6. Aluminum Toxicity

Plant growth is stunted in strongly acid soils. The principle cause of poor growth is Al toxicity with Mn toxicity and Fe toxicity occurring in some soils. With Al toxicity, the seedlings are very slow to develop and the leaves are a gray-green to reddish-purple characteristic of phosphate deficiency. The leaves are stubby and die back. Sensitive plants may fail to grow beyond the seedling stage. Root growth is severely restricted.

7. Manganese Toxicity

In cereals, Mn toxicity causes leaf tips to die and interveinal necrotic spots called "leaf freckle". With brassica, there is necrosis or scorching or chlorotic mottling of leaf margins; there may be interveinal chlorosis and

necrotic spotting; the leaves may curve or cup upward. With clover and alfalfa, Mn toxicity causes marginal spotty chlorosis and necrosis that proceeds inward as the toxicity increases; leaf margins are distorted and the leaf is cupped downward. Mn toxicity may resemble mild Fe deficiency.

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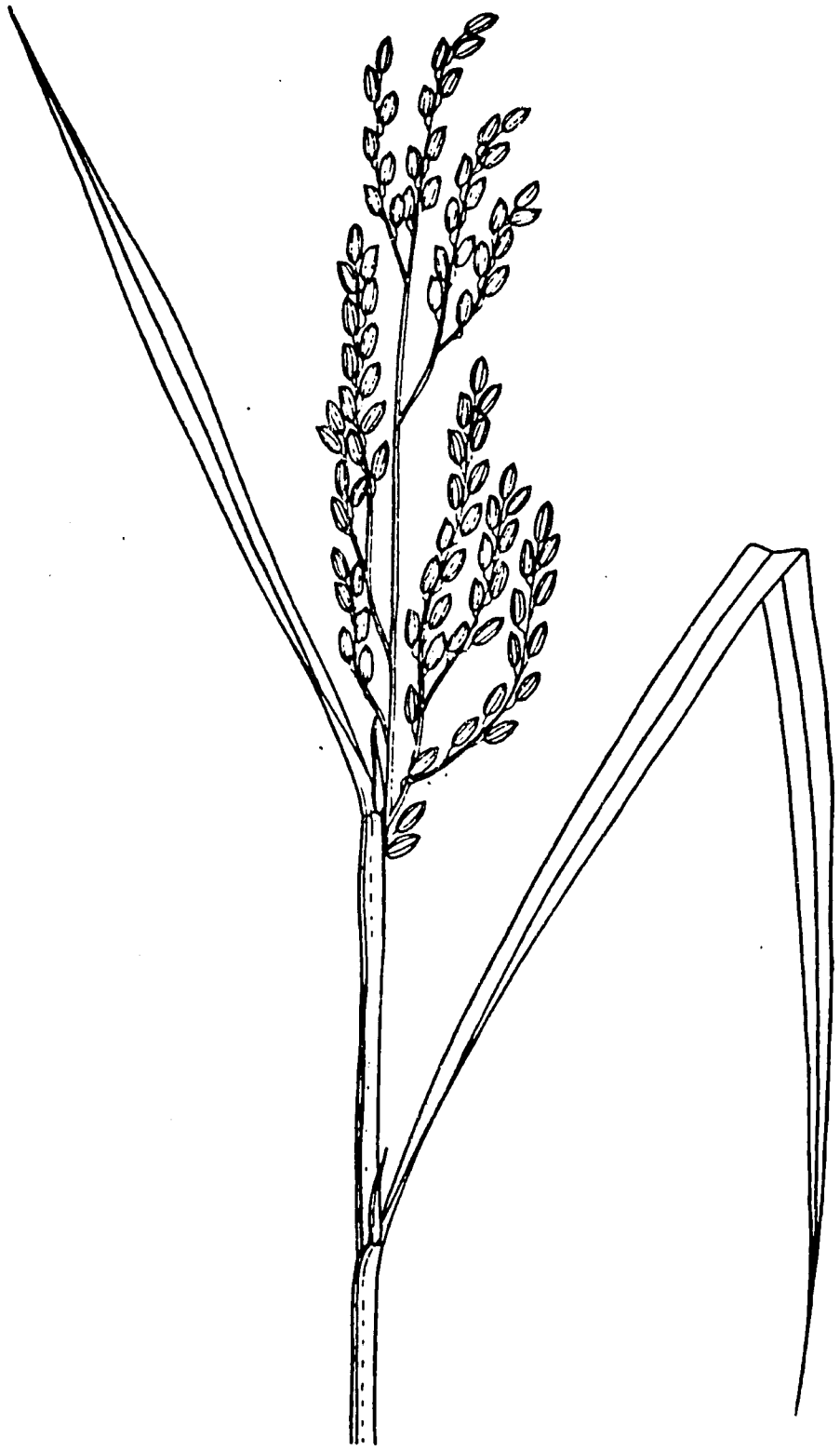
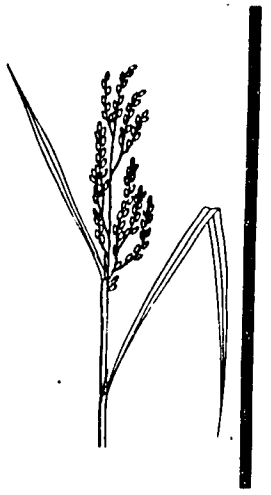
ENGINEERING





TOPOGRAPHIC MAPPING USING GRID METHOD AND LEVEL*

by W. Clyma and A. Early

Experience reveals a shortage of maps needed to provide essential background for farm planning and engineering design (scale 1:5000 or less). A map that shows horizontal distances, horizontai angles, and elevations is called a topographic map. The addition of elevation to a map results in the map showing topography (relief of the land surface). A contour map is the simplest way to show elevation on an otherwise two-dimensional sheet of paper. A contour is an imaginary line of constant elevation on the surface of the earth. The shoreline of a lake is a contour of constant elevation seen frequently in nature as the waterline. A contour line is linear connecting points on a map which represents points on the surface of the ground having the same elevation. The elevation of the contour line usually is indicated by numbers on the line.

The following characteristics of contour lines are useful guides in drawing and interpreting maps:

1. Evenly spaced contours show a uniform slope.

2. The distance between contours indicates the steepness of the slope. Wide spacing denotes flat slopes; close spacing, steep slopes.

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* Modified from an article in The Problem Identification Handbook. (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100. Fort Collins, CO.

3. Contours that increase in elevation represent hills. Those that decrease in elevation represent valleys. Contour elevations are shown at breaks in the contour to avoid confusion.

4. Irregular contours signify rough, rugged country.

5. Contour lines tend to parallel each other on uniform slopes.

6. Contours never meet except on a vertical surface such as a wall or cliff. They cannot cross except in the unusual case of an overhanging shelf. Knife-edge conditions seldom are found in natural formations.

7. Valleys usually are characterized by V-shaped contours, ridges by U-shaped contours.

8. The V's formed by contours crossing a stream point upstream.

9. The U's made by contours crossing a ridge line, point down the ridge.

10. All contour lines must close upon themselves either within or without the borders of the map.

METHODS OF MAPPING

There are three methods of making topographic maps for agricultural engineering surveying: grid method, angle and stadia method, and plane table and alidade method (telescope alidade with stadia hairs). The particular method used depends upon several factors:

1. Ability of the personnel,

2. Equipment available,

3. Personnel available,

4. Topography of the land to be mapped, and

5. Size of the area to be mapped.

Another method of mapping, which has agricultural application, is aerial photography. The aerial photography furnishes topographic details unavailable in other methods of mapping. By using stereoscopes, contours can be added to the aerial photograph with a minimum of field surveying for horizontal and vertical control. Aerial photographs may or may not be available in all areas.

THE GRID METHOD

The grid method of topographic mapping has several advantages. It can be done with a farm level and a steel tape, both of which are readily available. The grid method lends itself to topographic mapping of individual fields and farms where the ground surface is relatively flat. The effort spent in the field doing the survey is about equal to the effort spent in the office preparing the map. Because the running of contour lines across very flat ground is difficult, taking elevations at regularly spaced intervals should result in a better topographic map. The grid method is the most widely used method of surveying for land leveling because the relocation of each point is simple. The relocation of each point is essential in checking elevations as leveling progresses.

Procedure for the Grid Method of Mapping

Where possible, the area to be mapped should have two sides that intersect at right angles (90°) with each other. If that is not the case, the diagonals and all four sides of the field need to be measured, or if the fields are irregular in shape, a plane table survey of field boundaries is necessary before location of the grid points is possible. Two sides of the field then can be staked at regular intervals for the grid and the surveying can be done in the same manner as for two sides that intersect at 90 degrees. After a preliminary survey of the area to be mapped, two sides are selected to establish the grid. Each side is staked with tall stakes at regular intervals. The length of the interval depends on the use of the map. General topographic maps frequently are staked at 25 or 30 meter intervals. Maps for land leveling design and computations usually are staked at 10 to 15 meter intervals.

One side of the area then is numbered at each stake location from zero to the end of the stakes. The other side is lettered at each stake location from A to the end of the stakes. The stakes used at each grid point should be a minimum of 1 meter high; 2 meters is preferred.

After the two sides are staked, two additional sides are staked. The stakes start at one and continue to the end of the lettered points. The other row starts at B and continues to the end of the numbered stakes. The rodman then can

locate himself at any grid point by sighting along the four stakes that form the two lines that intersect at his particular grid point.

After the four rows of stakes are established at the grid points, the elevation of each grid point is established by profile leveling. Each grid point is designated by the appropriate letter and number. The survey is closed by returning to the bench mark after the elevation of each grid point is determined. It is important that the arrangement of the grid be shown in the notes on the right side of the page to assure the map is properly oriented when prepared in the office.

For watercourse survey purposes, staking is not necessary. General watercourse surveys require the use of a one-acre grid. The approximate location of the center of an acre can be obtained visually by pacing, but without taping or staking the location. A portable turning point is used at this location to give a representative elevation for the acre. Surveying begins and ends at a bench mark determined in the initial bench mark survey of the watercourse area.

A more intensive data collection scheme is required for the detailed survey of sample farmers' fields. Four elevation determinations per irrigation unit are required for this purpose. Each acre might have 2 to 10 of the smallest irrigation units. The intensity thus increases to 8 to 40 shots on a per acre basis, depending on the number of units per acre.

MAP PREPARATION

The topographic map is prepared from field notes. A map and the field notes from which they were prepared (Figure 1 and 2) immediately follow this article. For relatively flat areas, a contour interval of 0.25 meters is used. For a more rolling topography, 0.50 meter or 1.00 meter intervals can be used.

For watercourse mapping, a contour interval of 0.25 feet is required for general use. For land leveling design, a grid spacing of 50 feet is desirable on small leveling jobs and 100 feet is acceptable on large-scale leveling jobs. The required precision of leveling is $\pm$ 0.05 feet (0.10 maximum difference across the irrigated unit). Thus, if topographic maps are to be used for land leveling design work, the contour interval should be a maximum of 0.5 feet, with 0.25 feet the preferred interval.

Note that certain information is included on the topographic map. A title, location of the mapped area, survey personnel, date of the survey, scale, person preparing the map, date of map preparation, legend, north arrow, and important

natural and man-made topographic features always should be included on the map.

Maps frequently are prepared with one contour more heavily accentuated than the others. In Figure 2, the even meter contours, 99.00, 100.00, and 101.00 are more heavily accentuated to provide better contrast between the general relief and the detailed topography of the area.

The contours are entered on the map by placing a triangular scale or ruler between grid points of known elevation. The point of even numbered contour is proportioned between the two points, a procedure which assumes a uniform topography or slope in the vicinity.

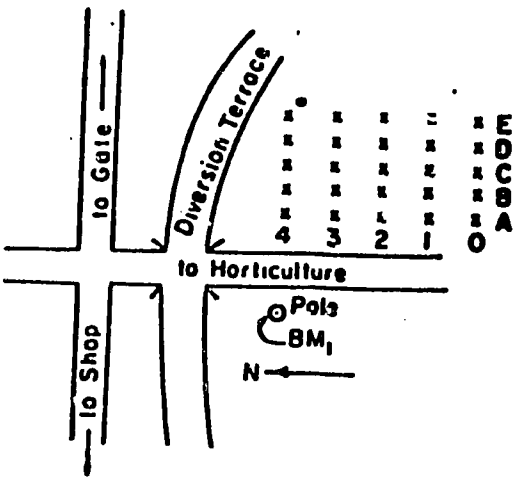
Topographic Leveling

No.	BS	HI	FS	Elev.
BM_1	1.20	101.20		100.00
A_0			2.21	98.99
A_1			2.47	98.73
A_2			2.11	99.09
A_3			1.38	99.82
B_3			1.44	99.76
B_2			1.86	99.34
B_1			2.08	99.14
B_0			2.21	98.99
C_0			2.09	99.11
C_1			2.00	99.20
C_2			1.65	99.55
C_3			1.25	99.95
C_4			0.53	100.67
D_4			0.53	100.67
D_3			1.06	100.14
D_2			1.27	99.93
D_1			1.77	99.43
D_0			1.85	99.35
E_0			1.44	99.76
E_1			1.04	100.16
E_2			0.90	100.30
E_3			0.60	100.60
E_4			0.26	100.94
TP_1	2.51	102.42	1.29	99.91
B_4			1.14	101.28
A_4			0.70	101.72
BM_1			2.44	99.98
	BS = 3.71		FS = 3.73	100.00

Error of closure = FS - BS
= 3.73 - 3.71
= 0.02 0.02 Check

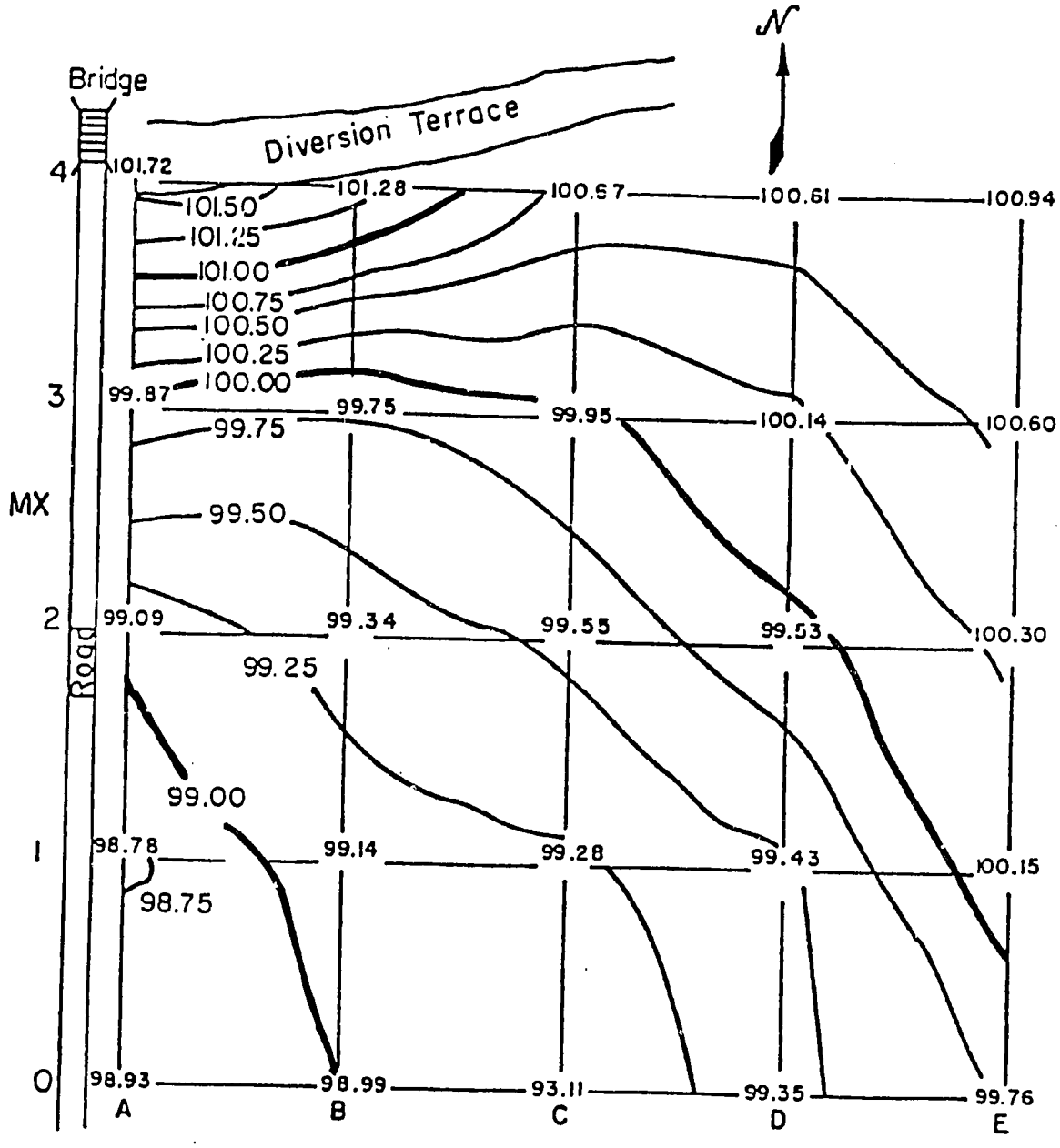
Cloudy, windy Tewolde W.
Aug. 19, 1965 Hailu S.

BM_1 — A point *x*, marked on the pole stand on the pole next to the bridge on the road to the horticulture area -- about 4 meters from the road and 52 meters from the southwest end of the bridge.



•x Denotes Grid Station

Figure 1. Field Notes for Topographic Map Using Grid Method of Mapping



TOPOGRAPHIC MAP

College Farm
Surveyed by Tewolde W. and Hailu S.
Date: August 19, 1965
Scale: 1:750
Plotted: by Hailu S.
Date: August 23, 1965

Figure 2. Topographic Map Based on Field Notes Contained in Table 1

DIFFERENTIAL LEVELING FOR BENCH MARK SURVEY OF THE WATERCOURSE*

by W. Clyma and A. Early

Differential leveling is the process of finding the differences in elevation of any two points. It usually requires several setups of the instrument along a general line between the two points. Each setup requires a rod reading on a point of unknown elevation. A bench mark survey is conducted to provide a widely spaced series of points (e.g., headgates, culverts, bridges) of known elevation from which a topographic survey is conducted at a later date.

THEORY OF LEVELING

Leveling is the process of determing the relative elevation of points some distance apart. Figure 1 illustrates the basic procedure.

A level is set up at a location approximately between a bench mark (BM) and a turning point (TP). A bench mark is relatively permanent, natural or artificial object bearing a marked point whose elevation is known or assumed. A

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* Modified from an article in The Problem Identification Handbook. (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100. Fort Collins, Colorado.

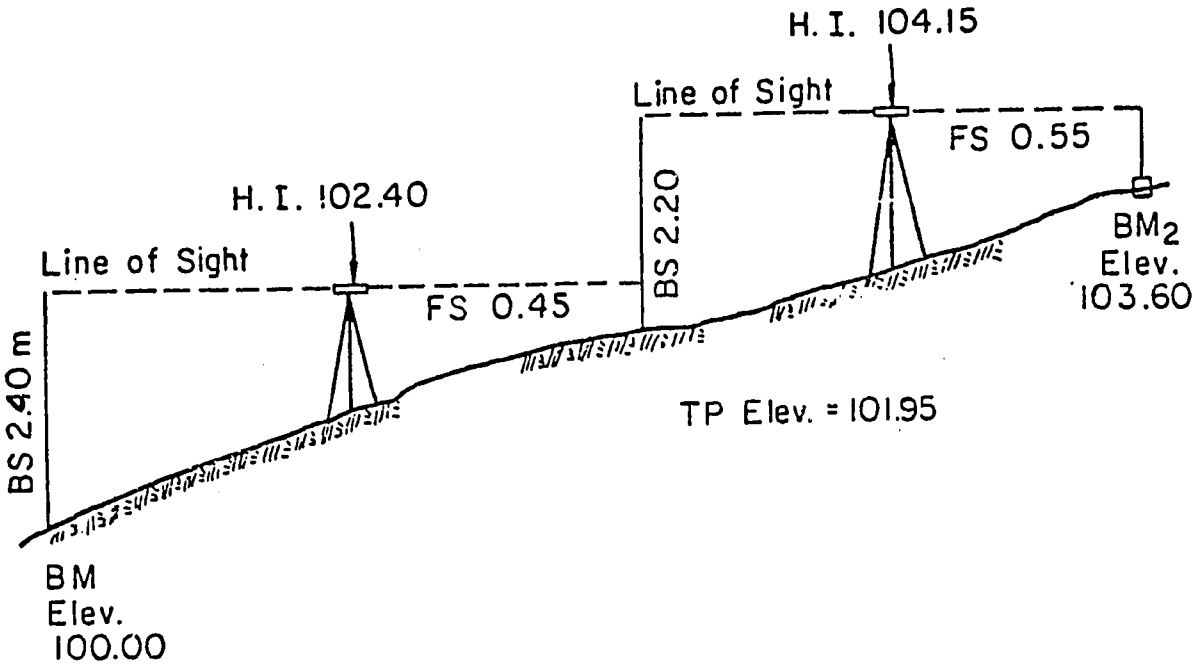


Figure 1. Theory of Differential Leveling

turning point is a temporary bench mark for the purpose of continuing a line of levels. Portable turning points are provided for field watercourse surveys.

For example, referring to Figure 1, if the elevation of the bench mark (BM1) is assumed to have an elevation of 100.000 meters, the elevation of the turning point (TP1) can be determined by leveling. First, the instrument is set up approximately half-way between BM1 and TP1 and is leveled. A rod reading is taken on BM1 of 2.40. This rod reading is termed a backsight (BS). A backsight is a rod reading taken on a bench mark or turning point of known elevation: it is the vertical distance between the BM and the line of sight of the instrument. The line of sight of the instrument is higher than the bench mark or the turning point. Therefore, the backsight is positive and could be described as a plus sight.

The height of instrument (HI) is the elevation of the line of sight when the instrument is level and corresponds to the line of sight of the instrument. The height of instrument is obtained by adding the backsight to the elevation of the BM1, 100.00, to obtain the HI, 102.40. By turning the telescope to bring into view the rod held on TP1 a rod reading called a foresight (FS) is obtained. A foresight is a rod reading taken on a turning point of any other point of unknown elevation for which the elevation is to be determined. The foresight is subtracted from the height of instrument and could be described as a minus sight. In the example of Figure 1, the FS, 0.45, is subtracted from the HI, 102.40, to obtain the elevation of TP, 101.95. Therefore, by a process known as leveling, we have determined the difference in elevation of two points. This method may now be used to check the elevations shown in Figure 1, and to determine the elevation of TP2.

Leveling Equations

From the above definitions, we can derive two equations that are beneficial in leveling. The equations are repeated many times during a leveling exercise, so a person who is learning to use the level should become thoroughly familiar with them. They are:

$$\text{Elev.} + \text{BS} = \text{HI}$$

$$\text{HI} + \text{FS} = \text{Elev.}$$

PROCEDURE FOR DIFFERENTIAL LEVELING

Several procedures and precautions should be observed for accurate differential leveling. Refer to Figures 2 and 3 for sample rod readings and a sample set of notes from a differential leveling exercise.

To begin a differential survey, the rodman holds a rod on BM1 while the levelman goes forward a convenient distance (not over 100 meters for a Bostrom-Brady farm level) and sets up the level. The levelman takes a reading on the rod and determines where the middle cross hair strikes the rod, in Figure 2 this is at 0.34. This is a backsight and the notekeeper records 0.34 in the BS column of the notes. Now the HI is determined by adding the BS to the elevation of the BM, (100.00 + 0.34 = 100.34), and is entered in the notes in the HI column. For the convenience of one who is learning the procedure, a plus sign can be placed above the BS column and a minus sign above the FS column to indicate how that column is used in note computations.

After the BS has been obtained, the rodman steps the distance from the BM to the instrument and then steps the same distance away from the instrument in the direction of BM2. Pacing is one of the acceptable methods of balancing the horizontal distances between the backsight and the foresight. The distance also can be measured by stadia, but the accuracy obtained by taping is not considered necessary. The effects of refraction, curvature of the earth, and lack of instrument adjustment are thereby eliminated. On slopes, a zigzag path may be taken to utilize the longer rod length available on the downhill sights.

CLOSED SURVEYS

To verify the accuracy of the leveling, a return check must always be made. That is, the line of levels must be continued from BM2 back over a slightly different route to BM1, the initial starting point. To make the return check independent of the first line of levels, after the FS is taken on BM2, lift the level slightly and relevel it so that the HI will be at a slightly different elevation. This results in a BS on BM2 different from the FS and should result in a better check of the line of levels. When the survey party has returned to BM1, a closed survey has been completed. All leveling exercises should be closed surveys so a check of the accuracy of the survey can be made. Figure 4 gives a sample traverse for a bench mark survey of a watercourse. Note that all available permanent structures are used as bench marks. These bench marks must be marked with both a waterproof maker and with a nail or screwdriver scratch for permanence. Figure 5 provides the sample survey notes for the traverse of Figure 4. Note the double tabling of points which are both turning points (TP) and bench marks (BM). Portable turning points are labeled PTP.

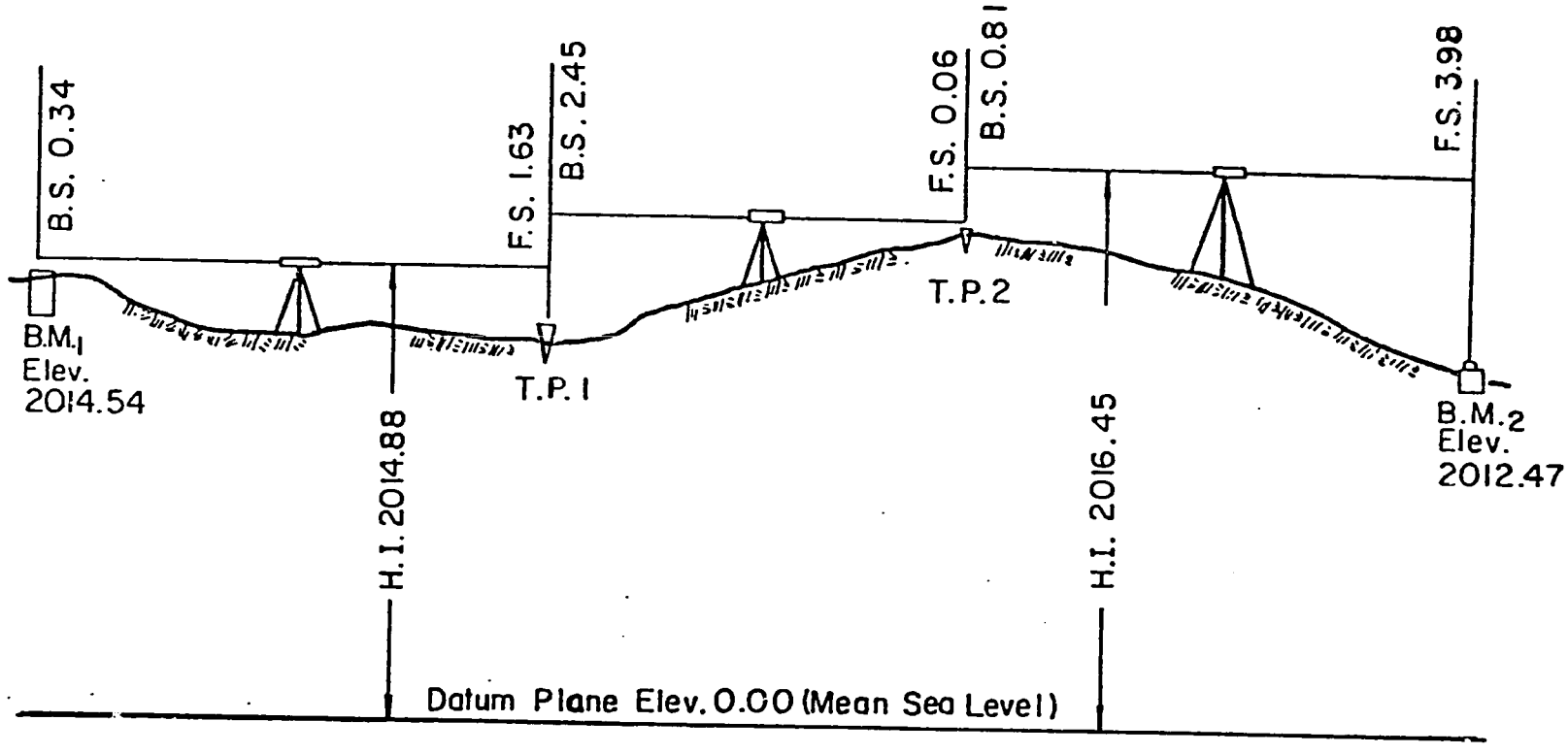


Figure 2. Illustration of Procedures for Taking Backsights and Foresights of Differential Leveling

Differential Leveling for Benchmarks

Sta.	BS	HI	FS	Elev.
BM_1	0.34	100.34		100.00
TP_1	2.45	101.16	1.63	98.71
TP_2	0.81	101.91	0.06	101.10
BM_2	3.98	101.91	3.98	97.93
TP_3	0.00	101.19	0.81	101.10
TP_4	1.98	100.71	2.46	98.73
BM_1			0.69	100.02
	BS = 9.65		FS = 9.63	

Error of closure = 9.65 - 9.63 = 0.02 check

Sunny, calm

Haily S. & N.
Tewolde W.
Aug. 18, 1965

BM_1: the southern bolt on the pole nearest to the irrigation lab -- about 5 m from eastern side door.

BM_2: Steel rod on the northeast corner of the cattleguard into the livestock area across from poultry.

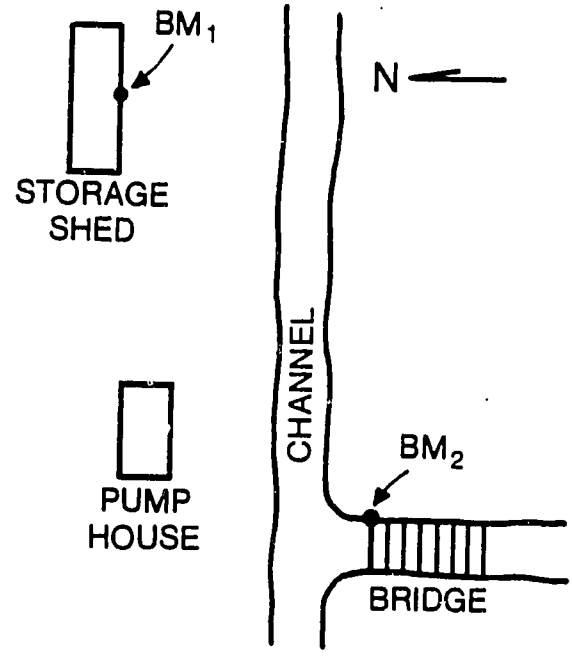
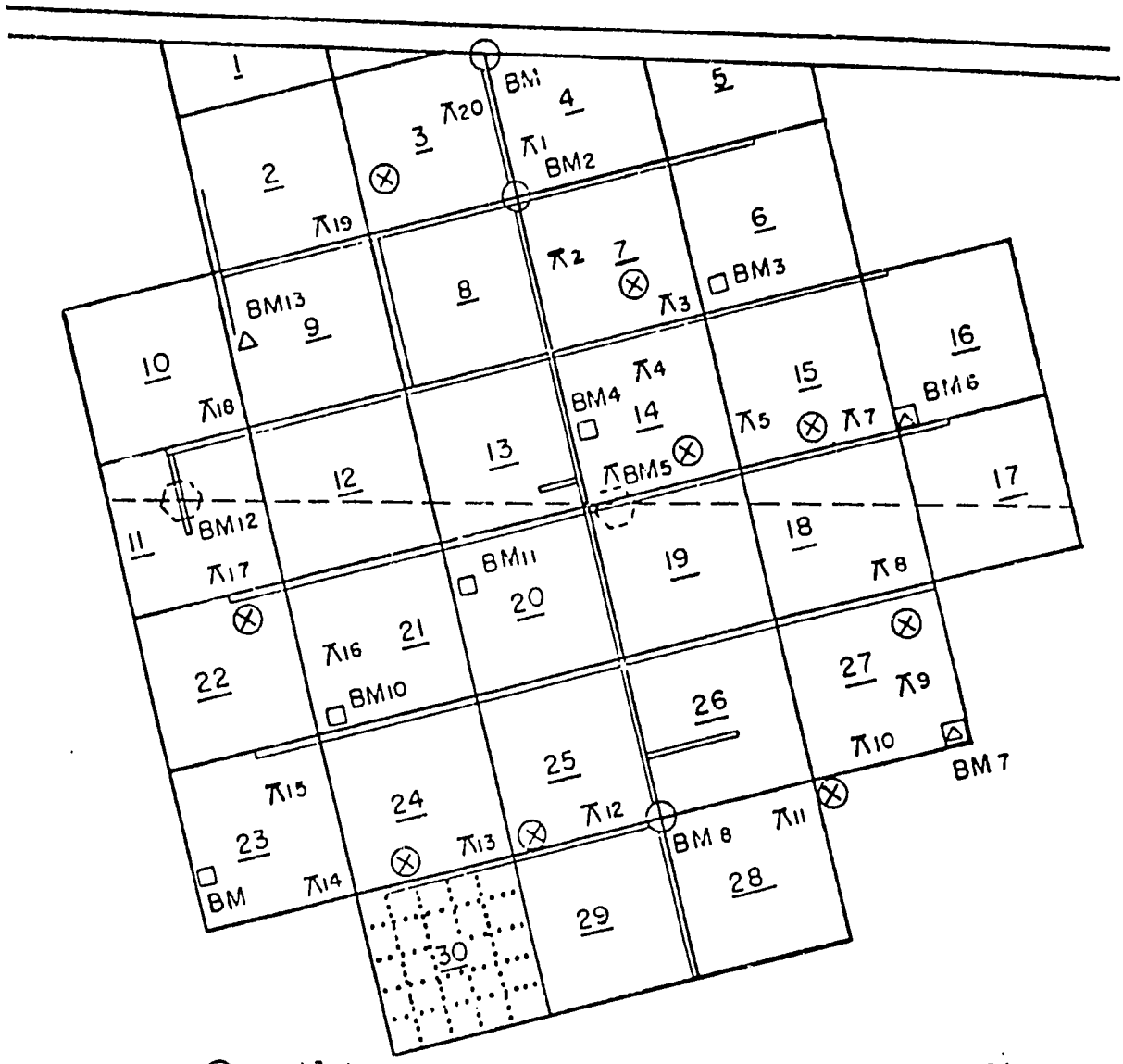


Figure 3. Example of Differential Leveling Notes



- ○ outlet
- culvert
- concrete field outlet
- square stone
- △ water-lifting device
- □ concrete base of power line
- ⊗ portable turning point
- π instrument setup point
- ····· acre line
- ——— square line
- – – – paved road
- ═══ watercourse

Figure 4. Sample Traverse for Bench Mark Survey of a Watercourse

Watercourse Benchmark Survey by Differential Leveling Area Commanded by an Outlet 110/JB, Lyallpur

Sunny, Hot, Calm

Wanyam
Zahid
Aug. 18, 1975

Sta.					
	BM_1	3.02	103.02		100.00
TP_1	BM_2	4.22	103.17	4.07	98.95
TP_2	TP_2	3.89	102.05	5.01	98.16
TP_3	BM_3	6.87	104.85	4.07	97.98
TP_4	BM_4	4.48	102.44	6.89	97.96
TP_5	BM_5	4.32	101.75	5.01	97.43
TP_6	TP_6	5.10	101.60	5.25	96.50
TP_7	TP_7	4.88	101.50	4.98	96.62
TP_8	BM_6	3.37	99.61	5.26	96.24
TP_9	TP_9	3.85	99.28	4.18	95.43
TP_{10}	BM_7	4.71	99.98	4.01	95.27
TP_{11}	TP_{11}	4.85	99.56	5.27	94.71
TP_{12}	BM_8	5.17	99.44	5.29	94.27
TP_{13}	TP_{13}	4.37	98.81	5.00	94.44
TP_{14}	TP_{14}	3.99	98.28	4.52	94.29
TP_{15}	BM_9	4.00	98.37	3.91	94.37
TP_{16}	BM_{10}	6.02	100.77	3.62	94.75
	BM_{11}			/5.91/	94.86
TP_{17}	TP_{17}	6.27	101.77	5.27	95.50
TP_{18}	BM_{12}	5.33	102.82	4.28	97.49
TP_{19}	BM_{13}	4.81	103.74	3.89	98.93
TP_{20}	TP_{20}	4.68	104.72	4.51	100.11

BS = 98.20 FS = 98.09 0.11 = Elev. Diff.

Error of Closure = 98.20 - 98.09 = 0.11

Outlet Scratch Mark — Upstream Side
Concrete Corner of Squares 3, 4, 7 and 8
Sq. 6: CBPL — Scratch
Sq. 14: CBPL — Scratch
Sq. 13, 14: Concrete Culvert — Upstream
Sq. 15, 16, 17, 18: Square Stone — Scratch
Sq. 25, 26, 28, 29: Square Stone — Scratch
Concrete Corner of Squares 25, 26, 28, 29
Sq. 23: CBPL — Scratch
Sq. 21: CBPL — Scratch
Sq. 20: CBPL — Scratch
Sq. 11: Concrete Culvert: Scratch — Downstream
Sq. 9: Steel Frame on Water-Lifting Device Base — Scratch

Outlet

Figure 5. Watercourse Benchmark Survey Notes by Differential Leveling

ERROR OF CLOSURE

If no errors are made in a closed survey or if the errors have compensated, the elevation determined for BM1 by the return check will be the same as the original elevation of BM1. Generally, these elevations are not exactly the same due to errors in rod readings or instrumental errors. The amount by which the original BM elevation and the BM elevation observed upon the return check fail to agree is called the error of closure.

Allowable errors of closure for a survey are a function of the accuracy of the instrument and the length of the survey or the number of times the instrument is set up. For a Bostrom-Brady level, the allowable error of closure equals 0.01 meters per two instrument setups (0.01/2 setups). For the notes shown in Figure 3, there were four instrument setups so the allowable error of closure was 0.02, the actual error for the survey. For general leveling purposes with available equipment, the allowable error in English units (feet) is given by:

$$\text{Allowable error} = 0.007 \sqrt{\frac{\text{length of traverse in feet}}{100}}$$

If the sample traverse for Figure 4 were 20,000 feet, then the allowable error is 0.0989 or 0.10 feet. Bench mark surveys that do not meet this standard must be resurveyed completely until the error of closure is less than the allowable error. The survey notes provided in Figure 5 does not meet the standard and must be repeated.

CHECKING THE LEVEL NOTES

The computations of the level notes always should be checked by comparing the difference between the sum of the backsights and the sum of the foresights with the differences between the initial and final elevation of the bench mark. This computation checks the notes for errors in arithmetic. The two differences must agree or an error in arithmetic has been made. No set of leveling notes is complete without an error of closure computation and check of the arithmetical accuracy of the notes before leaving the field.

USE OF THE BENCH MARK SURVEY

The bench mark survey, when completed to the required standard of accuracy becomes a basic reference for subsequent field surveys. The permanent bench marks then can become starting points for any portion of the profile leveling survey of the watercourse and of the topographic survey of the watercourse. This set of bench marks is then a set of known elevations which facilitate the completion of these other surveys.

PORTABLE TURNING POINTS

While profile leveling, bench marking or topographic surveying, the need for intermediate turning points arises frequently. The placement of the staff rod on the ground or on the bed of the watercourse can lead to errors of major magnitude if changes in rod elevation occur when the rod is rotated in contact with the soil. To avoid that problem, portable, stable turning points are provided for field use. Figure 6 shows this simple surveying item which is nothing more than a 4-inch square piece of #14 or #16 sheet metal with one-inch corners bent down at 90 degrees from the face to form four legs. A rivet in the center holds a chain handle to the bottom side. The rod is rotated on the rivet after the turning point is forced into the ground.

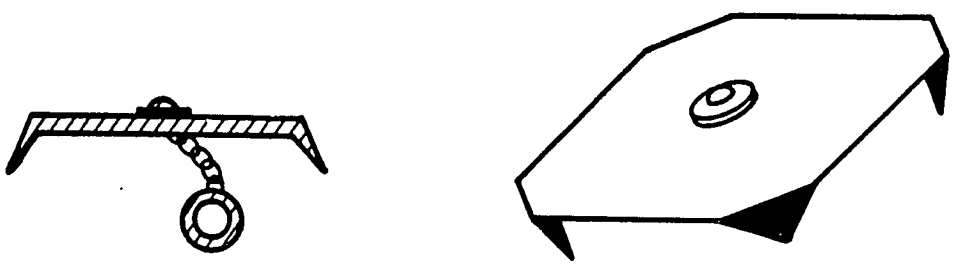


Figure 6. Portable Turning Point for Field Use

PROFILE LEVELING OF MAIN AND LATERAL CONVEYANCE CHANNELS*

by W. Clyma and A. Early

Profile leveling is the process of determining the elevation of the ground surface at a series of points at measured intervals along a drainage ditch, terrace, waterway, road, or any other ground surface where it is necessary to consider changes in elevation.

TAPING PROFILES

It is necessary to tape or otherwise measure the horizontal distances for a profile. Vertical distances along the profile have no meaning without the corresponding horizontal distances between changes in elevation.

Stakes or chaining pins usually are set along the fixed line for a profile survey. These stakes or chaining pins usually are set before the survey is made. Stakes are placed at fixed distances along a survey, i.e., 25 feet, 50 feet, or 100 feet, depending upon the detail required for the survey. In addition, stakes are set at points where the line changes direction and at every full station. For the profile survey of the watercourse main and the major branches, chaining pins should be used to mark the stations at 25 feet distance intervals.

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* Modified from an article in The Problem Identification Handbook. (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100.

A full station is 0 + 00, 1 + 00, 2 + 00, and so forth. Stakes set at any other point between the full stations are called plus stations and are designated, for example, 1 + 25. Note that 0 + 00 designates the beginning of the line. Distances along the line indicate the full stations and the plus stations. For instance, 150 feet is written as 1 + 50 feet. Thus, the digits to the left of the + designate the distance in multiples of 100', while those to the right indicate less than 100'. The station number is marked usually upon that side of the stake facing 0 + 00. Stakes are arranged, when possible, so the wide part of the 2 inch x 5 inch stake points to the next station on the line.

A stake is driven at each station located on the profile. Each station is entered in the field notes. Pins are no longer necessary to count tape lengths because the length of the line is recorded in the notes. For other than 100 feet tapes, two pins may be used to measure full tape lengths. When other than a full tape length is measured, the rear chainman holds the partial tape length at the appropriate point. The stake is located for that station. The notekeeper adds the partial tape length to his last station and records the new station. Because the head chainman has the zero end of the tape, the intermediate distances are read directly on the tape without subtraction.

Intermediate Sights

The purpose of the profile survey is to determine the true slope of the ground surface or watercourse bed surface. This means that where there is an obvious change in the slope of the ground or bed surface, a stake is placed and an intermediate sight (foresight or minus sight) is taken so the elevation of the ground surface at that point can be determined. The foresights for a profile are called intermediate sights because they are foresights intermediate or between the foresights taken on turning point (TP) for a continuing line of levels. The student beginning to take profiles has a tendency to make more intermediate rod readings than necessary. The guide to remember (so none is left out) is to take an intermediate shot wherever the ground surface changes slope. If in doubt, take the rod reading. It is simpler to have an extra rod reading than to leave out a necessary reading.

PROCEDURE FOR PROFILE LEVELING

Establish the centerline of the watercourse, terrace outlet channel, or road to be profiled. Measure the line accurately, setting stakes at all points where rod readings are to be taken. Set up the level near the line to be profiled. It is normal to offset the instrument from the line so as more nearly equal horizontal distances from the instrument to the rod can be obtained. A rod reading is obtained on the bench

mark (BM) and the height of instrument (HI) is determined. Frequently, the bench mark is located so more than one instrument setup is required before the rod can be read at the stakes located on the profile line. When this is necessary, the turning points are selected and the notes are as for a differential survey. Rod readings are observed on the ground or bed with the portable turning point adjacent to the stake of chaining pin for the intermediate shots. For turning points, all rod readings are taken on top of a stake, if the stake is used, or on the portable turning point, if chaining pins are used. When placing the rod adjacent to a stake for an intermediate shot, always try to select average ground. That is, the rod should not be placed in a hole on the top of a hill or on a clod. The location should represent the average of the ground surface immediately around the stake.

For an example of a ground surface profile and corresponding rod reading, see Table 1 and Figure 1 immediately following this article. After the instrument is leveled, a rod reading is obtained on the bench mark and the height of instrument computed. In the example, a backsight (BS) of 1.02 gives a height of instrument of 101.02, a rod reading then is obtained near 0 + 00 for the first shot, 0 + 38.03 for the second shot, and so forth, until station 0 + 72.56 has been read. A turning point then is necessary; being selected, a foresight of 1.60 is obtained on the top of the stake. The instrument is carried to a new position along the line, releveled, a backsight of 0.98 obtained on the turning point, and a new height of instrument computed. Now we are ready to take additional intermediate shots along the profile line. The process is continued until the profile is complete. A sample of a complete set of profile leveling notes is shown in Figure 2.

CLOSED SURVEYS

In profile leveling, as in differential leveling, a closed circuit of levels must be made to check the accuracy of the survey. This is done, as in differential leveling, by running a line of differential levels back to the bench mark from which the survey began.

ERROR OF CLOSURE

The method of checking the note computations and computing the error of closure is shown in Figure 2. Note that for a profile survey, the foresight (FS) and the backsights (BS) used for computing the error of closure are only those taken on the bench marks (BM) and turning points (TP). The intermediate rod readings are not used in the computation for error of closure. The only method of checking the intermediate rod readings is to rerun the entire profile.

PLOTTING PROFILES

Profiles usually are plotted on paper; the result is called a cross section (Figure 3). Special profile paper can be obtained to simplify plotting, but any ruled paper may be used. Because vertical distances in elevation usually are much less than horizontal distance covered by the profile, the vertical scale of a profile generally is exaggerated with respect to the horizontal scale to make differences in elevation more pronounced. The exaggeration usually is on a ratio of 10/1. That is, for a horizontal scale of 1:500, (i.e., 1 foot equals 500 feet) the vertical scale would be 1:50 (1 foot equals 50 feet). Because the points plotted on the paper from the profile represent "average ground", it is normal practice to draw smooth lines (not straight lines) from point to point.

The plotted profile is used for many purposes, such as: determination of depth of cut for a drainage or irrigation watercourse; determination of fill for a farm pond; and/or selection of grades for a drainage ditch, irrigation watercourse, or culvert.

Table 1. Notes For Profile Shown in Figure 1 (Left Side)

Profile Leveling

Sta.	BS	HI	FS	Elev.
BM_1	1.02	101.02		100.00
0+00			1.21	99.81
0+38.03			1.47	99.55
0+50.14			2.11	98.91
0+72.56			1.50	99.44
TP_1	0.98	109.40	1.69	99.31
1+80			1.09	99.31
1+42.43			1.21	99.19
1+89.75			2.12	98.28

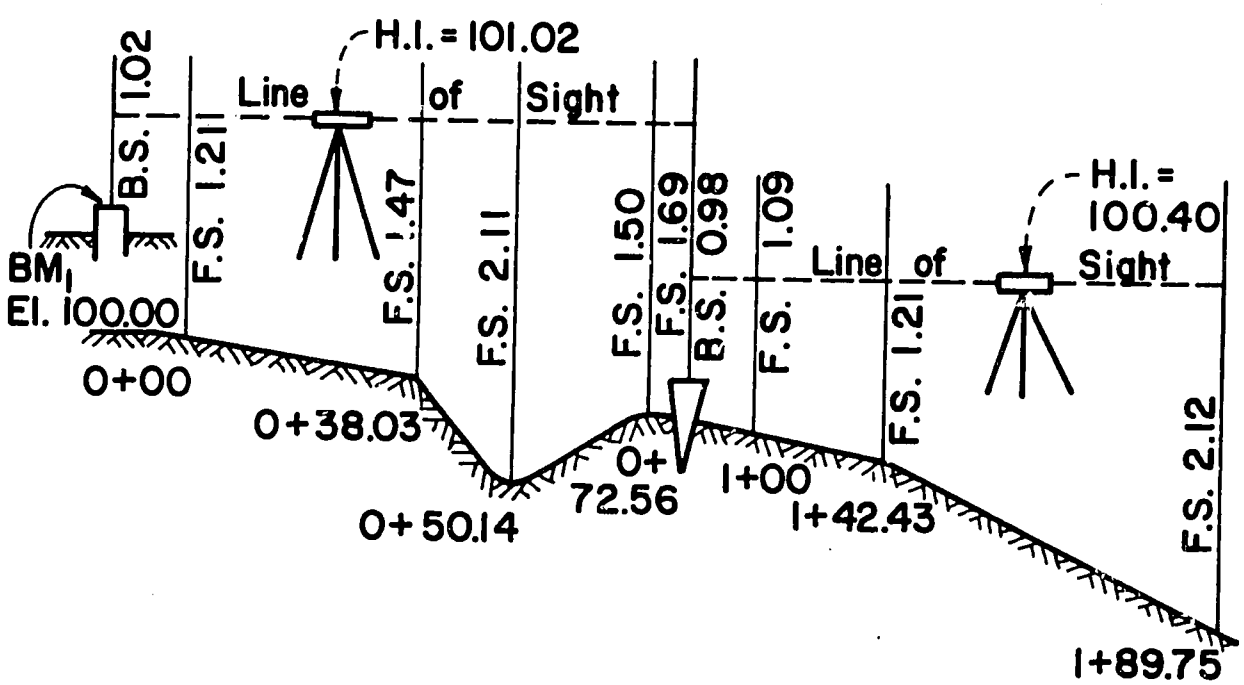


Figure 1. Rod Reading for Profile Leveling

Profile for Ag. Engr. Culvert

No.	BS	HI	FS	Elev.
BM_1	1.62	101.62		100.00
0+00			0.51	101.11
0+4.12			0.86	100.76
0+8.75			1.14	100.48
0+12.50			1.39	100.23
0+15.96			0.92	100.70
0+20.58			1.65	99.97
0+27.85			1.98	99.64
0+30.00			2.16	99.46
0+36.90			2.39	99.23
0+39.42			2.25	99.37
0+42.30			2.76	98.86
TP_1	0.23	99.70	2.15	99.47
0+48.4			1.26	98.44
0+58.56			1.91	97.79
0+60.00			1.95	97.75
0+65.83			1.93	97.77
0+69.90			3.05	96.65
0+72.18			3.44	96.26
0+72.65			3.60	96.10
0+73.19			3.48	96.22
0+76.49			3.30	96.40
0+81.55			3.50	96.20
TP_2	0.54	96.93	3.31	96.39
0+83.15		96.93	1.27	95.66
0+85.30			1.49	95.44
0+88.10			1.56	95.37
0+90.00			1.83	95.10
0+93.40			1.90	95.03
0+97.31			2.21	94.72
TP_3	3.32	99.70	0.55	96.38
TP_4	1.72	100.93	0.49	99.21
BM_1			0.92	100.01
	$\Sigma BS = 7.43$		$\Sigma FS = 7.42$	100.00

Error of closure = $\Sigma BS - \Sigma FS$
= 7.43 - 7.42
= 0.01 — 0.01 check

Tewolde W. R&N
Mehary T.

Cloudy, shower
Oct. 7, 1965

BM: an x mark on the retention wall at the north side of the Agri. Engr. building, about 2.60 m above the first step, under a lamp post.

Figure 2. Complete Set of Profile Leveling Notes

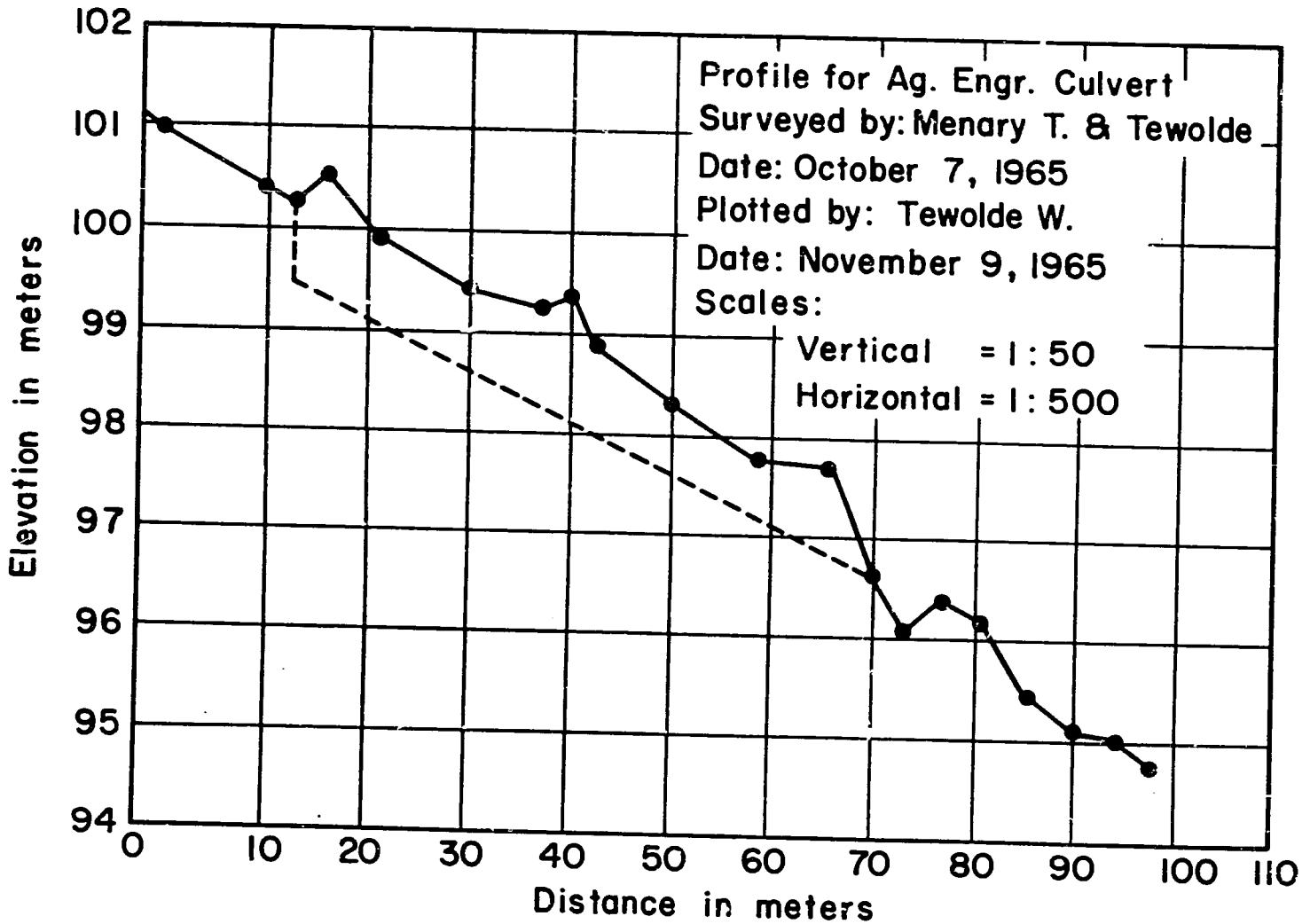
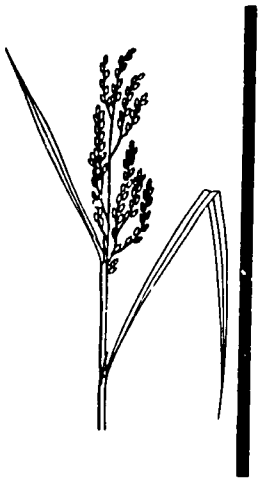


Figure 3. Cross Section Plot for a Profile Leveling Exercise



FIELD AND WATERCOURSE ORIENTATION MAPPING USING PLANE TABLE AND PEEP-SIGHT ALIDADE*

by W. Clyma and A. Early

The plane table and alidade frequently are used where layout maps of irregular field and watercourse orientations are needed. They permit 1) the map to be prepared while surveying is done; 2) watercourse and field layout are shown on map to be checked with the actual layout; and 3) design and staking is completed in one operation, thereby avoiding return trips to the office and/or field. The principal disadvantage of using the plane table and alidade is the extra field time necessary. When bad weather occurs, no work is possible.

The basic equipment consists of a tripod, drawing board, alidade equipped with peep-sight alignment hairs, rod, tape, and pencil, paper and scale for preparing the map. Paper is fastened to the board and positions plotted on the paper by sighting through the alidade for direction and determining the distance by taping.

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* Modified from an article in The Problem Identification Handbook. (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100. Fort Collins, CO.

THE PLANE TABLE

The plane table (Figure 1) is a rectangular board (1) usually 18 x 31 inches (46 x 79 cm) that can be attached to a tripod. The table is leveled by changing the legs' position and lengths. A spirit level is used to level the table (2).

The alidade also is illustrated in Figure 1 and has two peep-sight brackets (3). The vertical hairs are 18 inches apart. The alidade has a linear base (4) for support when resting on the table. The sighting edge of the support (5) usually is leveled. A small magnetic compass (6) properly orients the plane table.

SETTING UP THE PLANE TABLE

Set up the tripod and plane table at an appropriate central location with respect to the line of sight for the field layout or the watercourse to be mapped. Level the table using the level bubble on the separate level provided. Then rotate the table in a horizontal plane until magnetic north is at the top of the map or until another reference direction is selected. Designate the location of the instrument on the map arbitrarily or by using other known points to determine instrument location. A map then can be prepared using the alidade to sight locations and the tape to determine distances.

Other types of alidades can be used to determine both elevation and stadia distances. Because it is difficult to maintain a precisely leveled table, it may be advantageous to use the plane table for locations and the farm level for elevations. Though this procedure may duplicate equipment, the level eliminates most of the difficulties for good elevation control.

ORIENTING THE PLANE TABLE

Locating the instrument on the map to be made usually is accomplished by either compass or backsighting.

To orient the table by compass, place the alidade in the direction desirable for a north-south line. Then rotate the table until the compass needle points to magnetic north. Change the board and draw a line on the paper for future reference and to periodically check the orientation of the board.

Orientation of the board by backsighting requires two points be located in the field. The points may or may not be located on the map. If not on the map, the orientation of the line is assumed for best use of the paper in the construction of the map. Distances in all directions may be estimated and

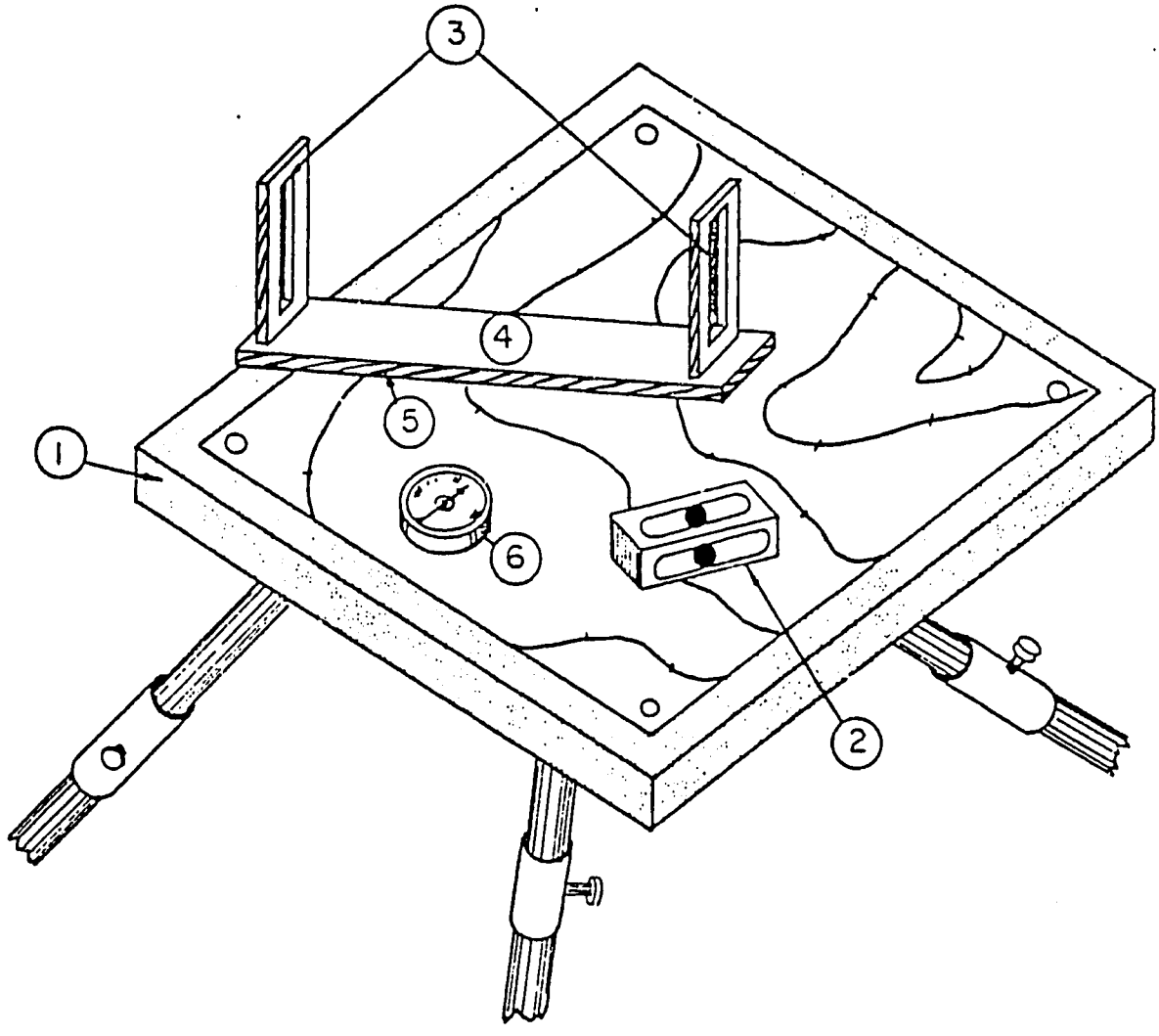

Figure 1. The Plane Table and Alidade

scaled to make sure the scale selected permits inclusion of all the area to be mapped.

If two points (A and B) already are located on the map, the instrument can be located at either point. Then point the alidade along the A-B line and rotate the table until A (or B) is sighted and aligned with the vertical hair.

If point A is located on the map and point B is a more desirable instrument location, set up the instrument at point A. The table initially may be oriented by compass or by some other known line. You then sight the instrument at point B and draw a line. The distance to B can be measured by pacing or taping, depending upon the accuracy required. Mark point B. Move the instrument to point B, set up, and point the alidade along line B-A on the map. Rotate the table until the vertical hair is aligned on point A.

After the table is oriented, locate several distance objects and identify short lines at the edge of the map with a description of what the objects are. The orientation of the table then can be checked periodically without having the rodman return to point A. By carefully selecting well-defined objects on the skyline, reorientation of the table is more accurate. Large distances require minute adjustments for proper orientation. Place a straight pin in the table at the point representing instrument location. Keep the alidade against the pin when sighting locations. Even with the pin, care is required to keep the line of sight of the alidade radiating from the station.

Locate points on the map that require precise locations by intersection or triangulation. With the instrument at one location, draw lines to represent the line of sight to the desired points. Relocate the instrument by carefully taping the distance to the new location. Draw the line of sight lines from the location to the desired points. The location of the point is where two lines intersect. By using three instrument locations, a triangle of error is formed around each point. The methods are indicated in Figure 2.

ILLUSTRATION OF METHOD

A sample field and watercourse layout survey and map are illustrated in Figure 3. Points A and B are points of known location. The distance between the points is taped. The plane table is set up over point A and the mapping sheet set up with the points A and B separated by the scaled length (usually 1' = 220'). The alidade is aligned to sight from A to B and the dotted line rays then are made to the corners of the field (1, 2, 3, and 4), the centerline of the watercourse (5 and 6) and the boundaries of the next field (7 and 8), centerline of the bund.

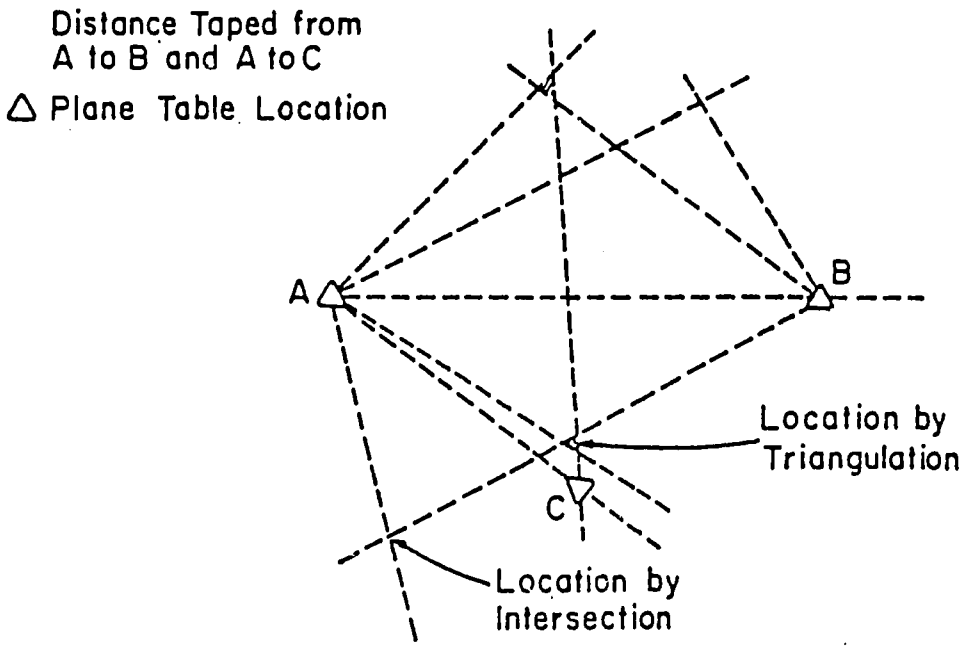

Figure 2. Illustration of the Intersection and Triangulation Methods of Locating Points

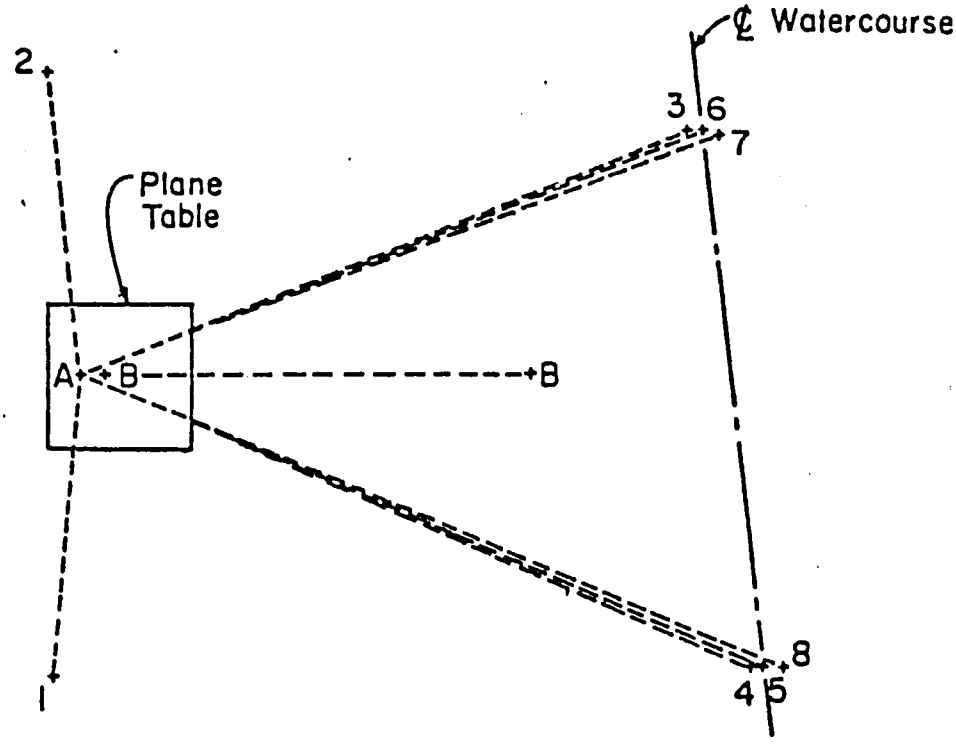

Figure 3. Step Number One in Plane Table Mapping (Plane Table over Point A)

The plane table is moved and set up over point B and oriented to point A (Figure 4). The points 1, 2, 3, 4, 5, 6, 7, and 8 are resighted and appropriate dotted line rays drawn as illustrated. Once the intersecting rays are obtained, the field boundaries are drawn, as shown, with solid lines. In a like manner, points B and D are chosen in the next field (Figure 4). The distances from B to C and C to D are taped and the procedure continues for mapping the entire area.

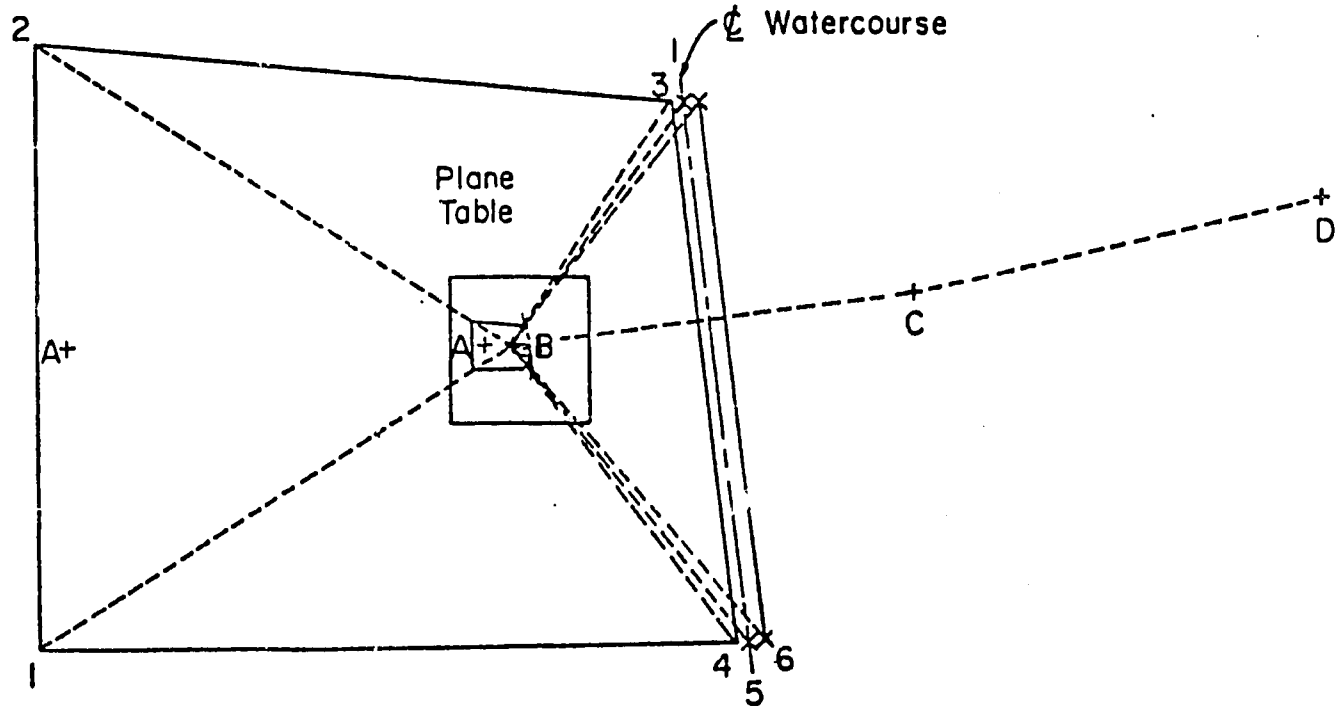

Figure 4. Step Number Two in Plane Table Mapping (Plane Table over Point B)

CUTTHROAT FLUME: INSTALLATION AND USE

by D. Molden

INTRODUCTION

The importance of being able to accurately measure the flow in open channels has led to the development of many types of flow measuring devices including flumes, weirs, and flow meters. The cutthroat flume is a recent addition to these. There are many advantages to the cutthroat flume which make it well suited for use in irrigation channels. These include:

1. good accuracy for both free flow and submerged flow conditions,
2. low head loss through the flume,
3. good for low gradient channels such as irrigation channels,
4. simplicity of fabrication, and
5. easy installation.

THEORETICAL CONSIDERATIONS

The cutthroat flume is a flat-bottomed flume with converging and diverging sections meeting at the throat (Figure 1). Unlike the Parshall flume which has parallel vertical walls at the throat, the cutthroat flume has no throat length; thus the name "cut"-throat. All cutthroat flumes of different sizes are geometrically similar resulting in similar flow patterns: this facilitates calibration of the flumes.

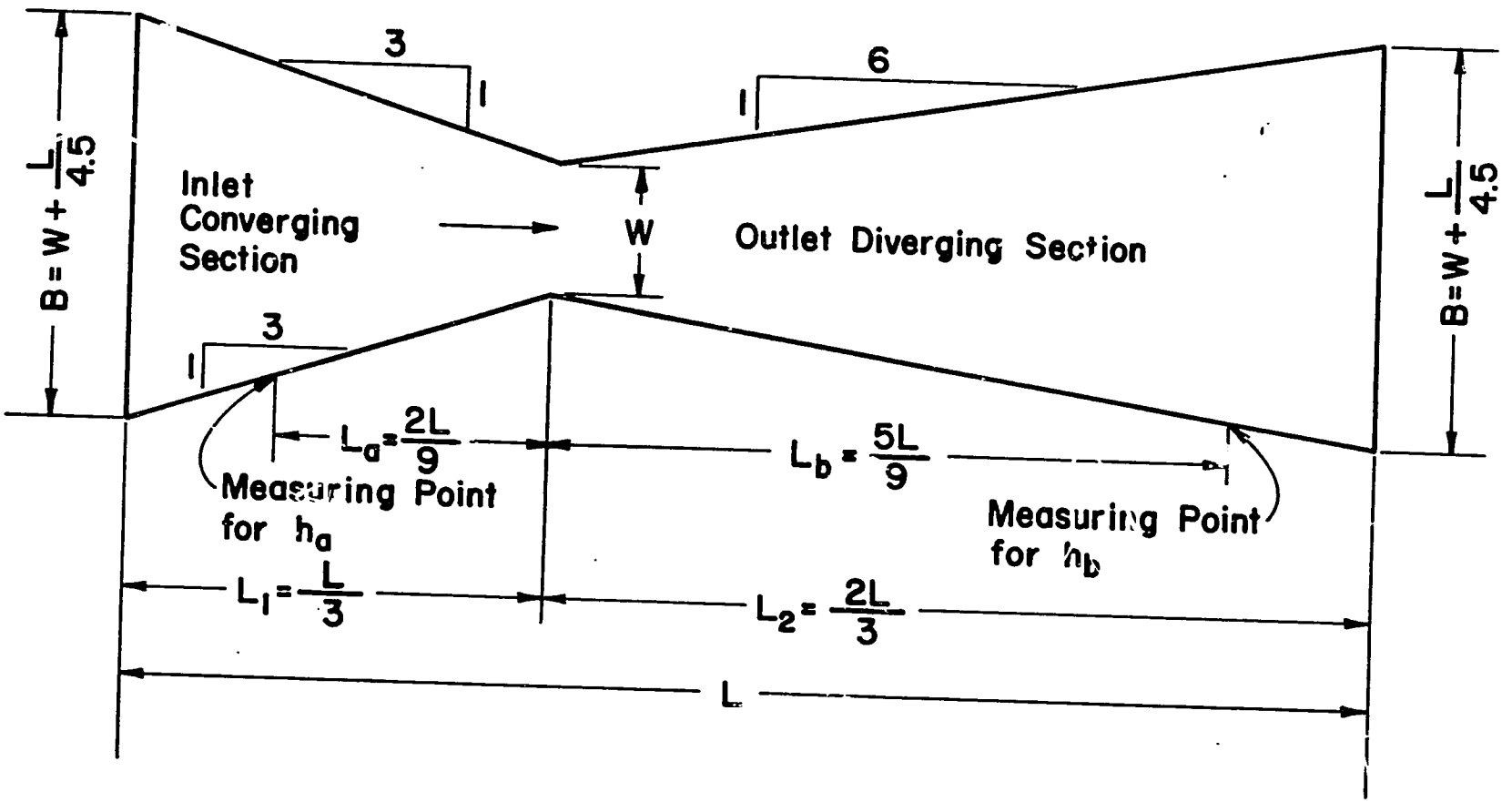

Figure 1. Sketch of a Cutthroat Flume

Free Flow Analysis

Free flow occurs when the flow is critical near the throat section (Figure 2). When free flow exists, the downstream depth does not influence the upstream depth resulting in a direct relationship between the upstream depth and the discharge. Only the upstream depth need be measured.

The relationship giving discharge as a function of upstream depth and flume geometry is an empirical formula. It is necessary to measure only the upstream depth. The discharge can either be found on a table (See Auxiliary Tables 3 and 8 following this article) or with the following rating equation:

$$Q = K_1 W^{1.025} h_a^{n_1}$$

where

Q = discharge (cfs),

W = throat width (ft),

h_a = upstream depth (ft), and

K_1, n_1 = coefficients.

The coefficients for selected flume sizes are given in Table 1.

Table 1. Summary of Coefficients and Transition Submergence for Selected Flume Lengths

Coefficients	Flume Length in Feet			
	1-1/2	3	6	9
K_1	6.40	4.500	3.740	3.500
n_1	2.00	1.840	1.645	1.560
K_2	3.75	2.580	2.040	1.700
n_2	1.60	1.475	1.390	1.380
S_t	.50	0.650	0.740	0.800

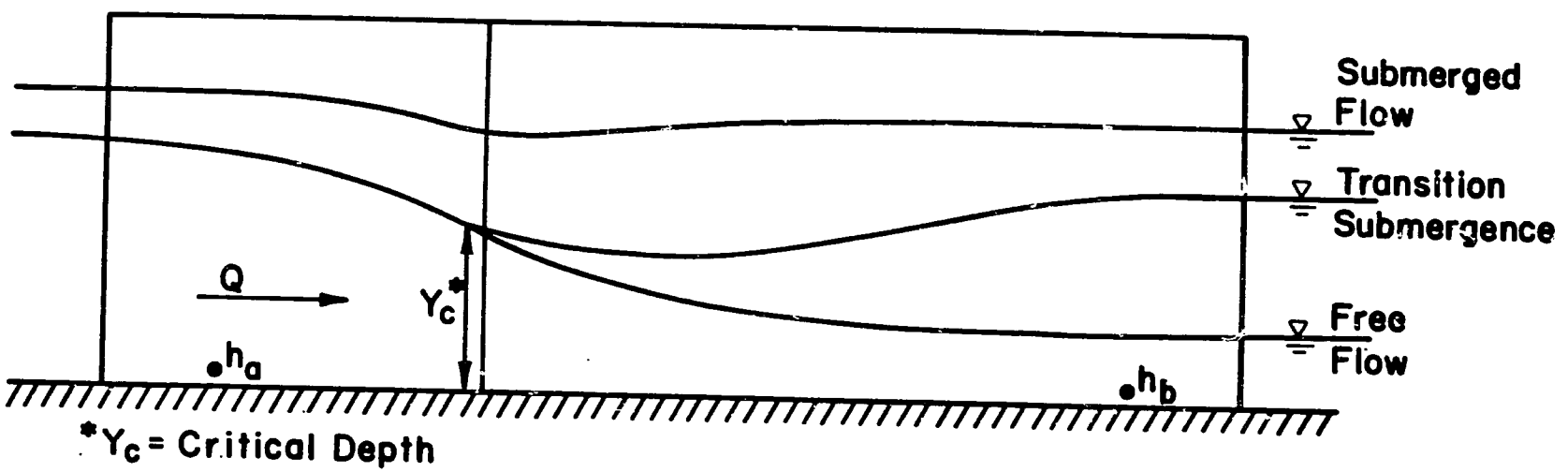

Figure 2. Possible Flow Conditions in a Cutthroat Flume

Submerged Flow Analysis

The flow becomes submerged when at all points through the flume the depth of flow is greater than critical depth (Figure 2). In this case, both upstream and downstream flow depths need to be measured. Discharge can either be obtained from a table (Auxiliary Tables 4 to 7, and 9 to 11) or from the following equation:

$$Q = \frac{K_2 W^{1.025} (h_a - h_b)^{n_1}}{\left[- \log (h_b/h_a)\right]^{n_2}}$$

where:

h_b = downstream depth (ft).

The coefficients used in the equation are given in Table 1.

Transition Submergence

The question arises, how do I know if a free flow or submerged condition exists? To answer this question, the submergence (S) which is the ratio of downstream to upstream flow depths (h_b/h_a) must be determined. The submergence is compared to the transition submergence (S_t) given in Table 1 which is the value of submergence where free flow changes to submerged flow. If the value of measured submergence is less than the transition submergence, then free flow exists. If the value of measured submergence is greater than the transition submergence, submerged flow exists.

FLUME SELECTION

Site Selection

There are many reasons for using flumes and many questions that can be answered by their use. With the purpose of measurement in mind, an appropriate site needs to be selected. There are a few important considerations to be taken into account before the flume is installed.

Installation of flumes will cause water to be stored behind the flume and the water level upstream from the flume to rise. Be sure enough freeboard (i.e., the extension of channel banks above the water surface) is available so that the channel banks will not be overtopped.

If you place the flume near an inlet structure, be careful that the inlet does not become submerged as a result of increased flow depths. Submergence of the outlet changes the flow which is being measured. Chances of inlet submergence are

greater on a flat gradient channel than a steep gradient channel. Operating the flume under free flow conditions will cause the rise in water level to be greater than if operating under submerged conditions. The fall in the channel bed is the difference between the elevation of the channel bed at the inlet structure and the channel bed at the flume. If the rise in water level at the flume approaches the fall in the channel bed, submergence may be a problem.

To determine if inlet submergence is occurring, before and after flume installation record the water level in the channel delivering water to the inlet structure just downstream of the inlet structure. If there is a change in these water levels after flume installation (assuming the flow in the delivery channel remains constant), inlet submergence has occurred. The flume then should be moved further away from the inlet structure.

A second method used to determine submergence calls for the installation of a second flume about 1000 feet (300 meters) downstream from the first flume. You then remove the upstream flume. If there is an increase in discharge in the downstream flume, the upstream flume is causing inlet submergence. If inlet submergence occurs, place the flume further upstream and check again for inlet submergence.

The direction of flow entering the flume must be parallel with the flume. The flume should be placed in a straight section of the channel away from any bends or flow constrictions (e.g., culverts). It is a general rule that a flume should be placed at least ten channel widths from a bend or structure. Water stored upstream from the cutthroat flume often appears to the farmer that the flume is "eating" water (that is, reducing the flow). This perception does not make for happy farmers! As it is important to maintain good relations with the farmer, the following suggestions might prove beneficial.

Completely explain your project to the farmer. Try to convince the farmer that the project's purpose is to help him to achieve better water management.

Never make false promises (for example, getting the water supply increased).

If the farmer is still unhappy and unconvinced of the impact of the flume, it is better not to argue. Seek out a more cooperative farmer.

Sizing the Flume

When considering flume selection, operating conditions and economy must be balanced. The following steps present a procedure for determining the flume size.

1. Obtain the dimensions of the channel.

2. Determine the maximum expected discharge.

3. Obtain the maximum flow depth corresponding to this discharge. If necessary, use the high water mark on the channel.

4. Find the maximum allowable channel water level without infringing greatly on the freeboard. This is especially important if the flume is to be installed for a long period.

5. Determine the increase in upstream flow depth. The downstream flow depth will remain approximately the same after flume installation. The rise in channel depth is then given by $h_a - h_b$.

6. Choose the throat width that will not cause overtopping of the channel banks. Overtopping of channel banks by an increase in the flow depth provides a limiting condition for selecting the minimum sized flume. (See Example Number One following article.)

Dimensions Check

The equations and tables relating flow depth to discharge were all determined in the laboratory with flumes of specified geometry. In order to obtain accurate flow measurements in the field, it is imperative to select flumes with dimensions meeting specifications. Each flume is geometrically similar so the dimensions can be found by using Figure 1. Auxiliary Table 2 lists dimensions of commonly used flumes.

Before accepting the flume each dimension should be carefully measured and checked against the specified dimensions. A tolerance of 1/16 inch (0.2 cm) is allowable. If the difference between measured and specified dimensions is greater than the tolerance, reject the flume.

In addition to checking the dimensions of the flume some qualitative observations should be made. The following checklist insures selection of a reliable flume.

1. Staff gages are perpendicular to the floor.

2. The distances to the staff gage or stilling well inlet are precisely L_a and L_b. If a staff gage is used, the distance is measured from the middle of the gage markings.

3. If stilling wells are used, the zero point of the staff gage in the stilling well coincides with the flume floor inside the converging and diverging sections of the flume.

4. Sides of the flume are perpendicular to the floor.

5. Sides are plane surfaces, free of buckles and bulges.

6. The floor bottom are a plane surface, free of buckles and bulges.

7. The flume walls come to a point at the throat section of the flume

8. There are cross braces across the top of the flume parallel to the flume floor at the center of both the inlet and outlet sections.

9. Metal strips have been placed on top of the flume walls on both sides of the flume and near the center of the inlet and outlet section.

10. If bolts or other means of attaching staff gages to flume walls are used, make sure these do not protrude into the flow.

Flume Installation

The flume should be level both in the longitudinal and transverse directions. The bottom of the flume is the point of reference to level the flume. In cases where the flume is to be installed in flowing water or the flume is already in flowing water, it is not possible to use the bottom of the flume as a reference point. Reference points should be made on the top of the flume to check if the flume is level. To establish these reference points:

1. Level the flume in both longitudinal and transverse sections using a carpenter's level near the throat of the flume.

2. With the flume bottom level, find a location on top of the flume either at the throat section or the crosspiece at the start of the throat section. Mark this location.

3. For the longitudinal section find a place on the walls of the inlet or outlet section that is level. Mark this location.

The flume can be installed for either free or submerged flow. The advantages of submerged flow conditions are that the flume can be placed directly on the channel bottom. Secondly, there is less head loss than in free flow since there is less increase in the flow depth upstream of the flume for submerged flow conditions. The advantage of free flow is the ease of measurement because only the upstream depth need be measured.

If free flow conditions are desired, the flume must be raised frequently from the bottom of the channel. To assure free flow, first determine the maximum expected flow depth (h_m) without the flume in place. Obtain the upstream flow depth (h_a) for the maximum expected flow rate using the appropriate table or equation. Place the flume at an elevation of at least ($h_m - h_a \times S_t$) from the channel bottom where S_t is the transition submergence. Remember: installation of a flume causes water to rise behind it. The upstream flow depth corresponding to the maximum discharge with the flume in place is h_a plus the elevation of the flume above the channel bottom. (See Example Number Two following this article.)

To install the flume, follow the steps below:

1. Place the flume in the center of the channel parallel to the direction of flow.

2. Adjust the flume until it is level in both longitudinal and transverse directions.

3. Properly seal the sides and bottom of the flume so that all the water passes through the flume. Plastic sheets or cloths can be used as cutoff walls.

4. If the flume has been in the channel for an extensive period its orientation may change. Occasionally check the flume to make sure it is level.

DISCHARGE DETERMINATION

Either stilling wells or staff gauges can be used to measure flow depth. In either case, they need to be located at the correct locations for accurate discharge determinations. Stilling wells have the advantage that the flow depth can be measured at a calm water surface as opposed to a staff gauge placed directly in the flow. In addition, continuous recorders can be used with stilling wells. If a staff gauge is used, it must be set vertically at the measuring points (Figure 1).

Reading a Staff Gauge

Staff gauges have a scale from which the depth of water can be determined from a fixed reference point (the bottom of the flume in this case). The divisions on a staff gauge is always in tenths independent of whether English or metric units are used (Figure 3).

The key to reading a staff gauge is recognizing that the markings are different from those on a ruler. Look closely at the markings between the tenth markings on the staff gauge. At the foot and tenth of a foot marks the black marks are trapezoidal with the point on the upward side of the trapezoid. There are four black markings between each tenth marking. On the third black mark from the bottom, there is another trapezoidal with the point on the downward side. This point marks the halfway point between tenths. After these observations, verify that the bottom edge of the black mark represents the 1/100 mark and the top edge

of the black mark corresponds to the next 1/100 reading. Note that the top of the black mark corresponds to an even number and the bottom of the black mark corresponds to an odd reading.

The following procedure demonstrates how to read a staff gauge.

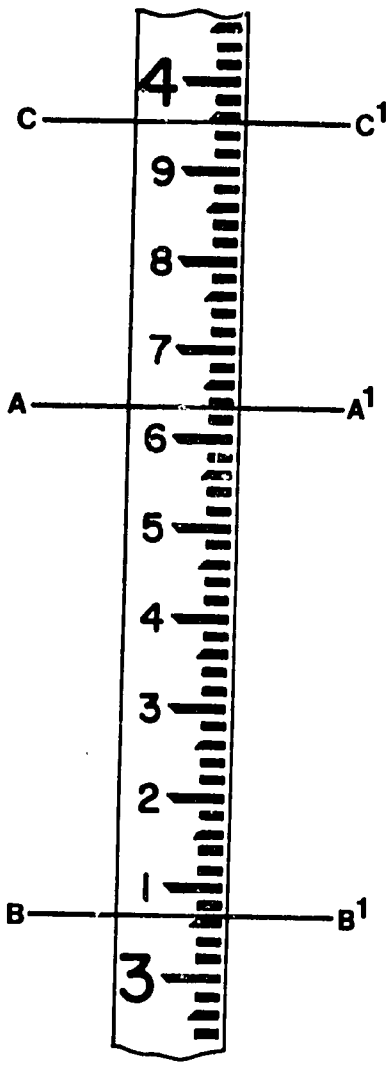

Figure 3. Staff Gauge

1. Determine the water level at the staff gauge. If the water is "bouncing", try to take the average of high and low depths. In this example, assume the water level is at AA^1.

2. The reading is above 3 feet but less than 4.

3. The reading is between six-tenths and seven-tenths of a foot.

4. The water level is at the bottom of the second black mark from the bottom corresponding to 3/100.

5. From Steps 2, 3, and 4 the total reading is obtained:

   Step 2: 3.00

   Step 3: .60

   Step 4: .03

   3.63

   The final reading is 3.63.

For practice, verify that the readings corresponding to BB^1 is 3.06 and CC^1 is 3.95.

Finding the Discharge

To determine the discharge through the flume, it is necessary to find whether free flow or submerged flow exist. This will indicate the appropriate tables or equations to be used. The steps are as follows:

1. Determine whether free flow or submerged flow exists.

   - Measure h_a and h_b.
   - Calculate the submergence ($S = h_b/h_a$)
   - Find the transition submergence (S_t) from Table 1.
   - If $S > S_t$ then submerged flow exists.
   - If $S < S_t$ then free flow exists.

2. Determine the discharge from the appropriate table (see Auxiliary Tables 3-11), or equations using the correct measurements.

   Examples:

   1. Given: 8 in x 3 ft flume (W = .67 ft)
      h_a = .40 ft
      h_b = .30 ft

   - Determine whether free flow or submerged flow exists.

     - $S = h_b/h_a = .30/.40 = .75$

     - $S_t = .65$ (from Table 1)

       Submerged flow exists.

   - From Table 5 find the discharge.

     - $h_a - h_b = .40 - .30 = .10$ ft

     - Find the column under $h_a - h_b$ corresponding to .10 feet. Find the row listing values of ha corresponding to .40 feet. At the intersection of the row and column the discharge is given.

       The discharge is .5 cfs.

- The discharge could also be found using Equation 2.

$$Q = \frac{K_2 W^{1.025}(h_a - h_b)^{n_1}}{\left[-\log(h_b/h_a)\right]^{n_2}}$$

$$= \frac{2.580 \times .67^{1.025}(.4-.3)^{1.84}}{\left[-\log(.75)\right]^{1.475}}$$

$$= .53 \text{ cfs}$$

2. Given:

   - 4 in x 3 ft flume (W = .333 ft)
   - h_a = .80 ft
   - h_b = .40 ft

   - Determine whether free or submerged flow exists

     $S = h_a/h_b = .40/.80 = .50$

     S_t = .65 (From Table 1)

     Free flow exists.

   From Table 3 for free flow, the discharge through the flume is found.

   - Locate the column corresponding to a 4 in x 3 ft flume.

   - Locate the row corresponding to h_a = .80 ft.

- The discharge is given at the intersection of the row and column.

  Q = 0.97 cfs

The discharge can be found using equation 1.

$$Q = K_1 W^{1.025} h_a^{n_1}$$

$$= 4.5(.333^{1.025})(.80^{1.84})$$

$$= 0.97 \text{ cfs.}$$

APPLICATIONS

Determination of losses in a conveyance channel requires installation of two flumes. For example, if the conveyance loss from the irrigation channel inlet to the field turnout is desired, a flume should be placed as close as possible to the channel inlet (avoiding inlet submergence). The second flume should be placed as close as possible to the farm outlet. The length of channel between the two flumes should be walked and notes should be made of any losses including spills, leaks, trading between farmers, and water diversions into other branches. After installation of flumes, the flow will take some time to adjust itself. Wait until steady-state conditions (h_a gauge reading remains constant with time) before taking readings.

Water Delivery Efficiency

Water delivery efficiency (E_d) is the ratio of flows of the downstream flume to the upstream flume.

$$E_d(\%) = 100 \times \frac{Q \text{ downstream}}{Q \text{ upstream}}$$

where:

Q upstream = flow measured in the upstream flume

Q downstream = flow measured in the downstream flume.

Channel Losses

Channel losses consist of seepage to the groundwater, spills, leaks, overtopping of the banks, and any other means by which water leaves the channel in an undesired manner. Losses may be reported in many ways. A few are given:

1. Percent Loss,

$$\text{Loss}(\%) = 100 - E_d(\%)$$

$$= \frac{Q\ \text{upstream} - Q\ \text{downstream}}{Q\ \text{upstream}} \times 100$$

2. Loss as discharge rate per unit length of channel,

$$\text{Loss} = \frac{Q\ \text{upstream} - Q\ \text{downstream}}{\text{length of channel}} \quad (5)$$

The loss can be reported for a specified length of channel by multiplying by the specified length. For example, loss in l/s per 100 m can be found be multiplying the loss by 100 m. This method can be used to compare different channel lengths.

3. Seepage Rate (length/time),

To get the seepage rate determine an average wetted perimeter over the length of the channel section. The seepage rate is given by:

Seepage rate =

$$\frac{Q\ \text{upstream} - Q\ \text{downstream}}{(\text{length of channel})(\text{wetted perimeter})} \quad (6)$$

Water Application Depth

Using a flume placed as close as possible to the field outlet, the average depth of water applied to the field can be found by setting the volume of water applied to the field equal to the area of the field multiplied by average depth:

$$Qt = dA \quad (7)$$

where

Q = inflow rate on to field (L^3/T)

t = time (T)

d = depth applied to field (L^2)

A = area of field (L)

The depth is then given by

$$d = \frac{Qt}{A} \ (L) \quad (8)$$

Application Efficiency

Application efficiency (E_a) is defined as the percent of water delivered that is added to root zone storage, given by the equation:

$$E_a(\%) = 100 \times \frac{dr}{d}$$

where

dr = the average depth of water infiltrated and stored in the root zone.

See subsequent article on "Evaluation of Furrow Irrigation Systems" and "Evaluation of Graded Border Irrigation Systems" for a more complete discussion.

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EXAMPLES

1. Sizing the Flume

Determine the throat width for a 3 foot length flume to be used under the following conditions:

Submerged flow
Maximum expected discharge = 4.0 cfs
Depth corresponding to maximum discharge = 1.0 ft

Maximum allowable depth = 1.3 ft

For the maximum flow:

h_b = maximum expected depth = 1.0 ft

$h_a - h_b$ = maximum allowable rise
= 1.3 - 1.0 = 0.3 ft

h_a = maximum allowable depth = 1.3 ft

From Tables 4, 5 and 6 determine the discharge when h_a = 1.3 ft and $h_a - h_b$ = .3 ft.

Flume Size	Discharge
4" x 3' flume	2.3 cfs
8" x 3' flume	4.6 cfs
12" x 3' flume	7.0 cfs

A 4" flume will not pass the required discharge with a .3 ft allowable canal rise. An 8" flume will pass more than 4 cfs without overtopping the banks. The 12" flume will be too large. Choose the 8" x 3' flume.

2. <u>To Insure Free Flow</u>

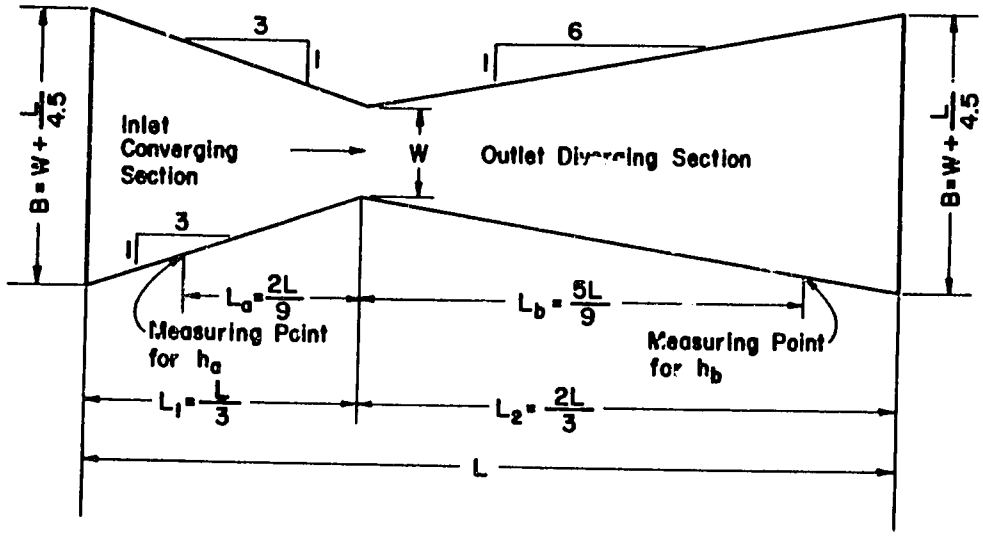
How high should a 4" by 3' flume be raised off the channel bed to assure free flow?

Given:

Maximum discharge = 1.0 cfs
Depth corresponding to maximum discharge = .8 ft

From Table 1, S_t = .65
From Table 3, h_a = .82 ft when Q = 1.0 cfs
$S_t \times h_a$ = .65 x .82 = .53 ft
Place the flume .8 - .53 = .27 ft or more above the channel bed.

After flume installation, the upstream depth is given by the distance from the channel bed to the flume plus h_a, the upstream depth measured from the flume bottom. For the maximum expected discharge of 1.0 cfs the upstream depth is .27 + .82 = 1.09 ft. The channel should be deep enough to allow well over 1.09 ft of flow. If not enough freeboard is available, the flume should be installed for submerged flow.



ENGLISH UNITS

Throat Width (in)	L (ft)	L_1 (in)	L_2 (in)	L_a (in)	L_b (in)	B (in)
2	1.5	6	12	4	10	6
4	1.5	6	12	4	10	8
8	1.5	6	12	4	10	12
16	1.5	6	12	4	10	20
4	3.0	12	24	8	20	12
8	3.0	12	24	8	20	16
12	3.0	12	24	8	20	20
16	3.0	12	24	8	20	24
8	6.0	24	48	16	40	24
16	6.0	24	48	16	40	32
24	6.0	24	48	16	40	40
36	6.0	24	48	16	40	52

METRIC UNITS

Throat Width (cm)	L (cm)	L_1 (cm)	L_2 (cm)	L_a (cm)	L_b (cm)	B (cm)
5	45	15	30	10	25	15
10	45	15	30	10	25	20
20	45	15	30	10	25	30
40	45	15	30	10	25	50
10	90	30	60	20	50	30
20	90	30	60	20	50	40
30	90	30	60	20	50	50
40	90	30	60	20	50	60
20	180	60	120	40	100	60
40	180	60	120	40	100	80
60	180	60	120	40	100	100
90	180	60	120	40	100	130

Auxiliary Table 2. Dimensions of Commonly Used Flumes

Auxiliary Table 3. Free Flow Calibrations for Selected Cutthroat Flumes
(Values Listed Are Discharged in cfs)

h_a, ft	4INX3FT	8INX3FT	12INX3FT	16INX3FT
.02	.00	.00	.00	.00
.04	.00	.01	.01	.02
.06	.01	.02	.03	.03
.08	.01	.03	.04	.06
.10	.02	.04	.07	.09
.12	.03	.06	.09	.12
.14	.04	.08	.12	.16
.16	.05	.10	.15	.21
.18	.06	.13	.19	.26
.20	.08	.15	.23	.31
.22	.09	.18	.28	.37
.24	.11	.21	.33	.44
.26	.12	.25	.38	.51
.28	.14	.29	.43	.58
.30	.16	.32	.49	.66
.32	.18	.36	.55	.74
.34	.20	.41	.62	.83
.36	.22	.45	.69	.92
.38	.25	.50	.76	1.02
.40	.27	.55	.83	1.12
.42	.30	.60	.91	1.22
.44	.32	.66	.99	1.33
.46	.35	.71	1.08	1.44
.48	.38	.77	1.17	1.56
.50	.41	.83	1.26	1.68
.52	.44	.89	1.35	1.81
.54	.47	.96	1.45	1.94
.56	.50	1.02	1.55	2.07
.58	.54	1.09	1.65	2.21
.60	.57	1.16	1.76	2.36
.62	.61	1.23	1.87	2.50
.64	.64	1.31	1.98	2.65
.66	.68	1.38	2.09	2.81
.68	.72	1.46	2.21	2.97
.70	.76	1.54	2.33	3.13
.72	.80	1.62	2.46	3.29
.74	.84	1.71	2.59	3.47
.76	.88	1.79	2.72	3.64
.78	.92	1.88	2.85	3.82
.80	.97	1.97	2.98	4.00
.82	1.01	2.06	3.12	4.19
.84	1.06	2.15	3.27	4.38
.86	1.10	2.25	3.41	4.57
.88	1.15	2.35	3.56	4.77
.90	1.20	2.45	3.71	4.97
.92	1.25	2.55	3.86	5.17
.94	1.30	2.65	4.02	5.38
.96	1.35	2.76	4.17	5.59
.98	1.40	2.86	4.34	5.81
1.00	1.46	2.97	4.50	6.03

Auxiliary Table 3. (continued)

h_a, ft	4INX3FT	8INX3FT	12INX3FT	16INX3FT
1.02	1.51	3.08	4.67	6.25
1.04	1.57	3.19	4.84	6.48
1.06	1.62	3.31	5.01	6.71
1.08	1.68	3.42	5.18	6.95
1.10	1.74	3.54	5.36	7.19
1.12	1.80	3.66	5.54	7.43
1.14	1.86	3.78	5.73	7.67
1.16	1.92	3.90	5.91	7.92
1.18	1.98	4.03	6.10	8.18
1.20	2.04	4.15	6.29	8.43
1.22	2.10	4.28	6.49	8.69
1.24	2.17	4.41	6.69	8.96
1.26	2.23	4.54	6.88	9.23
1.28	2.30	4.68	7.09	9.50
1.30	2.36	4.81	7.29	9.77
1.32	2.43	4.95	7.50	10.05
1.34	2.50	5.09	7.71	10.33
1.36	2.57	5.23	7.92	10.62
1.38	2.64	5.37	8.14	10.91
1.40	2.71	5.52	8.36	11.20
1.42	2.78	5.66	8.58	11.50
1.44	2.85	5.81	8.80	11.80
1.46	2.93	5.96	9.03	12.10
1.48	3.00	6.11	9.26	12.41
1.50	3.07	6.26	9.49	12.72
1.52	3.15	6.42	9.72	13.03
1.54	3.23	6.57	9.96	13.35
1.56	3.30	6.73	10.20	13.67
1.58	3.38	6.89	10.44	13.99
1.60	3.46	7.05	10.69	14.32
1.62	3.54	7.22	10.93	14.65
1.64	3.62	7.38	11.18	14.98
1.66	3.70	7.55	11.43	15.32
1.68	3.79	7.71	11.69	15.66
1.70	3.87	7.88	11.95	16.01
1.72	3.95	8.05	12.21	16.36
1.74	4.04	8.23	12.47	16.71
1.76	4.13	8.40	12.73	17.06
1.78	4.21	8.58	13.00	17.42
1.80	4.30	8.75	13.27	17.78
1.82	4.39	8.94	13.54	18.15
1.84	4.48	9.12	13.82	18.52
1.86	4.57	9.30	14.10	18.89
1.88	4.65	9.49	14.38	19.26
1.90	4.75	9.68	14.66	19.64
1.92	4.84	9.86	14.94	20.03
1.94	4.94	10.05	15.23	20.41
1.96	5.03	10.24	15.52	20.80
1.98	5.12	10.44	15.82	21.19
2.00	5.22	10.63	16.11	21.59

Auxiliary Table 4. Submerged Flow Calibrations for 4 in x 3 ft Cutthr at Flume (Values Listed Are Discharged in cfs)

h_a, ft \ $h_a - h_b$, ft	.02	.04	.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40
.02	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.04	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.06	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.08	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.10	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.12	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.14	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.16	.0	.0	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.18	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.20	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.22	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.24	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.26	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.28	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.30	.1	.1	.1	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
.32	.1	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
.34	.1	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
.36	.1	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
.38	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
.40	.2	.2	.2	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.42	.2	.2	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.44	.2	.2	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.46	.2	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.48	.2	.3	.3	.3	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.50	.2	.3	.3	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.52	.3	.3	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.54	.3	.3	.4	.4	.4	.4	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5
.56	.3	.4	.4	.4	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5
.58	.3	.4	.4	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5
.60	.3	.4	.5	.5	.5	.5	.5	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6
.62	.3	.4	.5	.5	.5	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6
.64	.4	.4	.5	.5	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6
.66	.4	.5	.5	.6	.6	.6	.6	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7
.68	.4	.5	.6	.6	.6	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7
.70	.4	.5	.6	.6	.7	.7	.7	.7	.7	.7	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8
.72	.4	.5	.6	.7	.7	.7	.7	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8
.74	.4	.6	.6	.7	.7	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8
.76	.5	.5	.7	.7	.8	.8	.8	.8	.8	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9
.78	.5	.5	.7	.7	.8	.8	.8	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9
.80	.5	.5	.7	.8	.8	.9	.9	.9	.9	.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.82	.5	.6	.7	.8	.9	.9	.9	.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.84	.5	.7	.8	.8	.9	.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.1
.86	.6	.7	.8	.9	.9	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
.88	.6	.7	.8	.9	1.0	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2
.90	.5	.7	.8	.9	1.0	1.0	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
.92	.6	.8	.9	1.0	1.0	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3
.94	.6	.8	.9	1.0	1.1	1.1	1.1	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
.96	.7	.8	.9	1.0	1.1	1.1	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4
.98	.7	.8	1.0	1.1	1.1	1.2	1.2	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
1.00	.7	.9	1.0	1.1	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.5	1.5	1.5

Auxiliary Table 4. (continued)

h_a, ft	$h_a - h_b$, ft																			
	.02	.04	.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40
1.02	.7	.9	1.0	1.1	1.2	1.3	1.3	1.4	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
1.04	.7	.9	1.1	1.2	1.2	1.3	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.6	1.6	1.6
1.06	.8	1.0	1.1	1.2	1.3	1.3	1.4	1.4	1.5	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
1.08	.8	1.0	1.1	1.2	1.3	1.4	1.4	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.7	1.7	1.7	1.7	1.7	1.7
1.10	.8	1.0	1.2	1.3	1.3	1.4	1.5	1.5	1.6	1.6	1.6	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
1.12	.8	1.0	1.2	1.3	1.4	1.5	1.5	1.6	1.6	1.7	1.7	1.7	1.7	1.7	1.8	1.8	1.8	1.8	1.8	1.8
1.14	.8	1.1	1.2	1.3	1.4	1.5	1.6	1.6	1.7	1.7	1.7	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.9
1.16	.9	1.1	1.3	1.4	1.5	1.5	1.6	1.7	1.7	1.7	1.8	1.8	1.8	1.9	1.9	1.9	1.9	1.9	1.9	1.9
1.18	.9	1.1	1.3	1.4	1.5	1.6	1.7	1.7	1.8	1.8	1.8	1.9	1.9	1.9	1.9	1.9	2.0	2.0	2.0	2.0
1.20	.9	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.8	1.8	1.9	1.9	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0
1.22	.9	1.2	1.4	1.5	1.6	1.7	1.7	1.8	1.9	1.9	1.9	2.0	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.1
1.24	1.0	1.2	1.4	1.5	1.6	1.7	1.8	1.8	1.9	1.9	2.0	2.0	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.2
1.26	1.0	1.2	1.4	1.6	1.7	1.8	1.8	1.9	2.0	2.0	2.0	2.1	2.1	2.1	2.2	2.2	2.2	2.2	2.2	2.2
1.28	1.0	1.3	1.5	1.6	1.7	1.8	1.9	1.9	2.0	2.1	2.1	2.1	2.2	2.2	2.2	2.2	2.3	2.3	2.3	2.3
1.30	1.0	1.3	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.1	2.1	2.2	2.2	2.2	2.3	2.3	2.3	2.3	2.3	2.4
1.32	1.0	1.3	1.5	1.7	1.8	1.9	2.0	2.0	2.1	2.2	2.2	2.2	2.3	2.3	2.3	2.4	2.4	2.4	2.4	2.5
1.34	1.1	1.4	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.2	2.3	2.3	2.3	2.4	2.4	2.4	2.4	2.5	2.5	2.5
1.36	1.1	1.4	1.6	1.7	1.9	2.0	2.1	2.1	2.2	2.3	2.3	2.4	2.4	2.4	2.5	2.5	2.5	2.5	2.5	2.6
1.38	1.1	1.4	1.5	1.8	1.9	2.0	2.1	2.2	2.3	2.3	2.4	2.4	2.5	2.5	2.5	2.5	2.6	2.6	2.6	2.6
1.40	1.1	1.5	1.7	1.8	2.0	2.1	2.2	2.2	2.3	2.4	2.4	2.5	2.5	2.5	2.6	2.6	2.6	2.6	2.7	2.7
1.42	1.2	1.5	1.7	1.9	2.0	2.1	2.2	2.3	2.4	2.4	2.5	2.5	2.6	2.6	2.6	2.7	2.7	2.7	2.7	2.7
1.44	1.2	1.5	1.7	1.9	2.0	2.2	2.3	2.3	2.4	2.5	2.5	2.6	2.6	2.7	2.7	2.7	2.8	2.8	2.8	2.8
1.46	1.2	1.5	1.8	1.9	2.1	2.2	2.3	2.4	2.5	2.5	2.6	2.6	2.7	2.7	2.8	2.8	2.8	2.8	2.9	2.9
1.48	1.2	1.6	1.8	2.0	2.1	2.3	2.4	2.4	2.5	2.6	2.6	2.7	2.7	2.8	2.8	2.9	2.9	2.9	2.9	2.9
1.50	1.3	1.6	1.8	2.0	2.2	2.3	2.4	2.5	2.6	2.6	2.7	2.8	2.8	2.9	2.9	2.9	3.0	3.0	3.0	3.0
1.52	1.3	1.6	1.9	2.1	2.2	2.3	2.5	2.5	2.6	2.7	2.8	2.8	2.9	2.9	3.0	3.0	3.0	3.0	3.1	3.1
1.54	1.3	1.7	1.9	2.1	2.3	2.4	2.5	2.6	2.7	2.8	2.8	2.9	2.9	3.0	3.0	3.1	3.1	3.1	3.1	3.2
1.56	1.3	1.7	2.0	2.2	2.3	2.4	2.6	2.7	2.7	2.8	2.9	2.9	3.0	3.0	3.1	3.1	3.2	3.2	3.2	3.2
1.58	1.4	1.7	2.0	2.2	2.4	2.5	2.6	2.7	2.8	2.9	2.9	3.0	3.1	3.1	3.1	3.2	3.2	3.2	3.3	3.3
1.60	1.4	1.8	2.0	2.2	2.4	2.5	2.7	2.8	2.8	2.9	3.0	3.1	3.1	3.2	3.2	3.3	3.3	3.3	3.3	3.4
1.62	1.4	1.8	2.1	2.3	2.4	2.6	2.7	2.8	2.9	3.0	3.1	3.1	3.2	3.2	3.3	3.3	3.4	3.4	3.4	3.4
1.64	1.4	1.8	2.1	2.3	2.5	2.6	2.8	2.9	3.0	3.0	3.1	3.2	3.2	3.3	3.3	3.4	3.4	3.5	3.5	3.5
1.66	1.5	1.9	2.2	2.4	2.5	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.3	3.4	3.4	3.5	3.5	3.5	3.6	3.6
1.68	1.5	1.9	2.2	2.4	2.6	2.7	2.9	3.0	3.1	3.2	3.2	3.3	3.4	3.4	3.5	3.5	3.6	3.6	3.6	3.7
1.70	1.5	1.9	2.2	2.5	2.6	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.4	3.5	3.5	3.6	3.6	3.7	3.7	3.7
1.72	1.6	2.0	2.3	2.5	2.7	2.8	3.0	3.1	3.2	3.3	3.4	3.4	3.5	3.6	3.6	3.7	3.7	3.7	3.8	3.8
1.74	1.6	2.0	2.3	2.5	2.7	2.9	3.0	3.1	3.3	3.3	3.4	3.5	3.6	3.6	3.7	3.7	3.8	3.8	3.9	3.9
1.76	1.6	2.0	2.4	2.6	2.8	2.9	3.1	3.2	3.3	3.4	3.5	3.6	3.6	3.7	3.8	3.8	3.9	3.9	3.9	4.0
1.78	1.6	2.1	2.4	2.6	2.8	3.0	3.1	3.3	3.4	3.5	3.6	3.6	3.7	3.8	3.8	3.9	3.9	4.0	4.0	4.0
1.80	1.7	2.1	2.4	2.7	2.9	3.0	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.8	3.9	3.9	4.0	4.0	4.1	4.1
1.82	1.7	2.2	2.5	2.7	2.9	3.1	3.2	3.4	3.5	3.6	3.7	3.8	3.8	3.9	4.0	4.0	4.1	4.1	4.2	4.2
1.84	1.7	2.2	2.5	2.8	3.0	3.1	3.3	3.4	3.5	3.7	3.7	3.8	3.9	4.0	4.0	4.1	4.1	4.2	4.2	4.3
1.86	1.7	2.2	2.6	2.8	3.0	3.2	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.0	4.1	4.2	4.2	4.3	4.3	4.3
1.88	1.8	2.3	2.6	2.9	3.1	3.3	3.4	3.5	3.7	3.8	3.9	4.0	4.0	4.1	4.2	4.2	4.3	4.3	4.4	4.4
1.90	1.8	2.3	2.6	2.9	3.1	3.3	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.3	4.4	4.4	4.5	4.5
1.92	1.8	2.3	2.7	2.9	3.2	3.4	3.5	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.3	4.4	4.4	4.5	4.5	4.6
1.94	1.9	2.4	2.7	3.0	3.2	3.4	3.6	3.7	3.9	4.0	4.1	4.2	4.3	4.3	4.4	4.5	4.5	4.6	4.6	4.7
1.96	1.9	2.4	2.8	3.0	3.3	3.5	3.6	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.5	4.6	4.7	4.7	4.7
1.98	1.9	2.4	2.8	3.1	3.3	3.5	3.7	3.8	4.0	4.1	4.2	4.3	4.4	4.5	4.5	4.6	4.7	4.7	4.8	4.8
2.00	1.9	2.5	2.8	3.1	3.4	3.6	3.7	3.9	4.0	4.2	4.3	4.4	4.5	4.5	4.6	4.7	4.8	4.8	4.9	4.9

Auxiliar, Table 4. (continued)

h_a, ft	$h_a - h_b$, ft .42	.44	.46	.48	.50	.52	.54	.56	.58	.60	.62	.64	.66	.68	.70
1.04	1.6	1.5	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
1.06	1.6	1.5	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
1.08	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
1.10	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
1.12	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
1.14	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
1.16	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
1.18	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
1.20	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
1.22	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
1.24	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
1.26	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
1.28	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
1.30	2.3	2.3	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
1.32	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
1.34	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
1.36	2.5	2.5	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
1.38	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
1.40	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
1.42	2.7	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
1.44	2.8	2.8	2.9	2.8	2.8	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
1.46	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
1.48	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
1.50	3.0	3.0	3.0	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
1.52	3.1	3.1	3.1	3.1	3.1	3.1	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
1.54	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
1.56	3.2	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
1.58	3.3	3.3	3.3	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
1.60	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
1.62	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
1.64	3.5	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
1.66	3.6	3.6	3.6	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
1.68	3.7	3.7	3.7	3.7	3.7	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
1.70	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.9	3.9	3.9	3.9	3.9	3.9
1.72	3.8	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	4.0	4.0	4.0	4.0	4.0
1.74	3.9	3.9	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
1.76	4.0	4.0	4.0	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1
1.78	4.1	4.1	4.1	4.1	4.1	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
1.80	4.1	4.2	4.2	4.2	4.2	4.2	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3
1.82	4.2	4.3	4.3	4.3	4.3	4.3	4.3	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
1.84	4.3	4.3	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.5	4.5	4.5	4.5	4.5
1.86	4.4	4.4	4.4	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.6	4.6	4.6
1.88	4.5	4.5	4.5	4.5	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.7	4.7	4.7
1.90	4.5	4.5	4.5	4.6	4.6	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.8	4.8
1.92	4.6	4.7	4.7	4.7	4.7	4.8	4.8	4.8	4.8	4.8	4.9	4.8	4.8	4.8	4.8
1.94	4.7	4.7	4.8	4.8	4.8	4.8	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9
1.96	4.8	4.8	4.9	4.9	4.9	4.9	4.9	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
1.98	4.9	4.9	4.9	5.0	5.0	5.0	5.0	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
2.00	4.9	5.0	5.0	5.1	5.1	5.1	5.1	5.1	5.2	5.2	5.2	5.2	5.2	5.2	5.2

Auxiliary Table 5. Submerged Flow Calibrations for 8 in x 3 ft Cutthroat Flume (Values Listed Are Discharged in cfs)

h_a, ft	$h_a - h_b$, ft .02	.04	.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40
.02	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.04	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.06	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.08	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.10	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.12	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.14	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.16	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.18	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.20	.1	.1	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
.22	.1	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
.24	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
.26	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
.28	.2	.2	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.30	.2	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.32	.3	.3	.3	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.34	.3	.3	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.36	.3	.4	.4	.4	.4	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5
.38	.3	.4	.4	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5
.40	.4	.4	.5	.5	.5	.5	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6
.42	.4	.5	.5	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6
.44	.4	.5	.6	.6	.6	.6	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7
.46	.4	.5	.6	.6	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7
.48	.5	.6	.7	.7	.7	.7	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8
.50	.5	.6	.7	.7	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8
.52	.5	.7	.7	.8	.8	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9
.54	.6	.7	.8	.8	.9	.9	.9	.9	.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.56	.6	.7	.8	.9	.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.58	.6	.8	.9	.9	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
.60	.7	.8	.9	1.0	1.1	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
.62	.7	.9	1.0	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
.64	.7	.9	1.0	1.1	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
.66	.8	.9	1.1	1.2	1.2	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
.68	.8	1.0	1.1	1.2	1.3	1.3	1.4	1.4	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
.70	.8	1.0	1.2	1.3	1.3	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
.72	.9	1.1	1.2	1.3	1.4	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
.74	.9	1.1	1.3	1.4	1.5	1.5	1.6	1.6	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
.76	.9	1.2	1.3	1.4	1.5	1.6	1.7	1.7	1.7	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
.78	1.0	1.2	1.4	1.5	1.6	1.7	1.7	1.8	1.8	1.8	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
.80	1.0	1.3	1.4	1.6	1.7	1.7	1.8	1.8	1.9	1.9	1.9	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
.82	1.0	1.3	1.5	1.6	1.7	1.8	1.9	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.1	2.1
.84	1.1	1.4	1.6	1.7	1.8	1.9	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.1	2.2	2.2	2.2	2.2	2.2	2.2
.86	1.1	1.4	1.6	1.8	1.9	2.0	2.0	2.1	2.1	2.2	2.2	2.2	2.2	2.2	2.2	2.3	2.3	2.3	2.3	2.3
.88	1.2	1.5	1.7	1.8	1.9	2.0	2.1	2.2	2.2	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
.90	1.2	1.5	1.7	1.9	2.0	2.1	2.2	2.2	2.3	2.3	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
.92	1.2	1.5	1.8	1.9	2.1	2.2	2.3	2.3	2.4	2.4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
.94	1.3	1.5	1.8	2.0	2.1	2.3	2.3	2.4	2.5	2.5	2.6	2.6	2.6	2.6	2.6	2.6	2.7	2.7	2.7	2.7
.96	1.3	1.7	1.9	2.1	2.2	2.3	2.4	2.5	2.6	2.6	2.6	2.7	2.7	2.7	2.7	2.7	2.8	2.8	2.8	2.8
.98	1.4	1.7	2.0	2.1	2.3	2.4	2.5	2.6	2.6	2.7	2.7	2.8	2.8	2.8	2.8	2.8	2.8	2.9	2.9	2.9
1.00	1.4	1.8	2.0	2.2	2.4	2.5	2.6	2.7	2.7	2.8	2.8	2.9	2.9	2.9	2.9	2.9	2.9	3.0	3.0	3.0

Auxiliary Table 5. (continued)

h_a, ft	$h_a - h_b$, ft																			
	.02	.04	.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40
1.02	1.5	1.8	2.1	2.3	2.4	2.6	2.7	2.8	2.8	2.9	2.9	3.0	3.0	3.0	3.0	3.1	3.1	3.1	3.1	3.1
1.04	1.5	1.9	2.2	2.4	2.5	2.6	2.7	2.8	2.9	3.0	3.0	3.1	3.1	3.1	3.1	3.2	3.2	3.2	3.2	3.2
1.06	1.5	1.9	2.2	2.4	2.6	2.7	2.8	2.9	3.0	3.1	3.1	3.2	3.2	3.2	3.3	3.3	3.3	3.3	3.3	3.3
1.08	1.6	2.0	2.3	2.5	2.7	2.8	2.9	3.0	3.1	3.2	3.2	3.3	3.3	3.3	3.4	3.4	3.4	3.4	3.4	3.4
1.10	1.6	2.1	2.3	2.6	2.7	2.9	3.0	3.1	3.2	3.3	3.3	3.4	3.4	3.4	3.5	3.5	3.5	3.5	3.5	3.5
1.12	1.7	2.1	2.4	2.6	2.8	3.0	3.1	3.2	3.3	3.4	3.4	3.5	3.5	3.6	3.6	3.6	3.6	3.6	3.6	3.7
1.14	1.7	2.2	2.5	2.7	2.9	3.1	3.2	3.3	3.4	3.5	3.5	3.6	3.6	3.7	3.7	3.7	3.7	3.7	3.8	3.8
1.16	1.8	2.2	2.5	2.8	3.0	3.1	3.3	3.4	3.5	3.6	3.6	3.7	3.7	3.8	3.8	3.8	3.9	3.9	3.9	3.9
1.18	1.8	2.3	2.6	2.9	3.1	3.2	3.4	3.5	3.6	3.7	3.7	3.8	3.8	3.9	3.9	3.9	4.0	4.0	4.0	4.0
1.20	1.9	2.3	2.7	2.9	3.1	3.3	3.4	3.6	3.7	3.8	3.8	3.9	4.0	4.0	4.0	4.1	4.1	4.1	4.1	4.1
1.22	1.9	2.4	2.7	3.0	3.2	3.4	3.5	3.7	3.8	3.9	3.9	4.0	4.1	4.1	4.2	4.2	4.2	4.2	4.2	4.2
1.24	1.9	2.5	2.8	3.1	3.3	3.5	3.6	3.8	3.9	4.0	4.0	4.1	4.2	4.2	4.3	4.3	4.3	4.4	4.4	4.4
1.26	2.0	2.5	2.9	3.2	3.4	3.6	3.7	3.9	4.0	4.1	4.2	4.2	4.3	4.3	4.4	4.4	4.5	4.5	4.5	4.5
1.28	2.0	2.6	3.0	3.2	3.5	3.7	3.8	4.0	4.1	4.2	4.3	4.3	4.4	4.5	4.5	4.5	4.6	4.6	4.6	4.6
1.30	2.1	2.6	3.0	3.3	3.6	3.7	3.9	4.1	4.2	4.3	4.4	4.4	4.5	4.6	4.6	4.7	4.7	4.7	4.8	4.8
1.32	2.1	2.7	3.1	3.4	3.6	3.8	4.0	4.2	4.3	4.4	4.5	4.6	4.6	4.7	4.7	4.8	4.8	4.9	4.9	4.9
1.34	2.2	2.8	3.2	3.5	3.7	3.9	4.1	4.3	4.4	4.5	4.5	4.7	4.8	4.8	4.9	4.9	5.0	5.0	5.0	5.0
1.36	2.2	2.8	3.2	3.6	3.8	4.0	4.2	4.4	4.5	4.6	4.7	4.8	4.9	4.9	5.0	5.0	5.1	5.1	5.1	5.2
1.38	2.3	2.9	3.3	3.6	3.9	4.1	4.3	4.5	4.6	4.7	4.8	4.9	5.0	5.1	5.1	5.2	5.2	5.2	5.3	5.3
1.40	2.3	3.0	3.4	3.7	4.0	4.2	4.4	4.6	4.7	4.8	4.9	5.0	5.1	5.2	5.2	5.3	5.3	5.4	5.4	5.4
1.42	2.4	3.0	3.5	3.8	4.1	4.3	4.5	4.7	4.8	4.9	5.0	5.1	5.2	5.3	5.4	5.4	5.5	5.5	5.5	5.6
1.44	2.4	3.1	3.5	3.9	4.2	4.4	4.6	4.8	4.9	5.0	5.2	5.3	5.3	5.4	5.5	5.6	5.6	5.6	5.7	5.7
1.46	2.5	3.2	3.6	4.0	4.2	4.5	4.7	4.9	5.0	5.2	5.3	5.4	5.5	5.6	5.6	5.7	5.7	5.8	5.8	5.8
1.48	2.5	3.2	3.7	4.0	4.3	4.6	4.8	5.0	5.1	5.3	5.4	5.5	5.6	5.7	5.7	5.8	5.9	5.9	6.0	6.0
1.50	2.6	3.3	3.8	4.1	4.4	4.7	4.9	5.1	5.2	5.4	5.5	5.6	5.7	5.8	5.9	5.9	6.0	6.1	6.1	6.1
1.52	2.6	3.3	3.8	4.2	4.5	4.8	5.0	5.2	5.3	5.5	5.6	5.7	5.8	5.9	6.0	6.1	6.1	6.2	6.2	6.3
1.54	2.7	3.4	3.9	4.3	4.6	4.9	5.1	5.3	5.5	5.6	5.7	5.9	6.0	6.1	6.1	6.2	6.3	6.3	6.4	6.4
1.56	2.7	3.5	4.0	4.4	4.7	5.0	5.2	5.4	5.6	5.7	5.9	6.0	6.1	6.2	6.3	6.3	6.4	6.5	6.5	6.6
1.58	2.8	3.5	4.1	4.5	4.8	5.1	5.3	5.5	5.7	5.8	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.6	6.7	6.7
1.60	2.8	3.6	4.1	4.6	4.9	5.2	5.4	5.6	5.8	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.8	6.9
1.62	2.9	3.7	4.2	4.6	5.0	5.3	5.5	5.7	5.9	6.1	6.2	6.4	6.5	6.6	6.7	6.8	6.8	6.9	7.0	7.0
1.64	2.9	3.8	4.3	4.7	5.1	5.4	5.6	5.8	6.0	6.2	6.4	6.5	6.6	6.7	6.8	6.9	7.0	7.0	7.1	7.1
1.66	3.0	3.8	4.4	4.8	5.2	5.5	5.7	5.9	6.1	6.3	6.5	6.6	6.7	6.8	6.9	7.0	7.1	7.2	7.2	7.3
1.68	3.1	3.9	4.5	4.9	5.3	5.6	5.8	6.1	6.3	6.4	6.6	6.7	6.9	7.0	7.1	7.2	7.3	7.3	7.4	7.4
1.70	3.1	4.0	4.5	5.0	5.4	5.7	5.9	6.2	6.4	6.6	6.7	6.9	7.0	7.1	7.2	7.3	7.4	7.5	7.5	7.6
1.72	3.2	4.0	4.6	5.1	5.5	5.8	6.0	6.3	6.5	6.7	6.8	7.0	7.1	7.3	7.4	7.5	7.5	7.6	7.7	7.8
1.74	3.2	4.1	4.7	5.2	5.6	5.9	6.2	6.4	6.6	6.8	7.0	7.1	7.3	7.4	7.5	7.6	7.7	7.8	7.8	7.9
1.76	3.3	4.2	4.8	5.3	5.6	6.0	6.3	6.5	6.7	6.9	7.1	7.3	7.4	7.5	7.6	7.7	7.8	7.9	8.0	8.1
1.78	3.3	4.2	4.9	5.3	5.7	6.1	6.4	6.6	6.9	7.1	7.2	7.4	7.5	7.7	7.8	7.9	8.0	8.1	8.1	8.2
1.80	3.4	4.3	4.9	5.4	5.8	6.2	6.5	6.7	7.0	7.2	7.4	7.5	7.7	7.8	7.9	8.0	8.1	8.2	8.3	8.4
1.82	3.4	4.4	5.0	5.5	5.9	6.3	6.6	6.9	7.1	7.3	7.5	7.7	7.8	7.9	8.1	8.2	8.3	8.4	8.5	8.5
1.84	3.5	4.5	5.1	5.6	6.0	6.4	6.7	7.0	7.2	7.4	7.6	7.8	7.9	8.1	8.2	8.3	8.4	8.5	8.6	8.7
1.86	3.6	4.5	5.2	5.7	6.1	6.5	6.8	7.1	7.3	7.6	7.8	7.9	8.1	8.2	8.4	8.5	8.6	8.7	8.8	8.8
1.88	3.6	4.6	5.3	5.8	6.2	6.6	6.9	7.2	7.5	7.7	7.9	8.1	8.2	8.4	8.5	8.6	8.7	8.8	8.9	9.0
1.90	3.7	4.7	5.4	5.9	6.3	6.7	7.0	7.3	7.6	7.8	8.0	8.2	8.4	8.5	8.7	8.8	8.9	9.0	9.1	9.2
1.92	3.7	4.7	5.5	6.0	6.4	6.8	7.2	7.5	7.7	7.9	8.1	8.3	8.5	8.7	8.8	8.9	9.0	9.1	9.2	9.3
1.94	3.8	4.8	5.5	6.1	6.6	6.9	7.3	7.6	7.8	8.1	8.3	8.5	8.6	8.8	8.9	9.1	9.2	9.3	9.4	9.5
1.96	3.8	4.9	5.6	6.2	6.7	7.0	7.4	7.7	8.0	8.2	8.4	8.6	8.8	9.0	9.1	9.2	9.4	9.5	9.6	9.7
1.98	3.9	5.0	5.7	6.3	6.8	7.2	7.5	7.8	8.1	8.3	8.6	8.8	8.9	9.1	9.2	9.4	9.5	9.6	9.7	9.8
2.00	4.0	5.0	5.8	6.4	6.9	7.3	7.6	7.9	8.2	8.5	8.7	8.9	9.1	9.2	9.4	9.5	9.7	9.8	9.9	10.0

Auxiliary Table 5. (continued)

h_a, ft	$h_a - h_b$, ft														
	.42	.44	.46	.48	.50	.52	.54	.56	.58	.60	.62	.64	.66	.68	.70
1.04	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
1.06	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
1.08	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
1.10	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
1.12	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
1.14	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
1.16	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
1.18	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
1.20	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
1.22	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3
1.24	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
1.26	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
1.28	4.6	4.6	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
1.30	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8
1.32	4.9	4.9	4.9	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
1.34	5.0	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
1.36	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
1.38	5.3	5.3	5.3	5.3	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
1.40	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
1.42	5.6	5.6	5.6	5.6	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
1.44	5.7	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
1.46	5.9	5.9	5.9	5.9	5.9	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
1.48	6.0	6.0	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
1.50	6.2	6.2	6.2	6.2	6.2	6.2	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
1.52	6.3	6.3	6.3	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
1.54	6.5	6.5	6.5	6.5	6.5	6.5	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
1.56	6.6	6.6	6.6	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7
1.58	6.7	6.8	6.8	6.8	6.8	6.8	6.8	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9
1.60	6.9	6.9	7.0	7.0	7.0	7.0	7.0	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
1.62	7.0	7.1	7.1	7.1	7.1	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
1.64	7.2	7.2	7.3	7.3	7.3	7.3	7.3	7.3	7.4	7.4	7.4	7.4	7.4	7.4	7.4
1.66	7.3	7.4	7.4	7.4	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
1.68	7.5	7.5	7.6	7.6	7.6	7.6	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
1.70	7.7	7.7	7.7	7.8	7.8	7.8	7.8	7.8	7.8	7.9	7.9	7.9	7.9	7.9	7.9
1.72	7.8	7.9	7.9	7.9	7.9	8.0	8.0	8.0	8.0	8.0	8.1	8.1	8.1	8.1	8.1
1.74	8.0	8.0	8.0	8.1	8.1	8.1	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2
1.76	8.1	8.2	8.2	8.2	8.3	8.3	8.3	8.3	8.3	8.3	8.4	8.4	8.4	8.4	8.4
1.78	8.3	8.3	8.4	8.4	8.4	8.5	8.5	8.5	8.5	8.5	8.5	8.6	8.6	8.6	8.6
1.80	8.4	8.5	8.5	8.6	8.6	8.6	8.7	8.7	8.7	8.7	8.7	8.8	8.8	8.8	8.8
1.82	8.6	8.6	8.7	8.7	8.8	8.8	8.8	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9
1.84	8.8	8.8	8.9	8.9	8.9	9.0	9.0	9.0	9.0	9.1	9.1	9.1	9.1	9.1	9.1
1.86	8.9	9.0	9.0	9.1	9.1	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.3	9.3	9.3
1.88	9.1	9.1	9.2	9.2	9.3	9.3	9.4	9.4	9.4	9.4	9.4	9.4	9.5	9.5	9.5
1.90	9.2	9.3	9.4	9.4	9.5	9.5	9.5	9.6	9.6	9.6	9.6	9.6	9.6	9.7	9.7
1.92	9.4	9.5	9.5	9.6	9.6	9.7	9.7	9.7	9.8	9.8	9.8	9.8	9.8	9.9	9.9
1.94	9.6	9.6	9.7	9.8	9.8	9.8	9.9	9.9	9.9	10.0	10.0	10.0	10.0	10.1	10.1
1.96	9.7	9.8	9.9	9.9	10.0	10.0	10.1	10.1	10.1	10.1	10.2	10.2	10.2	10.2	10.2
1.98	9.9	10.0	10.0	10.1	10.2	10.2	10.2	10.3	10.3	10.3	10.3	10.4	10.4	10.4	10.4
2.00	10.1	10.1	10.2	10.3	10.3	10.4	10.4	10.5	10.5	10.5	10.5	10.5	10.6	10.6	10.6

Auxiliary Table 6. Submerged Flow Calibrations for 12 in x 3 ft Cutthroat Flume (Values Listed Are Discharged in cfs)

h_a, ft	$h_a - h_b$, ft																			
	.02	.04	.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40
.02	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.04	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.06	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.08	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.10	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.12	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.14	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.16	.1	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
.18	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
.20	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
.22	.2	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.24	.2	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.26	.3	.3	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.28	.3	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.30	.3	.4	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5
.32	.4	.5	.5	.5	.5	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6
.34	.4	.5	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6
.36	.5	.6	.6	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7
.38	.5	.6	.7	.7	.7	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8
.40	.5	.7	.7	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8
.42	.6	.7	.8	.8	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9
.44	.6	.8	.9	.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.46	.7	.8	.9	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
.48	.7	.9	1.0	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
.50	.8	.9	1.1	1.1	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
.52	.8	1.0	1.1	1.2	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
.54	.8	1.1	1.2	1.3	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
.56	.9	1.1	1.3	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
.58	.9	1.2	1.3	1.4	1.5	1.6	1.6	1.6	1.6	1.6	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
.60	1.0	1.2	1.4	1.5	1.6	1.7	1.7	1.7	1.7	1.7	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
.62	1.0	1.3	1.5	1.6	1.7	1.7	1.8	1.8	1.8	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
.64	1.1	1.4	1.5	1.7	1.8	1.8	1.9	1.9	1.9	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
.66	1.1	1.4	1.6	1.8	1.9	1.9	2.0	2.0	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
.68	1.2	1.5	1.7	1.8	1.9	2.0	2.1	2.1	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
.70	1.3	1.5	1.8	1.9	2.0	2.1	2.2	2.2	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
.72	1.3	1.6	1.9	2.0	2.1	2.2	2.3	2.3	2.4	2.4	2.4	2.4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
.74	1.4	1.7	1.9	2.1	2.2	2.3	2.4	2.5	2.5	2.5	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
.76	1.4	1.8	2.0	2.2	2.3	2.4	2.5	2.6	2.6	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
.78	1.5	1.9	2.1	2.3	2.4	2.5	2.6	2.7	2.7	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
.80	1.5	1.9	2.2	2.4	2.5	2.6	2.7	2.8	2.9	2.9	2.9	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
.82	1.6	2.0	2.3	2.5	2.6	2.7	2.8	2.9	3.0	3.0	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
.84	1.6	2.1	2.4	2.6	2.7	2.9	3.0	3.0	3.1	3.2	3.2	3.2	3.2	3.2	3.3	3.3	3.3	3.3	3.3	3.3
.86	1.7	2.1	2.4	2.7	2.8	3.0	3.1	3.2	3.2	3.3	3.3	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
.88	1.8	2.2	2.5	2.8	2.9	3.1	3.2	3.3	3.4	3.4	3.5	3.5	3.5	3.5	3.5	3.6	3.6	3.6	3.6	3.6
.90	1.8	2.3	2.6	2.9	3.0	3.2	3.3	3.4	3.5	3.5	3.6	3.6	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
.92	1.9	2.4	2.7	3.0	3.1	3.3	3.4	3.5	3.6	3.7	3.7	3.8	3.8	3.8	3.8	3.8	3.9	3.9	3.9	3.9
.94	1.9	2.5	2.8	3.1	3.3	3.4	3.5	3.7	3.7	3.8	3.9	3.9	3.9	4.0	4.0	4.0	4.0	4.0	4.0	4.0
.96	2.0	2.5	2.9	3.2	3.4	3.5	3.7	3.8	3.9	3.9	4.0	4.1	4.1	4.1	4.1	4.1	4.2	4.2	4.2	4.2
.98	2.1	2.6	3.0	3.3	3.5	3.6	3.8	3.9	4.0	4.1	4.1	4.2	4.2	4.3	4.3	4.3	4.3	4.3	4.3	4.3
1.00	2.1	2.7	3.1	3.4	3.6	3.8	3.9	4.0	4.1	4.2	4.3	4.3	4.4	4.4	4.4	4.5	4.5	4.5	4.5	4.5

Auxiliary Table 6. (continued)

h_a, ft	$h_a - h_b$, ft .02	.04	.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40
1.02	2.2	2.8	3.2	3.5	3.7	3.9	4.0	4.2	4.3	4.4	4.4	4.5	4.5	4.6	4.6	4.6	4.6	4.7	4.7	4.7
1.04	2.3	2.9	3.3	3.6	3.8	4.0	4.2	4.3	4.4	4.5	4.6	4.6	4.7	4.7	4.8	4.8	4.8	4.8	4.8	4.8
1.06	2.3	2.9	3.4	3.7	3.9	4.1	4.3	4.4	4.6	4.7	4.7	4.8	4.9	4.9	4.9	5.0	5.0	5.0	5.0	5.0
1.08	2.4	3.0	3.5	3.8	4.0	4.2	4.4	4.6	4.7	4.8	4.9	5.0	5.0	5.1	5.1	5.1	5.1	5.1	5.2	5.2
1.10	2.5	3.1	3.6	3.9	4.2	4.4	4.6	4.7	4.8	4.9	5.0	5.1	5.2	5.2	5.3	5.3	5.3	5.3	5.3	5.4
1.12	2.5	3.2	3.7	4.0	4.3	4.5	4.7	4.8	5.0	5.1	5.2	5.3	5.3	5.4	5.4	5.5	5.5	5.5	5.5	5.5
1.14	2.6	3.3	3.8	4.1	4.4	4.6	4.8	5.0	5.1	5.2	5.3	5.4	5.5	5.6	5.6	5.6	5.7	5.7	5.7	5.7
1.16	2.7	3.4	3.9	4.2	4.5	4.8	5.0	5.1	5.3	5.4	5.5	5.6	5.7	5.7	5.8	5.8	5.8	5.9	5.9	5.9
1.18	2.7	3.5	4.0	4.3	4.6	4.9	5.1	5.3	5.4	5.5	5.7	5.7	5.8	5.9	5.9	6.0	6.0	6.0	6.1	6.1
1.20	2.8	3.5	4.1	4.4	4.8	5.0	5.2	5.4	5.6	5.7	5.8	5.9	6.0	6.1	6.1	6.2	6.2	6.2	6.2	6.2
1.22	2.9	3.5	4.2	4.6	4.9	5.1	5.4	5.6	5.7	5.9	6.0	6.1	6.2	6.2	6.3	6.3	6.4	6.4	6.4	6.4
1.24	2.9	3.7	4.3	4.7	5.0	5.3	5.5	5.7	5.9	6.0	6.1	6.2	6.3	6.4	6.5	6.5	6.6	6.6	6.6	6.6
1.26	3.0	3.8	4.4	4.8	5.1	5.4	5.6	5.8	6.0	6.2	6.3	6.4	6.5	6.6	6.6	6.7	6.7	6.8	6.8	6.8
1.28	3.1	3.9	4.5	4.9	5.3	5.5	5.8	6.0	6.2	6.3	6.5	6.6	6.7	6.8	6.8	6.9	6.9	7.0	7.0	7.0
1.30	3.2	4.0	4.6	5.0	5.4	5.7	5.9	6.1	6.3	6.5	6.6	6.7	6.8	6.9	7.0	7.1	7.1	7.2	7.2	7.2
1.32	3.2	4.1	4.7	5.1	5.5	5.8	6.1	6.3	6.5	6.6	6.8	6.9	7.0	7.1	7.2	7.3	7.3	7.4	7.4	7.4
1.34	3.3	4.2	4.8	5.3	5.6	5.9	6.2	6.4	6.6	6.8	7.0	7.1	7.2	7.3	7.4	7.4	7.5	7.6	7.6	7.6
1.36	3.4	4.3	4.9	5.4	5.8	6.1	6.4	6.6	6.8	7.0	7.1	7.3	7.4	7.5	7.6	7.6	7.7	7.8	7.8	7.8
1.38	3.5	4.4	5.0	5.5	5.9	6.2	6.5	6.7	7.0	7.1	7.3	7.4	7.6	7.7	7.8	7.8	7.9	7.9	8.0	8.0
1.40	3.5	4.5	5.1	5.6	6.0	6.4	6.7	6.9	7.1	7.3	7.5	7.6	7.7	7.8	7.9	8.0	8.1	8.1	8.2	8.2
1.42	3.6	4.6	5.2	5.7	6.2	6.5	6.8	7.1	7.3	7.5	7.6	7.8	7.9	8.0	8.1	8.2	8.3	8.3	8.4	8.4
1.44	3.7	4.7	5.4	5.9	6.3	6.6	7.0	7.2	7.4	7.6	7.8	8.0	8.1	8.2	8.3	8.4	8.5	8.6	8.6	8.7
1.46	3.8	4.8	5.5	6.0	6.4	6.8	7.1	7.4	7.6	7.8	8.0	8.1	8.3	8.4	8.5	8.6	8.7	8.8	8.8	8.9
1.48	3.8	4.9	5.6	6.1	6.6	6.9	7.3	7.5	7.8	8.0	8.2	8.3	8.5	8.6	8.7	8.8	8.9	9.0	9.0	9.1
1.50	3.9	5.0	5.7	6.3	6.7	7.1	7.4	7.7	7.9	8.2	8.3	8.5	8.7	8.8	8.9	9.0	9.1	9.2	9.2	9.3
1.52	4.0	5.1	5.8	6.4	6.8	7.2	7.6	7.9	8.1	8.3	8.5	8.7	8.8	9.0	9.1	9.2	9.3	9.4	9.4	9.5
1.54	4.1	5.2	5.9	6.5	7.0	7.4	7.7	8.0	8.3	8.5	8.7	8.9	9.0	9.2	9.3	9.4	9.5	9.6	9.7	9.7
1.56	4.1	5.3	6.0	6.6	7.1	7.5	7.9	8.2	8.4	8.7	8.9	9.1	9.2	9.4	9.5	9.6	9.7	9.8	9.9	9.9
1.58	4.2	5.4	6.2	6.8	7.3	7.7	8.0	8.3	8.6	8.9	9.1	9.3	9.4	9.6	9.7	9.8	9.9	10.0	10.1	10.2
1.60	4.3	5.5	6.3	6.9	7.4	7.8	8.2	8.5	8.8	9.0	9.2	9.4	9.6	9.8	9.9	10.0	10.1	10.2	10.3	10.4
1.62	4.4	5.6	6.4	7.0	7.5	8.0	8.3	8.7	9.0	9.2	9.4	9.6	9.8	10.0	10.1	10.2	10.3	10.4	10.5	10.6
1.64	4.5	5.7	6.5	7.2	7.7	8.1	8.5	8.8	9.1	9.4	9.6	9.8	10.0	10.2	10.3	10.4	10.6	10.7	10.8	10.8
1.66	4.5	5.8	6.6	7.3	7.8	8.3	8.7	9.0	9.3	9.6	9.8	10.0	10.2	10.4	10.5	10.7	10.8	10.9	11.0	11.1
1.68	4.6	5.9	6.8	7.4	8.0	8.4	8.8	9.2	9.5	9.8	10.0	10.2	10.4	10.6	10.7	10.9	11.0	11.1	11.2	11.3
1.70	4.7	6.0	6.9	7.6	8.1	8.6	9.0	9.3	9.7	9.9	10.2	10.4	10.6	10.8	10.9	11.1	11.2	11.3	11.4	11.5
1.72	4.8	6.1	7.0	7.7	8.3	8.7	9.2	9.5	9.8	10.1	10.4	10.6	10.8	11.0	11.2	11.3	11.4	11.5	11.7	11.7
1.74	4.9	6.2	7.1	7.8	8.4	8.9	9.3	9.7	10.0	10.3	10.6	10.8	11.0	11.2	11.4	11.5	11.7	11.8	11.9	12.0
1.76	5.0	6.3	7.2	8.0	8.6	9.1	9.5	9.9	10.2	10.5	10.8	11.0	11.2	11.4	11.6	11.7	11.9	12.0	12.1	12.2
1.78	5.0	6.4	7.4	8.1	8.7	9.2	9.7	10.0	10.4	10.7	11.0	11.2	11.4	11.6	11.8	12.0	12.1	12.2	12.3	12.4
1.80	5.1	6.5	7.5	8.2	8.9	9.4	9.8	10.2	10.6	10.9	11.2	11.4	11.6	11.8	12.0	12.2	12.3	12.5	12.6	12.7
1.82	5.2	6.6	7.6	8.4	9.0	9.5	10.0	10.4	10.7	11.1	11.3	11.6	11.8	12.0	12.2	12.4	12.5	12.7	12.8	12.9
1.84	5.3	6.8	7.7	8.5	9.2	9.7	10.2	10.6	10.9	11.3	11.5	11.8	12.0	12.3	12.4	12.6	12.8	12.9	13.0	13.2
1.86	5.4	6.9	7.9	8.7	9.3	9.9	10.3	10.7	11.1	11.4	11.7	12.0	12.3	12.5	12.7	12.8	13.0	13.2	13.3	13.4
1.88	5.5	7.0	8.0	8.8	9.5	10.0	10.5	10.9	11.3	11.6	11.9	12.2	12.5	12.7	12.9	13.1	13.2	13.4	13.5	13.6
1.90	5.6	7.1	8.1	8.9	9.6	10.2	10.7	11.1	11.5	11.8	12.1	12.4	12.7	12.9	13.1	13.3	13.5	13.6	13.8	13.9
1.92	5.6	7.2	8.3	9.1	9.8	10.3	10.8	11.3	11.7	12.0	12.3	12.6	12.9	13.1	13.3	13.5	13.7	13.9	14.0	14.1
1.94	5.7	7.3	8.4	9.2	9.9	10.5	11.0	11.5	11.9	12.2	12.5	12.8	13.1	13.3	13.6	13.8	13.9	14.1	14.2	14.4
1.96	5.8	7.4	8.5	9.4	10.1	10.7	11.2	11.7	12.1	12.4	12.8	13.0	13.3	13.6	13.8	14.0	14.2	14.3	14.5	14.6
1.98	5.9	7.5	8.7	9.5	10.2	10.8	11.4	11.8	12.3	12.6	13.0	13.3	13.5	13.8	14.0	14.2	14.4	14.6	14.7	14.9
2.00	6.0	7.6	8.8	9.7	10.4	11.0	11.6	12.0	12.4	12.8	13.2	13.5	13.8	14.0	14.2	14.4	14.6	14.8	15.0	15.1

Auxiliary Table 6. (continued)

h_a, ft	$h_a - h_b$, ft														
	.42	.44	.46	.48	.50	.52	.54	.56	.58	.60	.62	.64	.66	.68	.70
1.04	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8
1.06	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
1.08	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
1.10	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
1.12	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
1.14	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
1.16	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9
1.18	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
1.20	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
1.22	6.4	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
1.24	6.6	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7
1.26	6.8	6.8	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9
1.28	7.0	7.0	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
1.30	7.2	7.2	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3
1.32	7.4	7.4	7.4	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
1.34	7.6	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
1.36	7.8	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9
1.38	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1
1.40	8.3	8.3	8.3	8.3	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4
1.42	8.5	8.5	8.5	8.5	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6
1.44	8.7	8.7	8.7	8.7	8.7	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8
1.46	8.9	8.9	8.9	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
1.48	9.1	9.1	9.2	9.2	9.2	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3
1.50	9.3	9.4	9.4	9.4	9.4	9.4	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
1.52	9.6	9.6	9.6	9.6	9.6	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7
1.54	9.8	9.8	9.8	9.9	9.9	9.9	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
1.56	10.0	10.0	10.1	10.1	10.1	10.1	10.1	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
1.58	10.2	10.3	10.3	10.3	10.3	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4
1.60	10.4	10.5	10.5	10.6	10.6	10.6	10.6	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7
1.62	10.7	10.7	10.8	10.8	10.8	10.8	10.9	10.9	10.9	10.9	10.9	10.9	10.9	10.9	10.9
1.64	10.9	11.0	11.0	11.0	11.1	11.1	11.1	11.1	11.2	11.2	11.2	11.2	11.2	11.2	11.2
1.66	11.1	11.2	11.2	11.3	11.3	11.3	11.3	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4
1.68	11.4	11.4	11.5	11.5	11.6	11.6	11.6	11.6	11.6	11.7	11.7	11.7	11.7	11.7	11.7
1.70	11.6	11.7	11.7	11.8	11.8	11.8	11.8	11.9	11.9	11.9	11.9	11.9	11.9	11.9	11.9
1.72	11.8	11.9	12.0	12.0	12.0	12.1	12.1	12.1	12.1	12.1	12.2	12.2	12.2	12.2	12.2
1.74	12.1	12.1	12.2	12.2	12.3	12.3	12.3	12.4	12.4	12.4	12.5	12.5	12.5	12.5	12.5
1.76	12.3	12.4	12.4	12.5	12.5	12.6	12.6	12.6	12.6	12.6	12.7	12.7	12.7	12.7	12.7
1.78	12.5	12.6	12.7	12.7	12.8	12.8	12.9	12.9	12.9	12.9	12.9	13.0	13.0	13.0	13.0
1.80	12.8	12.9	12.9	13.0	13.0	13.1	13.1	13.1	13.2	13.2	13.2	13.3	13.3	13.3	13.3
1.82	13.0	13.1	13.2	13.2	13.3	13.3	13.4	13.4	13.4	13.4	13.4	13.5	13.5	13.5	13.5
1.84	13.3	13.3	13.4	13.5	13.6	13.6	13.6	13.7	13.7	13.7	13.7	13.7	13.8	13.8	13.8
1.86	13.5	13.6	13.7	13.7	13.8	13.9	13.9	13.9	14.0	14.0	14.0	14.0	14.1	14.1	14.1
1.88	13.7	13.8	13.9	14.0	14.1	14.1	14.2	14.2	14.2	14.3	14.3	14.3	14.4	14.4	14.4
1.90	14.0	14.1	14.2	14.3	14.3	14.[illegible]	14.4	14.5	14.5	14.5	14.5	14.6	14.6	14.7	14.7
1.92	14.2	14.3	14.4	14.5	14.6	14.7	14.7	14.7	14.8	14.8	14.8	14.8	14.8	14.9	14.9
1.94	14.5	14.5	14.7	14.8	14.9	14.9	15.0	15.0	15.1	15.1	15.1	15.1	15.1	15.2	15.2
1.96	14.7	14.9	15.0	15.0	15.1	15.2	15.2	15.3	15.3	15.4	15.4	15.4	15.4	15.4	15.5
1.98	15.0	15.1	15.2	15.3	15.4	15.5	15.5	15.6	15.6	15.6	15.7	15.7	15.7	15.7	15.8
2.00	15.3	15.4	15.5	15.6	15.7	15.7	15.8	15.8	15.9	15.9	16.0	16.0	16.0	16.0	16.1

Auxiliary Table 7. Submerged Flow Calibrations for 16 in x 3 ft Cutthroat Flume (Values Listed Are Discharged in cfs)

h_a, ft	$h_a - h_b$, ft																			
	.02	.04	.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40
.02	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.04	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.06	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
.08	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.10	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.12	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
.14	.1	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
.16	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2	.2
.18	.2	.2	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.20	.2	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3	.3
.22	.3	.3	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.24	.3	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4
.26	.4	.4	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5
.28	.4	.5	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6
.30	.5	.5	.6	.6	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7
.32	.5	.5	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7
.34	.6	.7	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8
.36	.6	.8	.8	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9	.9
.38	.7	.8	.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
.40	.7	.9	1.0	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
.42	.8	1.0	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
.44	.8	1.0	1.1	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
.46	.9	1.1	1.2	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
.48	1.0	1.2	1.3	1.4	1.5	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
.50	1.0	1.3	1.4	1.5	1.6	1.6	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
.52	1.1	1.3	1.5	1.6	1.7	1.7	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
.54	1.1	1.4	1.6	1.7	1.8	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
.56	1.2	1.5	1.7	1.8	1.9	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
.58	1.3	1.5	1.8	1.9	2.0	2.1	2.1	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
.60	1.3	1.7	1.9	2.0	2.1	2.2	2.3	2.3	2.3	2.3	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
.62	1.4	1.7	2.0	2.1	2.2	2.3	2.4	2.4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
.64	1.5	1.8	2.1	2.2	2.4	2.5	2.5	2.6	2.6	2.6	2.6	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
.66	1.5	1.9	2.2	2.4	2.5	2.6	2.7	2.7	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
.68	1.6	2.0	2.3	2.5	2.6	2.7	2.8	2.9	2.9	2.9	2.9	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
.70	1.7	2.1	2.4	2.6	2.7	2.8	2.9	3.0	3.0	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
.72	1.7	2.2	2.5	2.7	2.9	3.0	3.1	3.1	3.2	3.2	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
.74	1.8	2.3	2.6	2.8	3.0	3.1	3.2	3.3	3.4	3.4	3.4	3.4	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
.76	1.9	2.4	2.7	2.9	3.1	3.3	3.4	3.4	3.5	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
.78	2.0	2.5	2.8	3.1	3.2	3.4	3.5	3.6	3.7	3.7	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8
.80	2.0	2.6	2.9	3.2	3.4	3.5	3.7	3.8	3.8	3.9	3.9	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
.82	2.1	2.7	3.0	3.3	3.5	3.7	3.8	3.9	4.0	4.1	4.1	4.1	4.1	4.2	4.2	4.2	4.2	4.2	4.2	4.2
.84	2.2	2.8	3.2	3.4	3.7	3.8	4.0	4.1	4.2	4.2	4.3	4.3	4.3	4.3	4.4	4.4	4.4	4.4	4.4	4.4
.86	2.3	2.9	3.3	3.6	3.8	4.0	4.1	4.2	4.3	4.4	4.5	4.5	4.5	4.5	4.5	4.6	4.6	4.6	4.6	4.6
.88	2.4	3.0	3.4	3.7	3.9	4.1	4.3	4.4	4.5	4.6	4.6	4.7	4.7	4.7	4.7	4.8	4.8	4.8	4.8	4.8
.90	2.4	3.1	3.5	3.8	4.1	4.3	4.4	4.6	4.7	4.7	4.8	4.9	4.9	4.9	4.9	5.0	5.0	5.0	5.0	5.0
.92	2.5	3.2	3.6	4.0	4.2	4.4	4.6	4.7	4.8	4.9	5.0	5.1	5.1	5.1	5.1	5.1	5.2	5.2	5.2	5.2
.94	2.6	3.3	3.8	4.1	4.4	4.6	4.7	4.9	5.0	5.1	5.2	5.2	5.3	5.3	5.3	5.3	5.4	5.4	5.4	5.4
.96	2.7	3.4	3.9	4.2	4.5	4.7	4.9	5.1	5.2	5.3	5.4	5.4	5.5	5.5	5.5	5.6	5.6	5.6	5.6	5.6
.98	2.8	3.5	4.0	4.4	4.7	4.9	5.1	5.2	5.4	5.5	5.6	5.6	5.7	5.7	5.8	5.8	5.8	5.8	5.8	5.8
1.00	2.9	3.6	4.1	4.5	4.8	5.0	5.2	5.4	5.5	5.7	5.8	5.8	5.9	5.9	6.0	6.0	6.0	6.0	6.0	6.0

Auxiliary Table 7. (continued)

h_a, ft	$h_a - h_b$, ft																			
	.02	.04	.06	.08	.10	.12	.14	.16	.18	.20	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40
1.02	2.9	3.7	4.2	4.6	5.0	5.2	5.4	5.6	5.7	5.8	5.9	6.0	6.1	6.1	6.2	6.2	6.2	6.3	6.3	6.3
1.04	3.0	3.8	4.4	4.8	5.1	5.4	5.6	5.8	5.9	6.0	6.1	6.2	6.3	6.4	6.4	6.4	6.4	6.4	6.5	6.5
1.06	3.1	4.0	4.5	4.9	5.3	5.5	5.8	5.9	6.1	6.2	6.3	6.4	6.5	6.6	6.6	6.6	6.7	6.7	6.7	6.7
1.08	3.2	4.1	4.6	5.1	5.4	5.7	5.9	6.1	6.3	6.4	6.5	6.6	6.7	6.8	6.8	6.9	6.9	6.9	6.9	6.9
1.10	3.3	4.2	4.8	5.2	5.5	5.9	6.1	6.3	6.5	6.6	6.7	6.8	5.9	7.0	7.0	7.1	7.1	7.1	7.1	7.2
1.12	3.4	4.3	4.9	5.4	5.7	6.0	6.3	6.5	6.7	6.8	6.9	7.1	7.1	7.2	7.3	7.3	7.3	7.4	7.4	7.4
1.14	3.5	4.4	5.0	5.5	5.9	6.2	6.5	6.7	6.9	7.0	7.2	7.3	7.4	7.4	7.5	7.5	7.6	7.6	7.6	7.7
1.16	3.6	4.5	5.2	5.7	6.0	6.4	6.6	6.9	7.1	7.2	7.4	7.5	7.6	7.7	7.7	7.8	7.8	7.8	7.9	7.9
1.18	3.7	4.6	5.3	5.8	6.2	6.5	6.8	7.1	7.3	7.4	7.6	7.7	7.8	7.9	8.0	8.0	8.1	8.1	8.1	8.1
1.20	3.8	4.8	5.4	6.0	6.4	6.7	7.0	7.2	7.5	7.6	7.8	7.9	8.0	8.1	8.2	8.3	8.3	8.3	8.4	8.4
1.22	3.9	4.9	5.6	6.1	6.5	6.9	7.2	7.4	7.7	7.8	8.0	8.1	8.3	8.3	8.4	8.5	8.5	8.6	8.6	8.6
1.24	3.9	5.0	5.7	6.3	6.7	7.1	7.4	7.6	7.9	8.0	8.2	8.4	8.5	8.6	8.7	8.7	8.8	8.8	8.9	8.9
1.26	4.0	5.1	5.9	6.4	6.9	7.2	7.5	7.8	8.1	8.3	8.4	8.6	8.7	8.8	8.9	9.0	9.0	9.1	9.1	9.1
1.28	4.1	5.2	6.0	6.5	7.0	7.4	7.7	8.0	8.3	8.5	8.7	8.8	8.9	9.1	9.1	9.2	9.3	9.3	9.4	9.4
1.30	4.2	5.4	6.1	6.7	7.2	7.6	7.9	8.2	8.5	8.7	8.9	9.0	9.2	9.3	9.4	9.5	9.5	9.6	9.6	9.7
1.32	4.3	5.5	6.3	6.9	7.4	7.8	8.1	8.4	8.7	8.9	9.1	9.3	9.4	9.5	9.6	9.7	9.8	9.9	9.9	9.9
1.34	4.4	5.6	6.4	7.1	7.6	8.0	8.3	8.6	8.9	9.1	9.3	9.5	9.6	9.8	9.9	10.0	10.1	10.1	10.2	10.2
1.36	4.5	5.7	6.6	7.2	7.7	8.2	8.5	8.8	9.1	9.3	9.5	9.7	9.9	10.0	10.1	10.2	10.3	10.4	10.4	10.5
1.38	4.6	5.9	6.7	7.4	7.9	8.3	8.7	9.0	9.3	9.6	9.8	10.0	10.1	10.3	10.4	10.5	10.6	10.7	10.7	10.8
1.40	4.7	6.0	6.9	7.5	8.1	8.5	8.9	9.2	9.5	9.8	10.0	10.2	10.4	10.5	10.6	10.7	10.8	10.9	11.0	11.0
1.42	4.8	6.1	7.0	7.7	8.3	8.7	9.1	9.5	9.7	10.0	10.2	10.4	10.6	10.8	10.9	11.0	11.1	11.2	11.3	11.3
1.44	4.9	6.3	7.2	7.9	8.4	8.9	9.3	9.7	10.0	10.2	10.5	10.7	10.9	11.0	11.2	11.3	11.4	11.5	11.5	11.6
1.46	5.0	6.4	7.3	8.0	8.5	9.1	9.5	9.9	10.2	10.5	10.7	10.9	11.1	11.3	11.4	11.5	11.6	11.7	11.8	11.9
1.48	5.1	6.5	7.5	8.2	8.8	9.3	9.7	10.1	10.4	10.7	10.9	11.2	11.4	11.5	11.7	11.8	11.9	12.0	12.1	12.2
1.50	5.2	6.7	7.6	8.4	9.0	9.5	9.9	10.3	10.6	10.9	11.2	11.4	11.6	11.8	11.9	12.1	12.2	12.3	12.4	12.4
1.52	5.3	6.8	7.8	8.5	9.2	9.7	10.1	10.5	10.9	11.2	11.4	11.7	11.9	12.0	12.2	12.3	12.5	12.6	12.7	12.7
1.54	5.5	6.9	7.9	8.7	9.4	9.9	10.3	10.7	11.1	11.4	11.7	11.9	12.1	12.3	12.5	12.6	12.7	12.9	12.9	13.0
1.56	5.6	7.1	8.1	8.9	9.5	10.1	10.5	11.0	11.3	11.6	11.9	12.1	12.4	12.6	12.7	12.9	13.0	13.1	13.2	13.3
1.58	5.7	7.2	8.3	9.1	9.7	10.3	10.8	11.2	11.5	11.9	12.1	12.4	12.6	12.8	13.0	13.2	13.3	13.4	13.5	13.6
1.60	5.8	7.3	8.4	9.2	9.9	10.5	11.0	11.4	11.8	12.1	12.4	12.7	12.9	13.1	13.3	13.4	13.6	13.7	13.8	13.9
1.62	5.9	7.5	8.5	9.4	10.1	10.7	11.2	11.6	12.0	12.3	12.6	12.9	13.1	13.4	13.5	13.7	13.9	14.0	14.1	14.2
1.64	6.0	7.6	8.7	9.6	10.3	10.9	11.4	11.8	12.2	12.5	12.9	13.2	13.4	13.6	13.8	14.0	14.2	14.3	14.4	14.5
1.66	6.1	7.8	8.9	9.8	10.5	11.1	11.6	12.1	12.5	12.8	13.1	13.4	13.7	13.9	14.1	14.3	14.4	14.6	14.7	14.8
1.68	6.2	7.9	9.1	9.9	10.7	11.3	11.8	12.3	12.7	13.1	13.4	13.7	13.9	14.2	14.4	14.6	14.7	14.9	15.0	15.1
1.70	6.3	8.0	9.2	10.1	10.9	11.5	12.1	12.5	12.9	13.3	13.6	13.9	14.2	14.4	14.7	14.9	15.0	15.2	15.3	15.4
1.72	6.4	8.2	9.4	10.3	11.1	11.7	12.3	12.8	13.2	13.6	13.9	14.2	14.5	14.7	14.9	15.1	15.3	15.5	15.6	15.7
1.74	6.5	8.3	9.5	10.5	11.3	11.9	12.5	13.0	13.4	13.8	14.2	14.5	14.8	15.0	15.2	15.4	15.6	15.8	15.9	16.0
1.76	6.7	8.5	9.7	10.7	11.5	12.1	12.7	13.2	13.7	14.1	14.4	14.7	15.0	15.3	15.5	15.7	15.9	16.1	16.2	16.4
1.78	6.8	8.6	9.9	10.9	11.7	12.3	12.9	13.5	13.9	14.3	14.7	15.0	15.3	15.6	15.8	16.0	16.2	16.4	16.5	16.7
1.80	6.9	8.8	10.0	11.0	11.9	12.6	13.2	13.7	14.2	14.6	14.9	15.3	15.6	15.8	16.1	16.3	16.5	16.7	16.9	17.0
1.82	7.0	8.9	10.2	11.2	12.1	12.8	13.4	13.9	14.4	14.8	15.2	15.5	15.9	16.1	16.4	16.6	16.8	17.0	17.2	17.3
1.84	7.1	9.0	10.4	11.4	12.3	13.0	13.6	14.2	14.6	15.1	15.5	15.8	16.1	16.4	16.7	16.9	17.1	17.3	17.5	17.6
1.86	7.2	9.2	10.5	11.6	12.5	13.2	13.8	14.4	14.9	15.3	15.7	16.1	16.4	16.7	17.0	17.2	17.4	17.6	17.8	18.0
1.88	7.3	9.3	10.7	11.8	12.7	13.4	14.1	14.6	15.1	15.6	16.0	16.4	16.7	17.0	17.3	17.5	17.7	17.9	18.1	18.3
1.90	7.5	9.5	10.9	12.0	12.9	13.6	14.3	14.9	15.4	15.9	16.3	16.6	17.0	17.3	17.5	17.8	18.0	18.3	18.4	18.6
1.92	7.6	9.6	11.1	12.2	13.1	13.9	14.5	15.1	15.7	16.1	16.5	16.9	17.3	17.6	17.9	18.1	18.4	18.6	18.8	18.9
1.94	7.7	9.8	11.2	12.4	13.3	14.1	14.8	15.4	15.9	16.4	16.8	17.2	17.6	17.9	18.2	18.4	18.7	18.9	19.1	19.3
1.96	7.8	9.9	11.4	12.6	13.5	14.3	15.0	15.6	16.2	16.6	17.1	17.5	17.8	18.2	18.5	18.7	19.0	19.2	19.4	19.6
1.98	7.9	10.1	11.5	12.8	13.7	14.5	15.2	15.9	16.4	16.9	17.4	17.8	18.1	18.5	18.8	19.0	19.3	19.5	19.7	19.9
2.00	8.0	10.2	11.8	13.0	13.9	14.8	15.5	16.1	16.7	17.2	17.6	18.1	18.4	18.8	19.1	19.4	19.6	19.9	20.1	20.3

Auxiliary Table 7. (continued)

h_a, ft	$h_a - h_b$, ft														
	.42	.44	.46	.48	.50	.52	.54	.56	.58	.60	.62	.64	.66	.68	.70
1.04	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
1.06	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7	6.7
1.08	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9
1.10	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
1.12	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4
1.14	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
1.16	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9
1.18	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2
1.20	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4
1.22	8.6	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
1.24	8.9	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
1.26	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2
1.28	9.4	9.4	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
1.30	9.7	9.7	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
1.32	10.0	10.0	10.0	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1
1.34	10.2	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3	10.3
1.36	10.5	10.5	10.5	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6
1.38	10.8	10.8	10.8	10.8	10.9	10.9	10.9	10.9	10.9	10.9	10.9	10.9	10.9	10.9	10.9
1.40	11.1	11.1	11.1	11.1	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2
1.42	11.4	11.4	11.4	11.4	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
1.44	11.6	11.7	11.7	11.7	11.7	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8
1.46	11.9	12.0	12.0	12.0	12.0	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1
1.48	12.2	12.3	12.3	12.3	12.3	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4
1.50	12.5	12.5	12.5	12.5	12.6	12.6	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7
1.52	12.8	12.8	12.9	12.9	12.9	12.9	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
1.54	13.1	13.1	13.2	13.2	13.2	13.2	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3
1.56	13.4	13.4	13.5	13.5	13.5	13.6	13.6	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7
1.58	13.7	13.8	13.8	13.8	13.9	13.9	13.9	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
1.60	14.0	14.1	14.1	14.2	14.2	14.2	14.2	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3
1.62	14.3	14.4	14.4	14.5	14.5	14.5	14.5	14.5	14.6	14.6	14.5	14.6	14.6	14.6	14.6
1.64	14.6	14.7	14.7	14.8	14.8	14.9	14.9	14.9	15.0	15.0	15.0	15.0	15.0	15.0	15.0
1.66	14.9	15.0	15.1	15.1	15.2	15.2	15.2	15.2	15.2	15.3	15.3	15.3	15.3	15.3	15.3
1.68	15.2	15.3	15.4	15.4	15.5	15.5	15.5	15.5	15.6	15.7	15.7	15.7	15.7	15.7	15.7
1.70	15.5	15.6	15.7	15.8	15.8	15.8	15.9	15.9	15.9	16.0	16.0	16.0	16.0	16.0	16.0
1.72	15.8	15.9	16.0	16.1	16.1	16.2	16.2	16.2	16.2	16.2	16.4	16.4	16.4	16.4	16.4
1.74	16.2	16.3	16.3	16.4	16.5	16.5	16.5	16.6	16.6	16.6	16.7	16.7	16.7	16.7	16.7
1.76	16.5	16.6	16.7	16.7	16.8	16.9	16.9	16.9	16.9	16.9	17.1	17.1	17.1	17.1	17.1
1.78	16.8	16.9	17.0	17.1	17.1	17.2	17.2	17.3	17.3	17.3	17.3	17.4	17.4	17.4	17.4
1.80	17.1	17.2	17.3	17.4	17.5	17.5	17.6	17.6	17.6	17.7	17.7	17.8	17.8	17.8	17.8
1.82	17.4	17.5	17.7	17.7	17.8	17.9	17.9	18.0	18.0	18.0	18.0	18.1	18.1	18.1	18.1
1.84	17.8	17.9	18.0	18.1	18.2	18.2	18.3	18.3	18.4	18.4	18.4	18.4	18.5	18.5	18.5
1.86	18.1	18.2	18.3	18.4	18.5	18.6	18.6	18.7	18.7	18.7	18.8	18.8	18.9	18.9	18.9
1.88	18.4	18.5	18.7	18.8	18.9	18.9	19.0	19.0	19.1	19.1	19.1	19.1	19.3	19.3	19.3
1.90	18.8	18.9	19.0	19.1	19.2	19.3	19.3	19.4	19.4	19.5	19.5	19.5	19.5	19.6	19.6
1.92	19.1	19.2	19.3	19.5	19.6	19.6	19.7	19.8	19.8	19.8	19.9	19.9	19.9	20.0	20.0
1.94	19.4	19.5	19.7	19.8	19.9	20.0	20.1	20.1	20.2	20.2	20.2	20.3	20.3	20.4	20.4
1.96	19.8	19.9	20.0	20.2	20.3	20.3	20.4	20.5	20.5	20.5	20.5	20.6	20.6	20.7	20.8
1.98	20.1	20.2	20.4	20.5	20.6	20.7	20.8	20.9	20.9	21.0	21.0	21.0	21.0	21.0	21.2
2.00	20.4	20.5	20.7	20.9	21.0	21.1	21.2	21.2	21.3	21.3	21.4	21.4	21.4	21.4	21.5

Auxiliary Table 8. Free Flow Calibrations for Selected Cutthroat Flumes, Metric Units (Values Listed Are Discharged in m /s)

h_a^*	10X90CM	20X90CM	30X90CM	20X180CM	40X180CM	60X180CM	30X270CM	60X270CM	100X270C
.005	.000	.000	.000	.000	.000	.000	.000	.000	.001
.010	.000	.000	.000	.000	.000	.001	.000	.001	.002
.015	.000	.000	.000	.000	.001	.001	.001	.002	.003
.020	.000	.001	.001	.001	.002	.002	.001	.003	.005
.025	.000	.001	.001	.001	.002	.003	.002	.004	.007
.030	.001	.001	.002	.001	.003	.005	.003	.005	.009
.035	.001	.002	.002	.002	.004	.006	.003	.007	.011
.040	.001	.002	.003	.002	.005	.007	.004	.008	.014
.045	.001	.003	.004	.003	.006	.009	.005	.010	.017
.050	.001	.003	.004	.003	.007	.011	.006	.012	.020
.055	.002	.004	.005	.004	.008	.012	.007	.014	.023
.060	.002	.004	.006	.005	.009	.014	.008	.016	.026
.065	.002	.005	.007	.005	.011	.016	.009	.018	.030
.070	.003	.006	.008	.006	.012	.018	.010	.020	.034
.075	.003	.006	.009	.007	.014	.021	.011	.022	.038
.080	.003	.007	.011	.007	.015	.023	.012	.025	.042
.085	.004	.008	.012	.008	.017	.025	.013	.027	.046
.090	.004	.009	.013	.009	.018	.028	.015	.030	.050
.095	.005	.010	.014	.010	.020	.030	.016	.032	.054
.100	.005	.011	.016	.011	.022	.033	.017	.035	.059
.105	.006	.012	.017	.012	.024	.036	.018	.038	.063
.110	.006	.013	.019	.013	.026	.039	.020	.040	.068
.115	.007	.014	.021	.013	.027	.042	.021	.043	.073
.120	.007	.015	.022	.014	.029	.045	.023	.046	.078
.125	.008	.016	.024	.015	.032	.048	.024	.049	.083
.130	.008	.018	.026	.016	.034	.051	.026	.052	.089
.135	.009	.019	.028	.018	.036	.054	.027	.056	.094
.140	.010	.020	.030	.019	.038	.057	.029	.059	.099
.145	.010	.022	.031	.020	.040	.061	.031	.062	.105
.150	.011	.023	.034	.021	.043	.064	.032	.066	.111
.155	.012	.024	.036	.022	.045	.068	.034	.069	.117
.160	.012	.026	.038	.023	.047	.072	.036	.073	.122
.165	.013	.027	.040	.024	.050	.075	.037	.076	.129
.170	.014	.029	.042	.026	.052	.079	.039	.080	.135
.175	.014	.031	.045	.027	.055	.083	.041	.083	.141
.180	.015	.032	.047	.028	.058	.087	.043	.087	.147
.185	.016	.034	.049	.030	.060	.091	.045	.091	.154
.190	.017	.036	.052	.031	.063	.095	.047	.095	.160
.195	.018	.037	.054	.032	.066	.099	.049	.099	.167
.200	.018	.039	.057	.034	.068	.104	.051	.103	.174
.205	.019	.041	.060	.035	.071	.108	.052	.107	.180
.210	.020	.043	.062	.036	.074	.112	.055	.111	.187
.215	.021	.045	.065	.038	.077	.117	.057	.115	.194
.220	.022	.047	.068	.039	.080	.121	.059	.119	.201
.225	.023	.049	.071	.041	.083	.126	.061	.123	.209
.230	.024	.051	.074	.042	.086	.130	.063	.128	.216
.235	.025	.053	.077	.044	.089	.135	.065	.132	.223
.240	.026	.055	.080	.045	.092	.140	.067	.137	.231
.245	.027	.057	.083	.047	.096	.145	.069	.141	.238
.250	.028	.059	.086	.049	.099	.150	.072	.146	.246

Auxiliary Table 8. (continued)

h_a^*	10X90CM	20X90CM	30X90CM
.255	.029	.061	.089
.260	.030	.063	.092
.265	.031	.066	.096
.270	.032	.068	.099
.275	.033	.070	.102
.280	.034	.073	.106
.285	.035	.075	.109
.290	.037	.078	.113
.295	.038	.080	.116
.300	.039	.082	.120
.305	.040	.085	.124
.310	.041	.088	.127
.315	.043	.090	.131
.320	.044	.093	.135
.325	.045	.096	.139
.330	.046	.098	.143
.335	.048	.101	.147
.340	.049	.104	.151
.345	.050	.107	.155
.350	.052	.110	.159
.355	.053	.112	.164
.360	.054	.115	.168
.365	.056	.118	.172
.370	.057	.121	.177
.375	.059	.124	.181
.380	.060	.127	.185
.385	.062	.131	.190
.390	.063	.134	.195
.395	.065	.137	.199
.400	.066	.140	.204
.405	.068	.143	.209
.410	.069	.147	.213
.415	.071	.150	.218
.420	.072	.153	.223
.425	.074	.157	.228
.430	.076	.160	.233
.435	.077	.163	.238
.440	.079	.167	.243
.445	.080	.170	.248
.450	.082	.174	.253
.455	***	***	***
.460	***	***	***
.465	***	***	***
.470	***	***	***
.475	***	***	***
.480	***	***	***
.485	***	***	***
.490	***	***	***
.495	***	***	***
.500	***	***	***

Auxiliary Table 9. Submerged Flow Calibration for 10 cm x 90 cm Cutthroat Flume (Values Listed Are Discharged in m /s)

h_a^* \ $h_a^*-h_b^*$	.005	.010	.015	.020	.025	.030	.035	.040	.045	.050	.055	.060	.065	.070	.075	.080	.085	.090	.095	.100
.005	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
.010	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
.015	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
.020	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
.025	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
.030	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
.035	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
.040	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
.045	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
.050	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
.055	.001	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002
.060	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002
.065	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002
.070	.002	.002	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003
.075	.002	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003
.080	.002	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003
.085	.003	.003	.003	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004
.090	.003	.003	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004
.095	.003	.004	.004	.004	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005
.100	.003	.004	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005
.105	.004	.004	.005	.005	.005	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006
.110	.004	.005	.005	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006
.115	.004	.005	.006	.006	.006	.006	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007
.120	.004	.005	.006	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007
.125	.005	.006	.006	.007	.007	.007	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008
.130	.005	.006	.007	.007	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008
.135	.005	.007	.007	.008	.008	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009
.140	.006	.007	.008	.008	.009	.009	.009	.009	.009	.010	.010	.010	.010	.010	.010	.010	.010	.010	.010	.010
.145	.006	.007	.008	.009	.009	.010	.010	.010	.010	.010	.010	.010	.010	.010	.010	.010	.010	.010	.010	.010
.150	.006	.008	.009	.009	.010	.010	.010	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011
.155	.006	.008	.009	.010	.010	.011	.011	.011	.011	.011	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012
.160	.007	.008	.010	.010	.011	.011	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012
.165	.007	.009	.010	.011	.011	.012	.012	.013	.013	.013	.013	.013	.013	.013	.013	.013	.013	.013	.013	.013
.170	.007	.009	.010	.011	.012	.013	.013	.013	.013	.013	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014
.175	.008	.010	.011	.012	.013	.013	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014
.180	.008	.010	.011	.012	.013	.014	.014	.015	.015	.015	.015	.015	.015	.015	.015	.015	.015	.015	.015	.015
.185	.008	.011	.012	.013	.014	.014	.015	.015	.015	.016	.016	.016	.016	.016	.016	.016	.016	.016	.016	.016
.190	.009	.011	.012	.014	.014	.015	.015	.016	.016	.016	.017	.017	.017	.017	.017	.017	.017	.017	.017	.017
.195	.009	.011	.013	.014	.015	.016	.016	.017	.017	.017	.017	.017	.017	.018	.018	.018	.018	.018	.018	.018
.200	.009	.012	.013	.015	.016	.016	.017	.017	.018	.018	.018	.018	.018	.018	.018	.018	.018	.018	.018	.018
.205	.010	.012	.014	.015	.016	.017	.018	.018	.018	.019	.019	.019	.019	.019	.019	.019	.019	.019	.019	.019
.210	.010	.013	.015	.016	.017	.018	.018	.019	.019	.019	.020	.020	.020	.020	.020	.020	.020	.020	.020	.020
.215	.011	.013	.015	.016	.017	.018	.019	.019	.020	.020	.021	.021	.021	.021	.021	.021	.021	.021	.021	.021
.220	.011	.014	.016	.017	.019	.019	.020	.020	.021	.021	.021	.022	.022	.022	.022	.022	.022	.022	.022	.022
.225	.011	.014	.016	.018	.019	.020	.020	.021	.021	.022	.022	.022	.023	.023	.023	.023	.023	.023	.023	.023
.230	.012	.015	.017	.018	.019	.020	.021	.022	.022	.023	.023	.023	.023	.024	.024	.024	.024	.024	.024	.024
.235	.012	.015	.017	.019	.020	.021	.022	.023	.023	.024	.024	.024	.024	.024	.025	.025	.025	.025	.025	.025
.240	.012	.016	.018	.019	.021	.022	.023	.023	.024	.024	.025	.025	.025	.025	.026	.026	.026	.026	.026	.026
.245	.013	.016	.018	.020	.021	.022	.023	.024	.025	.025	.026	.026	.026	.026	.026	.027	.027	.027	.027	.027
.250	.013	.017	.019	.021	.022	.023	.024	.025	.026	.026	.026	.027	.027	.027	.027	.028	.028	.028	.028	.028

Auxiliary Table 9. (continued)

h_a^*	$h_a^*-h_b^*$																			
	.005	.010	.015	.020	.025	.030	.035	.040	.045	.050	.055	.060	.065	.070	.075	.080	.085	.090	.095	.100
.255	.014	.017	.020	.021	.023	.024	.025	.026	.026	.027	.027	.028	.028	.028	.028	.029	.029	.029	.029	.029
.260	.014	.018	.020	.022	.024	.025	.026	.027	.027	.028	.028	.029	.029	.029	.029	.030	.030	.030	.030	.030
.265	.014	.018	.021	.023	.024	.025	.026	.027	.028	.029	.029	.030	.030	.030	.030	.031	.031	.031	.031	.031
.270	.015	.019	.021	.023	.025	.026	.027	.028	.029	.030	.030	.031	.031	.031	.031	.032	.032	.032	.032	.032
.275	.015	.019	.022	.024	.026	.027	.028	.029	.030	.031	.031	.032	.032	.032	.032	.033	.033	.033	.033	.033
.280	.016	.020	.023	.025	.026	.028	.029	.030	.031	.031	.032	.033	.033	.033	.034	.034	.034	.034	.034	.034
.285	.016	.020	.023	.025	.027	.029	.030	.031	.032	.032	.033	.033	.034	.034	.035	.035	.035	.035	.035	.035
.290	.016	.021	.024	.026	.028	.029	.031	.032	.033	.033	.034	.034	.035	.035	.036	.036	.036	.036	.036	.036
.295	.017	.021	.024	.027	.029	.030	.031	.032	.033	.034	.035	.035	.036	.036	.037	.037	.037	.037	.037	.037
.300	.017	.022	.025	.027	.029	.031	.032	.033	.034	.035	.036	.036	.037	.037	.038	.038	.038	.038	.039	.039
.305	.018	.022	.026	.028	.030	.032	.033	.034	.035	.036	.037	.037	.038	.038	.039	.039	.039	.040	.040	.040
.310	.018	.023	.026	.029	.031	.033	.034	.035	.036	.037	.038	.038	.039	.040	.040	.040	.041	.041	.041	.041
.315	.019	.024	.027	.030	.032	.033	.035	.036	.037	.038	.039	.040	.040	.041	.041	.041	.042	.042	.042	.042
.320	.019	.024	.028	.030	.032	.034	.036	.037	.038	.039	.040	.041	.041	.042	.042	.043	.043	.043	.043	.043
.325	.020	.025	.028	.031	.033	.035	.037	.038	.039	.040	.041	.042	.042	.043	.043	.044	.044	.044	.044	.045
.330	.020	.025	.029	.032	.034	.036	.037	.039	.040	.041	.042	.043	.043	.044	.044	.045	.045	.045	.046	.046
.335	.020	.026	.030	.032	.035	.037	.038	.040	.041	.042	.043	.044	.044	.045	.046	.046	.046	.047	.047	.047
.340	.021	.026	.030	.033	.036	.038	.039	.041	.042	.043	.044	.045	.046	.046	.047	.047	.048	.048	.048	.048
.345	.021	.027	.031	.034	.036	.038	.040	.042	.043	.044	.045	.046	.047	.047	.048	.048	.049	.049	.049	.050
.350	.022	.028	.032	.035	.037	.039	.041	.043	.044	.045	.046	.047	.048	.048	.049	.050	.050	.050	.051	.051
.355	.022	.028	.032	.035	.038	.040	.042	.044	.045	.046	.047	.048	.049	.050	.050	.051	.051	.052	.052	.052
.360	.023	.029	.033	.036	.039	.041	.043	.045	.046	.047	.048	.049	.050	.051	.051	.052	.052	.053	.053	.053
.365	.023	.029	.034	.037	.040	.042	.044	.045	.047	.048	.049	.050	.051	.052	.053	.053	.054	.054	.054	.055
.370	.024	.030	.034	.038	.041	.043	.045	.046	.048	.049	.050	.051	.052	.053	.054	.054	.055	.055	.056	.056
.375	.024	.031	.035	.039	.041	.044	.046	.047	.049	.050	.051	.053	.053	.054	.055	.056	.056	.057	.057	.057
.380	.025	.031	.036	.039	.042	.045	.047	.048	.050	.051	.053	.054	.055	.055	.056	.057	.057	.058	.058	.059
.385	.025	.032	.037	.040	.043	.046	.048	.049	.051	.052	.054	.055	.056	.057	.057	.058	.059	.059	.060	.060
.390	.026	.033	.037	.041	.044	.046	.049	.050	.052	.054	.055	.056	.057	.058	.059	.059	.060	.060	.061	.061
.395	.026	.033	.038	.042	.045	.047	.050	.051	.053	.055	.055	.057	.058	.059	.060	.061	.061	.062	.062	.063
.400	.027	.034	.039	.043	.046	.048	.051	.052	.054	.056	.057	.058	.059	.060	.061	.062	.063	.063	.064	.064
.405	.027	.034	.039	.043	.047	.049	.052	.054	.055	.057	.058	.059	.061	.062	.062	.063	.064	.064	.065	.065
.410	.028	.035	.040	.044	.047	.050	.053	.055	.056	.058	.059	.061	.062	.063	.064	.064	.065	.066	.066	.067
.415	.028	.036	.041	.045	.048	.051	.054	.056	.057	.059	.061	.062	.063	.064	.065	.066	.067	.067	.068	.068
.420	.029	.036	.042	.046	.049	.052	.055	.057	.059	.060	.062	.063	.064	.065	.066	.067	.068	.069	.069	.070
.425	.029	.037	.042	.047	.050	.053	.056	.058	.060	.061	.063	.064	.065	.067	.068	.068	.069	.070	.071	.071
.430	.030	.038	.043	.047	.051	.054	.057	.059	.061	.062	.064	.065	.067	.068	.069	.070	.071	.071	.072	.072
.435	.030	.038	.044	.048	.052	.055	.058	.060	.062	.064	.065	.067	.068	.069	.070	.071	.072	.073	.073	.074
.440	.031	.039	.045	.049	.053	.056	.059	.061	.063	.065	.066	.068	.069	.070	.071	.072	.073	.074	.075	.075
.445	.031	.040	.045	.050	.054	.057	.060	.062	.064	.066	.068	.069	.070	.072	.073	.074	.075	.075	.076	.077
.450	.032	.040	.046	.051	.055	.058	.061	.063	.065	.067	.069	.070	.072	.073	.074	.075	.076	.077	.078	.078

Auxiliary Table 9. (continued)

h_a^*	$h_a^*-h_b^*$										
	.105	.110	.115	.120	.125	.130	.135	.140	.145	.150	.155
.255	.029	.029	.029	.029	.029	.029	.029	.029	.029	.029	.029
.260	.030	.030	.030	.030	.030	.030	.030	.030	.030	.030	.030
.265	.031	.031	.031	.031	.031	.031	.031	.031	.031	.031	.031
.270	.032	.032	.032	.032	.032	.032	.032	.032	.032	.032	.032
.275	.033	.033	.033	.033	.033	.033	.033	.033	.033	.033	.033
.280	.034	.034	.034	.034	.034	.034	.034	.034	.034	.034	.034
.285	.035	.035	.035	.035	.035	.035	.035	.035	.035	.035	.035
.290	.037	.037	.037	.037	.037	.037	.037	.037	.037	.037	.037
.295	.038	.038	.038	.038	.038	.038	.038	.038	.038	.038	.038
.300	.039	.039	.039	.039	.039	.039	.039	.039	.039	.039	.039
.305	.040	.040	.040	.040	.040	.040	.040	.040	.040	.040	.040
.310	.041	.041	.041	.041	.041	.041	.041	.041	.041	.041	.041
.315	.042	.042	.043	.043	.043	.043	.043	.043	.043	.043	.043
.320	.043	.043	.044	.044	.044	.044	.044	.044	.044	.044	.044
.325	.045	.045	.045	.045	.045	.045	.045	.045	.045	.045	.045
.330	.046	.046	.046	.046	.046	.046	.046	.046	.046	.046	.046
.335	.047	.047	.047	.048	.048	.048	.048	.048	.048	.048	.048
.340	.048	.049	.049	.049	.049	.049	.049	.049	.049	.049	.049
.345	.050	.050	.050	.050	.050	.050	.050	.050	.050	.050	.050
.350	.051	.051	.051	.051	.052	.052	.052	.052	.052	.052	.052
.355	.052	.052	.053	.053	.053	.053	.053	.053	.053	.053	.053
.360	.054	.054	.054	.054	.054	.054	.054	.054	.054	.054	.054
.365	.055	.055	.055	.055	.055	.056	.056	.056	.056	.056	.056
.370	.056	.056	.057	.057	.057	.057	.057	.057	.057	.057	.057
.375	.058	.058	.058	.058	.058	.058	.059	.059	.059	.059	.059
.380	.059	.059	.059	.059	.060	.060	.060	.060	.060	.060	.060
.385	.060	.061	.061	.061	.061	.061	.062	.062	.062	.062	.062
.390	.062	.062	.062	.062	.062	.062	.063	.063	.063	.063	.063
.395	.063	.063	.064	.064	.064	.064	.064	.065	.065	.065	.065
.400	.064	.065	.065	.065	.065	.065	.065	.066	.066	.066	.066
.405	.066	.066	.066	.067	.067	.067	.067	.067	.068	.068	.068
.410	.067	.068	.068	.068	.068	.068	.068	.069	.069	.069	.069
.415	.069	.069	.069	.070	.070	.070	.070	.070	.070	.071	.071
.420	.070	.070	.071	.071	.071	.071	.072	.072	.072	.072	.072
.425	.072	.072	.072	.073	.073	.073	.073	.073	.073	.074	.074
.430	.073	.073	.074	.074	.074	.075	.075	.075	.075	.075	.076
.435	.074	.075	.075	.076	.076	.076	.076	.076	.076	.076	.077
.440	.076	.076	.077	.077	.077	.078	.078	.078	.078	.078	.079
.445	.077	.078	.078	.079	.079	.079	.079	.080	.080	.080	.080
.450	.079	.079	.080	.080	.081	.081	.081	.081	.081	.081	.081

Auxiliary Table 10. Submerged Flow Calibration for 20 cm x 90 cm Cutthroat Flume (Values Listed Are Discharged in m /s)

h_a^* \ $h_a^*-h_b^*$	.005	.010	.015	.020	.025	.030	.035	.040	.045	.050	.055	.060	.065	.070	.075	.080	.085	.090	.095	.100
.005	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
.010	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
.015	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
.020	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
.025	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
.030	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
.035	.001	.001	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002
.040	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002
.045	.002	.002	.002	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003
.050	.002	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003
.055	.003	.003	.003	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004
.060	.003	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004
.065	.003	.004	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005
.070	.004	.005	.005	.005	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006
.075	.004	.005	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006
.080	.005	.006	.006	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007
.085	.005	.006	.007	.007	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008
.090	.006	.007	.008	.008	.008	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009
.095	.006	.008	.009	.009	.009	.009	.010	.010	.010	.010	.010	.010	.010	.010	.010	.010	.010	.010	.010	.010
.100	.007	.008	.009	.010	.010	.010	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011
.105	.007	.009	.010	.011	.011	.011	.011	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012
.110	.008	.010	.011	.011	.012	.012	.012	.013	.013	.013	.013	.013	.013	.013	.013	.013	.013	.013	.013	.013
.115	.008	.010	.012	.012	.013	.013	.013	.013	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014
.120	.009	.011	.012	.013	.014	.014	.014	.015	.015	.015	.015	.015	.015	.015	.015	.015	.015	.015	.015	.015
.125	.009	.012	.013	.014	.015	.015	.016	.016	.016	.016	.016	.016	.016	.016	.016	.016	.016	.016	.016	.016
.130	.010	.013	.014	.015	.016	.016	.017	.017	.017	.018	.018	.018	.018	.018	.018	.018	.018	.018	.018	.018
.135	.011	.013	.015	.016	.017	.017	.018	.018	.018	.019	.019	.019	.019	.019	.019	.019	.019	.019	.019	.019
.140	.011	.014	.016	.017	.018	.018	.019	.019	.019	.020	.020	.020	.020	.020	.020	.020	.020	.020	.020	.020
.145	.012	.015	.017	.018	.019	.020	.020	.020	.021	.021	.022	.022	.022	.022	.022	.022	.022	.022	.022	.022
.150	.012	.016	.018	.019	.020	.021	.021	.022	.022	.022	.023	.023	.023	.023	.023	.023	.023	.023	.023	.023
.155	.013	.016	.018	.020	.021	.022	.022	.023	.023	.023	.024	.024	.024	.024	.024	.024	.024	.024	.024	.024
.160	.014	.017	.019	.021	.022	.023	.024	.024	.024	.025	.025	.026	.026	.026	.026	.026	.026	.026	.026	.026
.165	.014	.018	.020	.022	.023	.024	.025	.025	.026	.026	.026	.027	.027	.027	.027	.027	.027	.027	.027	.027
.170	.015	.019	.021	.023	.024	.025	.026	.027	.027	.027	.028	.029	.029	.029	.029	.029	.029	.029	.029	.029
.175	.016	.020	.022	.024	.026	.027	.027	.028	.029	.029	.029	.029	.031	.031	.031	.031	.031	.031	.031	.031
.180	.016	.021	.023	.025	.027	.028	.029	.029	.030	.030	.031	.031	.032	.032	.032	.032	.032	.032	.032	.032
.185	.017	.021	.024	.026	.028	.029	.030	.031	.031	.032	.032	.032	.034	.034	.034	.034	.034	.034	.034	.034
.190	.018	.022	.025	.028	.029	.030	.031	.032	.033	.033	.034	.034	.034	.036	.036	.036	.036	.036	.036	.036
.195	.018	.023	.026	.029	.030	.032	.033	.034	.034	.035	.035	.035	.035	.037	.037	.037	.037	.037	.037	.037
.200	.019	.024	.027	.030	.032	.033	.034	.035	.036	.036	.037	.037	.037	.037	.039	.039	.039	.039	.039	.039
.205	.020	.025	.028	.031	.033	.034	.036	.037	.037	.038	.038	.039	.039	.039	.041	.041	.041	.041	.041	.041
.210	.021	.026	.030	.032	.034	.036	.037	.038	.039	.040	.040	.040	.041	.041	.043	.043	.043	.043	.043	.043
.215	.021	.027	.031	.033	.035	.037	.039	.040	.040	.041	.042	.042	.042	.042	.042	.045	.045	.045	.045	.045
.220	.022	.028	.032	.035	.037	.039	.040	.041	.042	.043	.043	.044	.044	.044	.044	.047	.047	.047	.047	.047
.225	.023	.029	.033	.036	.038	.040	.041	.043	.044	.044	.045	.046	.046	.046	.046	.049	.049	.049	.049	.049
.230	.024	.030	.034	.037	.039	.041	.043	.044	.045	.046	.047	.047	.048	.048	.048	.048	.051	.051	.051	.051
.235	.024	.031	.035	.038	.041	.043	.044	.046	.047	.048	.049	.049	.050	.050	.050	.050	.053	.053	.053	.053
.240	.025	.032	.036	.040	.042	.044	.046	.047	.049	.050	.050	.051	.051	.052	.052	.052	.055	.055	.055	.055
.245	.026	.033	.037	.041	.044	.046	.048	.049	.050	.051	.052	.053	.053	.054	.054	.054	.054	.057	.057	.057
.250	.027	.034	.039	.042	.045	.047	.049	.051	.052	.053	.054	.055	.055	.056	.056	.056	.056	.059	.059	.059

Auxiliary Table 10. (continued)

h_a^* \ $h_a^*-h_b^*$	.005	.010	.015	.020	.025	.030	.035	.040	.045	.050	.055	.060	.065	.070	.075	.080	.085	.090	.095	.100
.255	.028	.035	.040	.043	.046	.049	.051	.052	.054	.055	.056	.056	.057	.057	.058	.058	.058	.061	.061	.061
.260	.028	.036	.041	.045	.048	.050	.052	.054	.055	.057	.058	.058	.059	.059	.060	.060	.060	.060	.063	.063
.265	.029	.037	.042	.046	.049	.052	.054	.056	.057	.058	.059	.060	.061	.061	.062	.062	.062	.062	.066	.066
.270	.030	.038	.043	.047	.051	.053	.056	.057	.059	.060	.061	.062	.063	.063	.064	.064	.064	.065	.068	.068
.275	.031	.039	.045	.049	.052	.055	.057	.059	.061	.062	.063	.064	.065	.066	.066	.066	.067	.067	.067	.070
.280	.032	.040	.046	.050	.054	.056	.059	.061	.062	.064	.065	.066	.067	.068	.068	.069	.069	.069	.069	.073
.285	.033	.041	.047	.052	.055	.058	.060	.063	.064	.066	.067	.068	.069	.070	.070	.071	.071	.071	.071	.075
.290	.033	.042	.048	.053	.057	.060	.062	.064	.066	.068	.069	.070	.071	.072	.072	.073	.073	.073	.074	.074
.295	.034	.043	.050	.054	.058	.061	.064	.066	.068	.070	.071	.072	.073	.074	.075	.075	.075	.076	.076	.076
.300	.035	.045	.051	.056	.060	.063	.066	.068	.070	.071	.073	.074	.075	.076	.077	.077	.078	.078	.078	.078
.305	.036	.046	.052	.057	.061	.065	.067	.070	.072	.073	.075	.076	.077	.078	.079	.080	.080	.080	.081	.081
.310	.037	.047	.054	.059	.063	.066	.069	.071	.074	.075	.077	.078	.079	.080	.081	.082	.082	.083	.083	.083
.315	.038	.048	.055	.060	.064	.068	.071	.073	.075	.077	.079	.080	.082	.083	.083	.084	.085	.085	.085	.086
.320	.039	.049	.056	.062	.066	.070	.073	.075	.077	.079	.081	.082	.084	.085	.086	.086	.087	.088	.088	.088
.325	.040	.050	.058	.063	.068	.071	.074	.077	.079	.081	.083	.085	.086	.087	.088	.089	.089	.090	.090	.091
.330	.041	.051	.059	.065	.069	.073	.076	.079	.081	.083	.085	.087	.088	.089	.090	.091	.092	.092	.093	.093
.335	.041	.053	.060	.066	.071	.075	.078	.081	.083	.085	.087	.089	.090	.092	.093	.093	.094	.095	.095	.096
.340	.042	.054	.062	.068	.072	.076	.080	.083	.085	.087	.089	.091	.093	.094	.095	.096	.097	.097	.098	.098
.345	.043	.055	.063	.069	.074	.078	.082	.085	.087	.090	.092	.093	.095	.096	.097	.098	.099	.100	.100	.101
.350	.044	.056	.064	.071	.076	.080	.083	.087	.089	.092	.094	.095	.097	.098	.100	.101	.102	.102	.103	.103
.355	.045	.057	.066	.072	.077	.082	.085	.089	.091	.094	.096	.098	.099	.101	.102	.103	.104	.105	.105	.106
.360	.046	.059	.067	.074	.079	.083	.087	.091	.093	.096	.098	.100	.102	.103	.104	.106	.107	.107	.108	.109
.365	.047	.060	.069	.075	.081	.085	.089	.092	.095	.098	.100	.102	.104	.106	.107	.108	.109	.110	.111	.111
.370	.048	.061	.070	.077	.082	.087	.091	.094	.097	.100	.102	.105	.106	.108	.109	.111	.112	.112	.113	.114
.375	.049	.062	.071	.078	.084	.089	.093	.096	.100	.102	.105	.107	.109	.110	.112	.113	.114	.115	.116	.117
.380	.050	.064	.073	.080	.086	.091	.095	.099	.102	.104	.107	.109	.111	.113	.114	.116	.117	.118	.119	.119
.385	.051	.065	.074	.082	.088	.093	.097	.101	.104	.107	.109	.111	.113	.115	.117	.118	.119	.120	.121	.122
.390	.052	.066	.076	.083	.089	.094	.099	.103	.106	.109	.111	.114	.116	.118	.119	.121	.122	.123	.124	.125
.395	.053	.067	.077	.085	.091	.096	.101	.105	.108	.111	.114	.116	.118	.120	.122	.123	.125	.126	.127	.128
.400	.054	.069	.079	.087	.093	.098	.103	.107	.110	.113	.116	.119	.121	.123	.124	.126	.127	.128	.129	.130
.405	.055	.070	.080	.088	.095	.100	.105	.109	.112	.116	.118	.121	.123	.125	.127	.128	.130	.131	.132	.133
.410	.056	.071	.082	.090	.096	.102	.107	.111	.115	.118	.121	.123	.126	.128	.129	.131	.133	.134	.135	.136
.415	.057	.073	.083	.091	.098	.104	.109	.113	.117	.120	.123	.126	.128	.130	.132	.134	.135	.137	.138	.139
.420	.058	.074	.085	.093	.100	.106	.111	.115	.119	.122	.125	.128	.131	.133	.135	.136	.138	.139	.141	.142
.425	.059	.075	.086	.095	.102	.108	.113	.117	.121	.125	.128	.131	.133	.135	.137	.139	.141	.142	.143	.144
.430	.060	.077	.088	.097	.104	.110	.115	.119	.123	.127	.130	.133	.136	.138	.140	.142	.143	.145	.146	.147
.435	.061	.078	.089	.098	.106	.112	.117	.122	.126	.129	.133	.136	.138	.141	.143	.145	.146	.148	.149	.150
.440	.062	.079	.091	.100	.107	.114	.119	.124	.128	.132	.135	.138	.141	.143	.145	.147	.149	.151	.152	.153
.445	.063	.081	.092	.102	.109	.116	.121	.126	.130	.134	.137	.141	.143	.146	.148	.150	.152	.153	.155	.156
.450	.064	.082	.094	.103	.111	.118	.123	.128	.133	.136	.140	.143	.146	.148	.151	.153	.155	.156	.158	.159

Auxiliary Table 10. (continued)

h_a^*	$h_a^*-h_b^*$										
	.105	.110	.115	.120	.125	.130	.135	.140	.145	.150	.155
.255	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061
.260	.063	.063	.063	.063	.063	.063	.063	.063	.063	.063	.063
.265	.066	.066	.066	.066	.066	.066	.066	.066	.066	.066	.066
.270	.068	.068	.068	.068	.068	.068	.068	.068	.068	.068	.068
.275	.070	.070	.070	.070	.070	.070	.070	.070	.070	.070	.070
.280	.073	.073	.073	.073	.073	.073	.073	.073	.073	.073	.073
.285	.075	.075	.075	.075	.075	.075	.075	.075	.075	.075	.075
.290	.078	.078	.078	.078	.078	.078	.078	.078	.078	.078	.078
.295	.080	.080	.080	.080	.080	.080	.080	.080	.080	.080	.080
.300	.082	.082	.082	.082	.082	.082	.082	.082	.082	.082	.082
.305	.085	.085	.085	.085	.085	.085	.085	.085	.085	.085	.085
.310	.083	.088	.088	.088	.088	.088	.088	.088	.088	.088	.088
.315	.086	.086	.090	.090	.090	.090	.090	.090	.090	.090	.090
.320	.088	.088	.093	.093	.093	.093	.093	.093	.093	.093	.093
.325	.091	.091	.096	.096	.096	.096	.096	.096	.096	.096	.096
.330	.093	.093	.093	.098	.098	.098	.098	.098	.098	.098	.098
.335	.096	.096	.096	.101	.101	.101	.101	.101	.101	.101	.101
.340	.098	.099	.099	.104	.104	.104	.104	.104	.104	.104	.104
.345	.101	.101	.101	.101	.107	.107	.107	.107	.107	.107	.107
.350	.104	.104	.104	.104	.110	.110	.110	.110	.110	.110	.110
.355	.106	.107	.107	.107	.112	.112	.112	.112	.112	.112	.112
.360	.109	.109	.110	.110	.110	.115	.115	.115	.115	.115	.115
.365	.112	.112	.112	.112	.113	.118	.118	.118	.118	.118	.118
.370	.114	.115	.115	.115	.115	.121	.121	.121	.121	.121	.121
.375	.117	.118	.118	.118	.118	.118	.124	.124	.124	.124	.124
.380	.120	.120	.121	.121	.121	.121	.127	.127	.127	.127	.127
.385	.123	.123	.124	.124	.124	.124	.131	.131	.131	.131	.131
.390	.125	.126	.126	.127	.127	.127	.127	.134	.134	.134	.134
.395	.128	.129	.129	.130	.130	.130	.130	.137	.137	.137	.137
.400	.131	.132	.132	.133	.133	.133	.133	.140	.140	.140	.140
.405	.134	.135	.135	.136	.136	.136	.136	.136	.143	.143	.143
.410	.137	.137	.138	.139	.139	.139	.139	.139	.147	.147	.147
.415	.140	.140	.141	.142	.142	.142	.142	.142	.142	.150	.150
.420	.143	.143	.144	.145	.145	.145	.145	.146	.146	.153	.153
.425	.145	.146	.147	.148	.148	.148	.149	.149	.149	.157	.157
.430	.148	.149	.150	.151	.151	.152	.152	.152	.152	.152	.160
.435	.151	.152	.153	.154	.154	.155	.155	.155	.155	.155	.163
.440	.154	.155	.156	.157	.157	.158	.158	.158	.159	.159	.167
.445	.157	.158	.159	.160	.161	.161	.161	.162	.162	.162	.162
.450	.160	.161	.162	.163	.164	.164	.165	.165	.165	.165	.165

Auxiliary Table 11. Submerged Flow Calibration for 30 cm x 90 cm Cutthroat Flume (Values Listed Are Discharged in m /s)

h_a^* \ $h_a^*-h_b^*$	.005	.010	.015	.020	.025	.030	.035	.040	.045	.050	.055	.060	.065	.070	.075	.080	.085	.090	.095	.100
.005	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
.010	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
.015	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
.020	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
.025	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
.030	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002
.035	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002	.002
.040	.002	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003	.003
.045	.003	.003	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004
.050	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004	.004
.055	.004	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005	.005
.060	.005	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006	.006
.065	.005	.006	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007
.070	.006	.007	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008	.008
.075	.007	.008	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009	.009
.080	.007	.009	.010	.010	.010	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011
.085	.008	.010	.011	.011	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012	.012
.090	.009	.011	.012	.012	.013	.013	.013	.013	.013	.013	.013	.013	.013	.013	.013	.013	.013	.013	.013	.013
.095	.009	.012	.013	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014	.014
.100	.010	.013	.014	.015	.015	.016	.016	.016	.016	.016	.016	.016	.016	.016	.016	.016	.016	.016	.016	.016
.105	.011	.014	.015	.016	.017	.017	.017	.017	.017	.017	.017	.017	.017	.017	.017	.017	.017	.017	.017	.017
.110	.012	.015	.016	.017	.018	.019	.019	.019	.019	.019	.019	.019	.019	.019	.019	.019	.019	.019	.019	.019
.115	.013	.016	.018	.019	.020	.020	.020	.020	.021	.021	.021	.021	.021	.021	.021	.021	.021	.021	.021	.021
.120	.013	.017	.019	.020	.021	.022	.022	.022	.022	.022	.022	.022	.022	.022	.022	.022	.022	.022	.022	.022
.125	.014	.018	.020	.021	.022	.023	.024	.024	.024	.024	.024	.024	.024	.024	.024	.024	.024	.024	.024	.024
.130	.015	.019	.021	.023	.024	.025	.025	.025	.026	.026	.026	.026	.026	.026	.026	.026	.026	.026	.026	.026
.135	.016	.020	.023	.024	.025	.026	.027	.027	.027	.028	.028	.028	.028	.028	.028	.028	.028	.028	.028	.028
.140	.017	.021	.024	.026	.027	.028	.029	.029	.029	.030	.030	.030	.030	.030	.030	.030	.030	.030	.030	.030
.145	.018	.022	.025	.027	.029	.030	.030	.031	.031	.031	.031	.031	.031	.031	.031	.031	.031	.031	.031	.031
.150	.019	.024	.027	.029	.030	.031	.032	.033	.033	.033	.034	.034	.034	.034	.034	.034	.034	.034	.034	.034
.155	.020	.025	.028	.030	.032	.033	.034	.035	.035	.035	.036	.036	.036	.036	.036	.036	.036	.036	.036	.036
.160	.021	.026	.029	.032	.034	.035	.036	.037	.037	.037	.037	.038	.038	.038	.038	.038	.038	.038	.038	.038
.165	.022	.027	.031	.033	.035	.037	.038	.039	.039	.039	.040	.040	.040	.040	.040	.040	.040	.040	.040	.040
.170	.023	.029	.032	.035	.037	.039	.040	.041	.041	.042	.042	.042	.042	.042	.042	.042	.042	.042	.042	.042
.175	.024	.030	.034	.037	.039	.040	.042	.043	.043	.044	.044	.044	.045	.045	.045	.045	.045	.045	.045	.045
.180	.025	.031	.035	.038	.041	.042	.044	.045	.045	.046	.046	.046	.047	.047	.047	.047	.047	.047	.047	.047
.185	.026	.033	.037	.040	.042	.044	.046	.047	.048	.048	.049	.049	.049	.049	.049	.049	.049	.049	.049	.049
.190	.027	.034	.038	.042	.044	.046	.048	.049	.050	.050	.051	.051	.051	.052	.052	.052	.052	.052	.052	.052
.195	.028	.035	.040	.043	.046	.048	.050	.051	.052	.053	.053	.054	.054	.054	.054	.054	.054	.054	.054	.054
.200	.029	.037	.042	.045	.048	.050	.052	.053	.054	.055	.056	.056	.056	.056	.057	.057	.057	.057	.057	.057
.205	.030	.038	.043	.047	.050	.052	.054	.056	.057	.058	.058	.059	.059	.059	.060	.060	.060	.060	.060	.060
.210	.031	.039	.045	.049	.052	.054	.056	.058	.059	.060	.061	.061	.062	.062	.062	.062	.062	.062	.062	.062
.215	.032	.041	.046	.051	.054	.056	.058	.060	.061	.062	.063	.064	.064	.064	.064	.065	.065	.065	.065	.065
.220	.034	.042	.048	.052	.056	.058	.061	.062	.064	.065	.066	.066	.067	.067	.067	.068	.068	.068	.068	.068
.225	.035	.044	.050	.054	.058	.061	.063	.065	.066	.067	.068	.069	.070	.070	.070	.071	.071	.071	.071	.071
.230	.036	.045	.052	.056	.060	.063	.065	.067	.069	.070	.071	.072	.072	.073	.073	.073	.074	.074	.074	.074
.235	.037	.047	.053	.058	.062	.065	.067	.069	.071	.072	.074	.074	.075	.075	.076	.076	.077	.077	.077	.077
.240	.038	.048	.055	.060	.064	.067	.070	.072	.074	.075	.076	.077	.078	.078	.079	.079	.080	.080	.080	.080
.245	.039	.050	.057	.062	.066	.069	.072	.074	.076	.078	.079	.080	.081	.081	.082	.082	.082	.083	.083	.083
.250	.041	.051	.059	.064	.068	.072	.074	.077	.079	.080	.082	.083	.084	.084	.085	.085	.085	.086	.086	.086

Auxiliary Table 11. (continued)

h_a^* \ $h_a^*-h_b^*$	.005	.010	.015	.020	.025	.030	.035	.040	.045	.050	.055	.060	.065	.070	.075	.080	.085	.090	.095	.100
.255	.042	.053	.060	.066	.070	.074	.077	.079	.081	.083	.084	.086	.086	.087	.088	.088	.088	.089	.089	.089
.260	.043	.054	.062	.068	.072	.076	.079	.082	.084	.086	.087	.088	.089	.090	.091	.091	.091	.091	.092	.092
.265	.044	.056	.064	.070	.075	.078	.082	.084	.087	.088	.090	.091	.092	.093	.094	.094	.094	.095	.096	.096
.270	.046	.058	.066	.072	.077	.081	.084	.087	.089	.091	.093	.094	.095	.096	.097	.097	.098	.098	.099	.099
.275	.047	.059	.068	.074	.079	.083	.087	.090	.092	.094	.096	.097	.098	.099	.100	.101	.101	.101	.101	.102
.280	.048	.061	.070	.076	.081	.086	.089	.092	.095	.097	.099	.100	.101	.102	.103	.104	.104	.105	.105	.106
.285	.049	.063	.071	.078	.084	.088	.092	.095	.097	.100	.102	.103	.105	.106	.106	.107	.108	.108	.108	.109
.290	.051	.064	.073	.080	.086	.090	.094	.097	.100	.103	.105	.106	.108	.109	.110	.110	.111	.111	.112	.112
.295	.052	.066	.075	.082	.088	.093	.097	.100	.103	.105	.108	.109	.111	.112	.113	.114	.114	.115	.115	.115
.300	.053	.068	.077	.085	.090	.095	.099	.103	.106	.108	.111	.112	.114	.115	.116	.117	.118	.118	.119	.119
.305	.055	.069	.079	.087	.093	.098	.102	.106	.109	.111	.114	.115	.117	.119	.120	.121	.121	.122	.122	.122
.310	.056	.071	.081	.089	.095	.100	.105	.108	.112	.114	.117	.119	.120	.122	.123	.124	.125	.125	.126	.126
.315	.057	.073	.083	.091	.098	.103	.107	.111	.114	.117	.120	.122	.124	.125	.126	.127	.128	.129	.130	.130
.320	.059	.075	.085	.093	.100	.105	.110	.114	.117	.120	.123	.125	.127	.128	.130	.131	.132	.133	.133	.134
.325	.060	.076	.087	.096	.102	.108	.113	.117	.120	.123	.126	.128	.130	.132	.133	.135	.135	.136	.137	.137
.330	.061	.078	.089	.098	.105	.111	.115	.120	.123	.126	.129	.131	.134	.135	.137	.138	.139	.140	.141	.141
.335	.063	.080	.091	.100	.107	.113	.118	.122	.126	.129	.132	.135	.137	.139	.140	.142	.143	.144	.144	.145
.340	.064	.082	.093	.102	.110	.116	.121	.125	.129	.133	.136	.138	.140	.142	.144	.145	.146	.147	.148	.149
.345	.066	.083	.095	.105	.112	.118	.124	.128	.132	.136	.139	.141	.144	.146	.147	.149	.150	.151	.152	.153
.350	.067	.085	.098	.107	.115	.121	.127	.131	.135	.139	.142	.145	.147	.149	.151	.153	.154	.155	.156	.157
.355	.069	.087	.100	.109	.117	.124	.129	.134	.138	.142	.145	.148	.151	.153	.155	.156	.158	.159	.160	.161
.360	.070	.089	.102	.112	.120	.126	.132	.137	.142	.145	.149	.152	.154	.156	.158	.160	.161	.163	.164	.165
.365	.071	.091	.104	.114	.122	.129	.135	.140	.145	.149	.152	.155	.158	.160	.162	.164	.165	.167	.168	.169
.370	.073	.093	.106	.116	.125	.132	.138	.143	.148	.152	.155	.158	.161	.164	.166	.168	.169	.170	.172	.173
.375	[illegible]	.095	.108	.119	.127	.135	.141	.146	.151	.155	.159	.162	.165	.167	.169	.171	.173	.174	.176	.177
.380	.076	.096	.110	.121	.130	.138	.144	.149	.154	.158	.162	.165	.168	.171	.173	.175	.177	.178	.180	.181
.385	.077	.098	.113	.124	.133	.140	.147	.152	.157	.162	.166	.169	.172	.175	.177	.179	.181	.182	.184	.185
.390	.079	.100	.115	.126	.135	.143	.150	.156	.161	.165	.169	.172	.176	.178	.181	.183	.185	.186	.188	.189
.395	.080	.102	.117	.129	.138	.146	.153	.159	.164	.168	.172	.176	.179	.182	.185	.187	.189	.191	.192	.193
.400	.082	.104	.119	.131	.141	.149	.156	.162	.167	.172	.176	.180	.183	.186	.188	.191	.193	.195	.196	.197
.405	.083	.106	.122	.134	.143	.152	.159	.165	.170	.175	.179	.183	.187	.190	.192	.195	.197	.199	.200	.202
.410	.085	.108	.124	.136	.146	.155	.162	.168	.174	.179	.183	.187	.190	.193	.196	.199	.201	.203	.205	.206
.415	.087	.110	.126	.139	.149	.157	.165	.171	.177	.182	.187	.191	.194	.197	.200	.203	.205	.207	.209	.210
.420	.088	.112	.128	.141	.152	.160	.168	.175	.180	.186	.190	.194	.198	.201	.204	.207	.209	.211	.213	.215
.425	.090	.114	.131	.144	.154	.163	.171	.178	.184	.189	.194	.198	.202	.205	.208	.211	.213	.215	.217	.219
.430	.091	.116	.133	.146	.157	.166	.174	.181	.187	.193	.197	.202	.206	.209	.212	.215	.217	.220	.222	.223
.435	.093	.118	.135	.149	.160	.169	.177	.184	.191	.196	.201	.205	.209	.213	.216	.219	.222	.224	.226	.228
.440	.094	.120	.138	.152	.163	.172	.180	.188	.194	.200	.205	.209	.213	.217	.220	.223	.226	.228	.230	.232
.445	.096	.122	.140	.154	.166	.175	.184	.191	.197	.203	.208	.213	.217	.221	.224	.227	.230	.233	.235	.237
.450	.098	.124	.143	.157	.168	.178	.187	.194	.201	.207	.212	.217	.221	.225	.228	.232	.234	.237	.239	.241

Auxiliary Table 11. (continued)

h_a^* \ $h_a^*-h_b^*$	.105	.110	.115	.120	.125	.130	.135	.140	.145	.150	.155
.255	.089	.089	.089	.089	.089	.089	.089	.089	.089	.089	.089
.260	.092	.092	.092	.092	.092	.092	.092	.092	.092	.092	.092
.265	.096	.096	.096	.096	.096	.096	.096	.096	.096	.096	.096
.270	.099	.099	.099	.099	.099	.099	.099	.099	.099	.099	.099
.275	.102	.102	.102	.102	.102	.102	.102	.102	.102	.102	.102
.280	.106	.106	.106	.106	.106	.106	.106	.106	.106	.106	.106
.285	.109	.109	.109	.109	.109	.109	.109	.109	.109	.109	.109
.290	.113	.113	.113	.113	.113	.113	.113	.113	.113	.113	.113
.295	.116	.116	.116	.116	.116	.116	.116	.116	.116	.116	.116
.300	.120	.120	.120	.120	.120	.120	.120	.120	.120	.120	.120
.305	.123	.124	.124	.124	.124	.124	.124	.124	.124	.124	.124
.310	.126	.127	.127	.127	.127	.127	.127	.127	.127	.127	.127
.315	.130	.130	.131	.131	.131	.131	.131	.131	.131	.131	.131
.320	.134	.134	.135	.135	.135	.135	.135	.135	.135	.135	.135
.325	.138	.138	.139	.139	.139	.139	.139	.139	.139	.139	.139
.330	.141	.142	.142	.143	.143	.143	.143	.143	.143	.143	.143
.335	.145	.146	.146	.147	.147	.147	.147	.147	.147	.147	.147
.340	.149	.150	.150	.151	.151	.151	.151	.151	.151	.151	.151
.345	.153	.154	.154	.154	.155	.155	.155	.155	.155	.155	.155
.350	.157	.158	.158	.158	.159	.159	.159	.159	.159	.159	.159
.355	.161	.162	.162	.162	.164	.164	.164	.164	.164	.164	.164
.360	.165	.166	.166	.166	.166	.168	.168	.168	.168	.168	.168
.365	.169	.170	.170	.170	.171	.172	.172	.172	.172	.172	.172
.370	.173	.174	.174	.175	.175	.177	.177	.177	.177	.177	.177
.375	.178	.178	.179	.179	.179	.179	.181	.181	.181	.181	.181
.380	.182	.182	.183	.183	.184	.184	.185	.185	.185	.185	.185
.385	.186	.187	.187	.188	.188	.188	.190	.190	.190	.190	.190
.390	.190	.191	.192	.192	.192	.193	.193	.195	.195	.195	.195
.395	.194	.195	.196	.196	.197	.197	.197	.199	.199	.199	.199
.400	.199	.200	.200	.201	.201	.202	.202	.204	.204	.204	.204
.405	.203	.204	.205	.205	.206	.206	.206	.206	.209	.209	.209
.410	.207	.208	.209	.210	.210	.211	.211	.211	.213	.213	.213
.415	.212	.213	.214	.214	.215	.216	.216	.216	.216	.218	.218
.420	.216	.217	.218	.219	.220	.220	.221	.221	.221	.223	.223
.425	.220	.222	.223	.224	.224	.225	.225	.226	.226	.228	.228
.430	.225	.226	.227	.228	.229	.230	.230	.230	.231	.231	.233
.435	.229	.231	.232	.233	.234	.234	.235	.235	.235	.235	.238
.440	.234	.235	.237	.238	.239	.239	.240	.240	.240	.240	.243
.445	.238	.240	.241	.242	.243	.244	.245	.245	.245	.246	.246
.450	.243	.245	.246	.247	.248	.249	.250	.250	.250	.251	.251

GROUNDWATER OBSERVATION WELLS

by J. Baxter

The position or distance of groundwater from the soil surface can have a profound influence on the design or operation of an irrigation system. High water tables can lead to waterlogged soil conditions and reduced crop yields; thus, drainage will have to be provided. When drainage is required, it is important to know the position and hydraulic gradient of the water table and the hydraulic conductivity of the soil. In arid regions, high water tables also may cause salts to accummulate on the soil surface from direct evaporation; thus, it is often important to keep the water table two or more meters below the soil surface. Information concerning the amount of water that might be available from the water table for crop evapotranspiration needs also is valuable. If the water table depth exceeds 20 feet, contributions from the water table to meet crop requirements will be negligible. Thus, the depth of the water table and its fluctuations during the growing season are important.

Information concerning groundwater can be obtained from a variety of sources. Existing wells, ponds, hand pumps, and so forth, throughout a given area, should be inspected. Well drillers, hydrologists, water users, and farmers, should be consulted to get their opinions as to the normal annual fluctuation of the water table. Drillers' logs, if available, should be obtained in order to identify the composition and thickness of strata and the aquifer.

Shallow wells (less than 5 meters) or piezometers can be installed by hand, utilizing a screw or bucket type auger. Usually observation wells are installed on a grid system and sometimes in clusters when the aquifer is stratified.

Clusters of observation wells are installed at differing depths so that information on individual stratum can be identified. When detailed information on water levels are needed (for example, near canals and drains), a line of wells may be installed to better define the hydraulic gradient.

After the observation wells have been installed, information concerning hydraulic conductivity, specific yield, transmissibility, storage coefficient, and salinity can be collected in addition to water table levels.

Piezometers or small observation wells are small diameter pipes which are perforated only at the end, and are used to measure the water table or hydraulic potential of the aquifer at the depth of the perforations. Instructions for the installation of piezometers are outlined below.

PROCEDURE FOR INSTALLATION OF PIEZOMETERS

1. Piezometers should be placed on a grid system, preferably at field intersections.

2. If elevation changes and slope of the hydraulic gradient are important, elevation of the soil surface should be determined at each piezometer for reference.

3. Auger the hole. A bucket type auger is satisfactory for all soil types. Bore to a level at least two feet (60 centimeters) lower than the expected lowest level of the water table. The diameter of the augered hole should match the outside diameter of the pipe.

4. The bottom two to three feet (60-90 centimeters) of the well casing (metal or plastic pipe) should be perforated. If available, coarse sand or pea gravel should be poured into the augered hole to fill the bottom 6 inches (15 centimeters).

5. The pipe should be set so that it extends at least four inches above the ground surface and threaded to accept a cap. The cap should be screwed on with sufficient force that it cannot be opened manually by unauthorized personnel who might drop soil or debris into the well.

6. Excavate a collar shaped area, one foot (30 centimeters) in diameter, around the pipe. Fill this excavation with concrete to the level of the soil surface. The primary purpose of this concrete collar is to prevent water from infiltrating down the pipe stem from the surface and to prevent the possibility of theft.

MEASURING TUBEWELL DISCHARGE

by D. Molden

There are many techniques to measure the flow of water from tubewells. If the tubewell is discharging into an open channel, standard measuring devices, such as flumes, current meters or weirs can be placed in the channel to measure discharge. Care must be taken not to allow seepage or overflow from the channel in front of the point of measurement. If the tubewell is discharging into a closed conduit, instruments such as orifices or venturi meters can be used. Many times these measuring devices are not available. The Purdue Coordinate Method and the California Pipe Method provide good estimates of tubewell discharge from a horizontal pipe.

PURDUE COORDINATE METHOD

The Purdue Coordinate Method has proved to be a practical, quick method of flow measurement. The method utilizes the fall of a stream of water flowing from the mouth of a round horizontal pipe. The inertia of the water from the tube determines the trajectory of the fall.

Coordinates along the falling water have been determined which are utilized to determine discharge (Figure 1). They are:

1. D (in.) - the inside pipe diameter
2. X (in.) - the distance from the end of the pipe
3. Y (in.) - the fall of the stream over distance X.

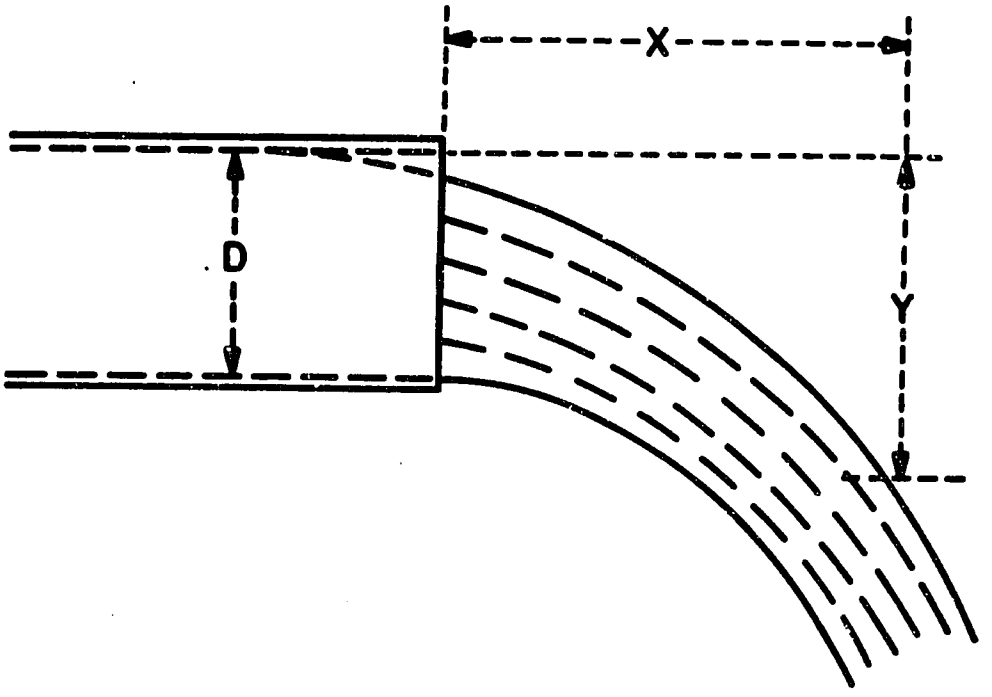


Figure 1. Purdue Method of Measuring Flow From a Horizontal Pipe

To determine discharge with these coordinates, set X to a specified distance, measure Y and whenever possible obtain the discharge from Table 1 which immediately follows this article.

For diameters other than those in Table 1, the discharge is related empirically to these coordinates by:

English:

$$Q = \frac{0.0071\ D^2X}{\sqrt{Y}}$$

where Q is in cfs; D, W and Y are in inches.

Metric:

$$Q = \frac{0.0195\ D^2X}{\sqrt{Y}}$$

where Q is in l/s; D, X, and Y are in cm.

These empirical relationships are approximate. For accurate relationships actual calibration should be done.

Method:

1. Check to make sure that the pipe is level and that the pipe length is straight for six or more diameters before the mouth.

2. Measure the inside diameter, D, of the pipe.

3. Using a carpenter's square or folding rule measure a distance X from the mouth of the tube. To use the table, set X at either 6 inches, 12 inches or 18 inches. If the depth of water inside the pipe is less than 0.8 D, take X as 0 inches.

4. Measure Y corresponding to the given X. If X is 0, measure Y at the end of the pipe.

5. Using Table 1, determine the discharge in cubic feet per second.

Example:

D = 5 inches

X = 12 inches

Y = 6 inches

From Table 1, the discharge is 0.87 cfs.

Limitations:

1. The pipe must be straight for a distance of six diameters before the mouth.

2. The method is accurate only when the pipe is level. The method will overestimate discharge if the pipe slopes upward and underestimate discharge if the pipe slopes downward.

CALIFORNIA PIPE METHOD

For pipes flowing partially full at the mouth and when the approach velocity is at a minimum (so that the jet does not shoot far from the pipe), the California Pipe Method can be used (Figure 2). The coordinates used are:

D - the internal diameter of the pipe and

a - the distance measured in the plane of the end of the pipe, from the top inside surface of the pipe to the water surface.

The discharge, Q, in cfs is given by:
English:

$$Q = 8.69 \left(1 - \frac{a}{D}\right)^{1.88} D^{2.48} \qquad (3)$$

where Q is in cfs and a and D are in feet.

Metric:

$$Q = 5.14 \times 10^{-5} \left(1 - \frac{a}{D}\right)^{1.88} D^{2.48} \qquad (4)$$

where Q is in m^3/s, a and D are in cm.

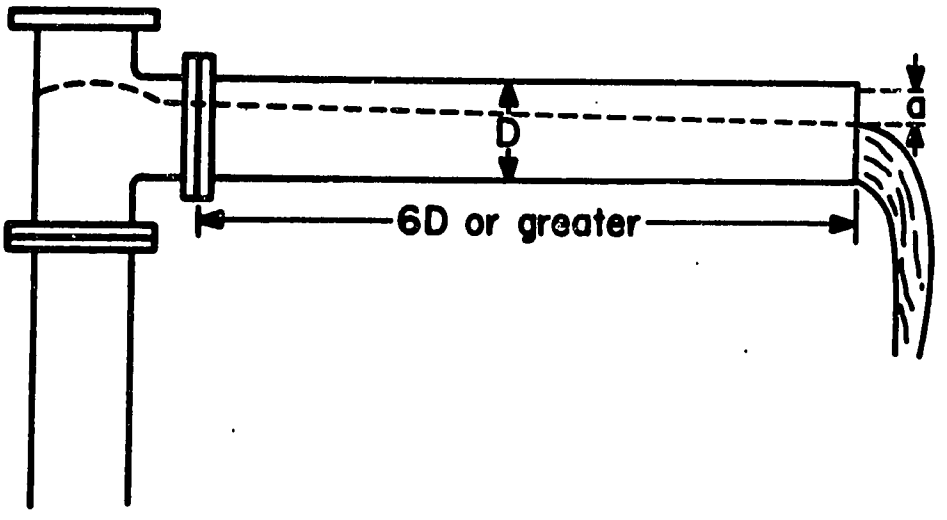


Figure 2. California Pipe Method of Measuring Flow

To use this method these steps must be followed:

1. Make sure the pipe is level.

2. Check to see that the pipe is discharging partially full.

3. Check to see that the velocity of water is low so that there is not a large jet coming out of the pipe. If there is a large jet, use the Purdue Coordinate Method.

4. Measure the inside diameter, D.

5. At the mouth of the pipe, hold the ruler on the plane of the opening. Measure the distance from the top of the inside of the pipe to the water surface to get a.

6. Use equation (3) for discharge in cfs, equation (4) for discharge in m^3/s.

The Purdue Coordinate Method is valid also for this partially full, low water velocity discharge. In some cases, however, it may be easier to use the California Pipe Method.

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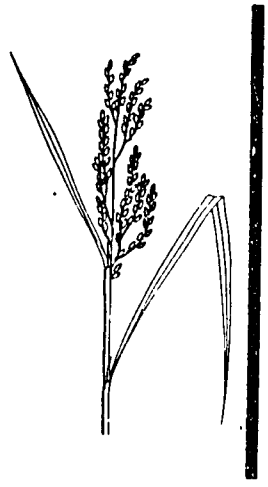
Table 1. Discharge From Horizontal Round Pipes (cfs) After U.S.B.R. Water Measurement Manual (1967)

Vertical Coordinate Y (in)	Horizontal Coordinate X = 0" Dia. 3"	X = 0" 4"	X = 0" 5"	X = 0" 6"	X = 6" 3"	X = 6" 4"	X = 6" 5"	X = 6" 6"
0.5	.13							
1.0	0.12	0.29	0.59	0.94	0.40	0.76	1.27	1.78
1.5	0.08	0.22	0.49	0.81	0.33	0.65	1.07	1.56
2.0	0.04	0.17	0.38	0.71	0.29	0.56	0.91	1.36
2.5	0.02	0.11	0.30	0.56	0.26	0.49	0.81	1.24
3.0		0.05	0.20	0.45	0.22	0.45	0.74	1.11
3.5			0.12	0.33	0.20	0.40	0.67	1.00
4.0			0.07	0.27	0.19	0.37	0.61	0.95
4.5					0.17	0.33	0.57	
5.0					0.16	0.30		

	X = 12" 3"	X = 12" 4"	X = 12" 5"	X = 12" 6"	X = 18" 3"	X = 18" 4"	X = 18" 5"	X = 18" 6"
1.0	0.71	1.27	2.23	3.12				
1.5	0.61	1.05	1.80	2.67	0.84	1.56	2.56	3.68
2.0	0.53	0.92	1.56	2.34	0.75	1.34	2.12	3.12
2.5	0.47	0.85	1.38	2.09	0.67	1.20	1.92	2.79
3.0	0.42	0.78	1.27	1.94	0.60	1.07	1.78	2.56
3.5	0.39	0.72	1.16	1.78	0.57	1.00	1.65	2.40
4.0	0.37	0.67	1.07	1.67	0.53	0.94	1.54	2.28
4.5	0.35	0.64	1.00	1.56	0.51	0.89	1.45	2.17
5.0	0.33	0.61	0.96	1.47	0.49	0.85	1.38	2.06
5.5	0.32	0.58	0.91	1.40	0.47	0.81	1.33	1.96
6.0	0.31	0.56	0.87	1.34	0.45	0.78	1.27	1.89



METHODS OF MEASURING SEEPAGE RATES*

by D. Kemper

INTRODUCTION

Numerous methods measure seepage from channels: They include both field and laboratory investigations. Each has unique characteristics which make it useful under certain conditions. Following is a description of three different methods of measuring seepage rates and a review of additional types of methods which could be used for developing water budgets.

Factors that influence seepage rates are many and complex. Among the more important ones are soil characteristics of the channel bed, length of time the channel has been operating, depth of groundwater, sediment load in the water, depth of water in the channel, temperature of both water and soil, barometric pressure, biological factors, and salts contained in both the water and soil. Although the literature contains much information about the relationship between these parameters and seepage rates, the seepage process is so complex that individual tests often are necessary for research studies, developing water budgets, or prior to and after the construction of channel improvements. Worstell (1976) provides an excellent review of seepage measurement techniques.

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* Modified from an article in The Problem Identification Handbook. (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100. Fort Collins, CO.

The most common methods of measuring seepage are categorized as 1) those that yield results indicating an average seepage from a length of channel and 2) those in which information simply gives the permeability of a sample of the channel bed. If the latter type of measurement is employed, additional information on hydraulic gradients is necessary for the actual seepage to be computed. In most salinity related investigations, methods that indicate actual seepage rates prove to be of most worth. Three of the most frequently employed methods include the inflow-outflow method, ponding method, and seepage-meter method.

INFLOW-OUTFLOW METHOD

The inflow-outflow method is reliable and commonly used when seepage rates from relatively long lengths are to be measured. The method involves measuring the inflow and the outflow to the channel section under investigation, including all diversions from and return flows to the channel. By computing the net loss in the channel, the actual seepage rate can be determined. Because the usual units of seepage rate are feet-per-day ($ft^3/ft^2/day$), the conversion from the total loss in the section requires a knowledge of the length and wetted perimeter (average) of the channel. The seepage rate can thus be expressed as:

$$SR = \frac{(\text{Inflow-Outflow}) \times 8.64 \times 10^4}{A}$$

in which SR is the seepage rate in ft/day (average for channel section); 8.64×10^4 is the number of seconds per day; A is the wetted area of the channel in square feet; and the difference between inflow and outflow is in cfs (ft^3/sec).

Although the inflow-outflow method indicates seepage rates under actual operating conditions, several factors should be carefully observed or significant errors will result. Maintenance of constant flow depths in the channel during the tests is essential to eliminate the effects of bank and channel storage. Also, an accounting must be made of all return flows from higher lands and diversions or leaks from the channel. Occasionally, if seepage rates are small, it may be useful to note rainfall and evaporation, although these factors generally are inconsequential. Finally, it is most important to consider the flow measuring devices to be employed. In the absence of measuring structures in the system when flows are small, they generally can be measured by small flumes or weirs. In the larger flow situations, current meter measurements are necessary. Most calibrated devices, if operated correctly, can be expected to measure water within at least five percent; current meter measurements, however, require careful attention by experienced personnel to maintain accuracies below five percent.

PONDING METHOD

The ponding method involves measuring the rate of fall of the water surface in a pond created in the channel section. Though an objection often is raised that still water may seep at a different rate than flowing water, the difference probably is small in comparison to errors associated with other measurement methods regarding seepage. By knowing the geometric properties of the section, it is possible to compute the seepage rate according to the following formula:

$$SR = \frac{\Delta E \times SW_a \times 24}{WP_a \times T}$$

where ΔE is the drop in water surface elevation in feet; SW_a is the average surface width in feet; WP_a is the average wetted perimeter in feet; and T is the time of the run in hours. The layout for conducting a ponding test is shown in Figure 1. Further information about the analysis can be found in Skogerboe and Walker (1972).

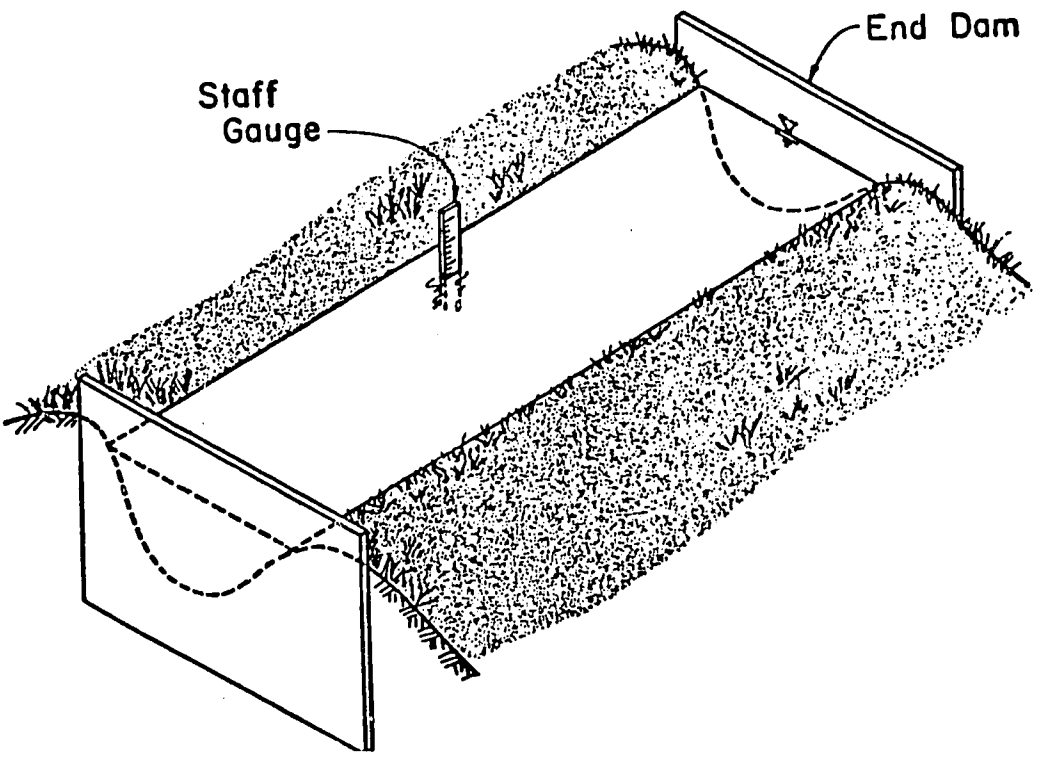

Figure 1. Layout for Ponding Measurements

The ponding method usually provides the basis for comparison with other methods because it usually can be expected to yield the best results. However, it does have disadvantages. The construction of the dikes often is expensive. The method also must be conducted when the channel is not in use or during periods of interrupted channel operation. Furthermore, providing water to fill the ponds may be a significant problem. However, if the channel discharges are very large in relation to the seepage rates, the ponding method is the best procedure by which the seepage rates can be determined. In fact, under such conditions, the errors expected in other methods (for example, the inflow-outflow method) may completely mask the seepage loss.

SEEPAGE-METER METHOD

Seepage meters determine seepage rates under normal operating conditions, but only for a small area at a time. Nevertheless, by taking readings at several points along the channel section, a fairly average value can be determined. The measurements involve pressing a cylindrical bell into the channel bed. Attached to the bell by a plastic hose is a submerged plastic bag filled with water. The water that seeps into the channel bed is replaced by water in the bag that is under the same pressure as the channel flows and thus represents the same head against the channel surface. The seepage rate can be computed from a knowledge of the area of the bell, the seepage from the bell as determined by weighing the plastic bag before and after the test, and the elapsed time of the test. The seepage rate then may be determined by:

$$SR = \frac{Q}{A \times T}$$

in which Q is the amount seeped through the channel bank in feet^3; A is the area of the bell in square feet; and T is the elapsed time in days.

The seepage meter works well unless the bed material is disturbed badly causing the meter to overestimate the seepage rates. The seepage meter method is difficult to apply when flow depths are too great or the channel velocities are too fast. Gravel, moss, or highly vegetated channels also present difficulties in properly evaluating seepage rates.

OTHER METHODS

Numerous other techniques yield useful seepage rate results under certain conditions. One group is classified as measurements of soil permeabilities that can be used to compute seepage rates. These techniques include the well-

permeameter method, variable head permeameter method, and the laboratory permeameter method (Robinson and Rohwer, 1957). The second group is those that use trace materials to determine seepage loss. They include the salt-penetration technique, the radioactive isotopes technique, and fluorescent dyes (Robinson and Rohwer, 1957; Liang and Richardson, 1971).

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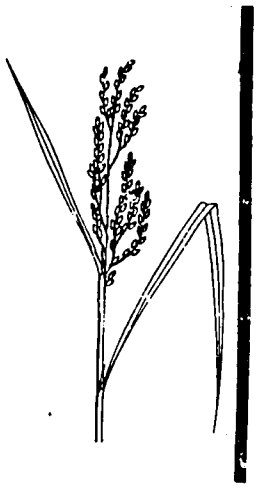

GUIDELINES FOR IRRIGATION EVALUATIONS*

by W. Clyma and A. Early

Good water management requires irrigation schedules to be planned in advance to best utilize water at the time and in the amounts it is available. The specialist can perform valuable service by encouraging the adoption of practices that result in success for the irrigators. Irrigation schedules should be developed to: 1) provide for the best use of the water available; 2) supply each crop during its critical demand period; and 3) apply water in a manner that maintains root-zone moisture in the right amount, but which avoids waste; and 4) allows for the flexibility needed to meet differences in seasonal climatic variations. When evaluating irrigation efficiency, the following suggestions will be of benefit.

- Plan

  - Contact farmers at least a day in advance to confirm their schedule and plans. Contact and confirm schedule a second time early on the day of the proposed evaluations.

- Soil Moisture Sampling

  - When using the King Tube Sampler, determine the exact depths of soil sampled.

  - Remember to cover the cutting end of the tube with one hand as soon as possible after removing the tube from the hole.

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* Modified from an article in The Problem Identification Handbook. (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100. Fort Collins, CO.

- Close plastic bag as soon as sample is placed inside.

- Weigh the sample on the evening of the same day in which the sample is taken.

- Estimate moisture content of the sample by the "feel" method immediately after weighing it.

- Expose the sample to the sun only after weighing and estimating soil moisture.

- Weigh the sample again immediately following exposure to the sun.

- Collect the samples together for a composite sample: mechanical and soil moisture characteristic analyses then can be completed at a later date.

- Take care of weighing scale

- Clean sampler periodically.

- Water Measurement

  - Check that the flume is leveled and remains level at all readings.

  - Record the time of each reading.

  - Notes all changes in the area irrigated and the time at which the changes are made.

  - Note any breakages of the watercourse and bunds along with the time they occurred, duration, and actions taken by the farmer to correct the problem.

- Field Book and Notes

  The following should be included in the evaluated data completed on each farm.

  - Date

  - Observer(s)

  - Start and stop times

- Location (sq. no. and acre no.)
- Sketch map
- H_a and H_b and discharge (calculate discharge at farm and field outlets to insure that the values are reasonable)
- Crop and height
- Outlet number
- Distance from outlet
- Farmer's name
- Date of last irrigation
- Area of field or its dimensions
- Flume dimensions

● <u>Inquiry</u>

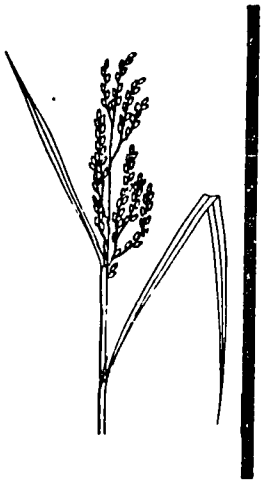
The following questions should be put to the person irrigating.

- How did he decide to irrigate the crop today? The following factors may have affected his decision:

  The appearance of the crop, the appearance of the soil, the time of last irrigation, the weather and season, or by digging in the soil. Note the irrigator's responses.

- How did he choose to irrigate this field and crop today when he has many fields and a limited supply of water? Why?

- What are his watercourse losses?
- What are his field losses?
- How deep does the water go? How deep do the roots go?
- How much water is he putting on the field?
- How did he decide when to shut off water to the field?



EVALUATION OF FURROW IRRIGATION SYSTEMS*

by T. Ley and W. Clyma

INTRODUCTION

Performance evaluation of furrow irrigation systems requires collection and analysis of data relating to both operation and the management. The procedures suggested for collection and analysis of data can be used at two levels, depending on the detail desired. The less detailed approach provides satisfactory evaluation of the system's performance using a minimum number of analyses. The more detailed approach adds information on the operating aspects of the system. Discussion of the procedures for collecting and analyzing the more detailed types of data is provided in a later section. An equipment list is provided. The following sections discuss the data to be collected, the chronological evaluation procedure, and suggested analyses of the data for an evaluation of irrigation practices.

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* Prepared under the support of the U.S. Agency for International Development, Contracts AID/NE-C-1351 and AID/DSAN-C-0058. All reported opinions, conclusions or recommendations are those of the authors and not those of the funding agency of the U.S. Government.

LESS DETAILED EVALUATION

Preliminary Data

Much preliminary data should be collected and analyzed before evaluation of an irrigation system occurs. These data include physical information of the site and information from the farmer concerning his particular system and its operation. Suggested questions to ask the farmer when obtaining this information are included in Auxiliary Sheet A. Other more specific questions should arise based on the farmer's answers to the general questions. However, all of the following categories should be address.

1. Farmer operation and management: Farmer management may be constraining the level of performance which can be attained. The farmer's general level of knowledge of irrigation principles and practices needs to be evaluated. Understanding why or how a farmer does certain things is vital. This aspect of evaluating irrigation performance often may be overlooked. The result is incomplete knowledge of the irrigation system.

2. Water supply: The farmer knows the available water supply, source, delivery, and frequency. He may have only a general knowledge of the flow rate and quality, factors that should be measured during evaluation. On-farm conveyance losses may be a big problem. Measure the losses if necessary.

3. Crop characteristics: The cultivated crops and the planting dates of each must be known. Use available data in the literature on the crops' seasonal water requirements, rates and stages of growth, maximum potential rooting depths, time from planting to effective cover, and climatic data estimating crop water use through the irrigation season. Measure the crop root zone at each irrigation for crops with expanding root systems. The measured root zone for a perennial crop (such as alfalfa) often can be assumed valid for the entire season unless there is a highly fluctuating water table. The crop root zone at each irrigation determines the available soil-water reservoir at that time and is necessary to determine the soil-water deficiency, the stress at the time of irrigation, and performance parameters, e.g., water application and water requirement efficiencies.

4. Physical characteristics: Measure and record the field dimensions. Drive stakes into the ground at 25 meters (m) intervals along the length (adjust for size of field as necessary). Measure and record surface elevation at each stake (station) using a field rod and

level. Plot the surface profile (elevation versus length). Measure and record furrow spacings at several locations in the field. Determine if the downstream boundary condition is ponded or free outflow. Determine where and how to measure furrow inflow and runoff.

5. Soil survey: If available, obtain information on soils (at the farm level) from maps and classifications from a local or regional office (e.g., USDA Soil Conservation Service or similar governmental agency). Such information aids the design of data collection procedures. Soil types and textures are known and maps usually depict the variation of surface textures in a field. If this information is not available, a soil survey is necessary to determine the soil types and uniformity in the field studied. Collect soil samples in a minimum of 10 locations in the field (i.e., at five locations along the length and two along the width). Take samples from a minimum of four depths within the expected root zone (i.e., every 30 centimeters (cm) in an expected 1.2 m root zone, adjust as necessary. Analyze samples to determine soil types.

Once soil types and variations through the field are known, the apparent specific gravity of the soil (bulk density) and the field capacity and wilting point of the soil must be determined. Garcia (1978) presents procedures for these measurements. Depending on the results of the soil survey, the sample collection procedure is defined. For a field with uniform soils, collect data on the above soil properties in a minimum of three locations in the field to obtain a good average. For a field with non-uniform soils, the above soil properties must be determined for each major soil type. A minimum of three replication of samples is necessary to obtain an average. In all cases, sample with depth.

Accurate definition of the above soil properties, though time-consuming, is necessary to eliminate having to repeat any sampling. The data are most easily collected before the crop is planted. Some change of apparent specific gravity of the plow layer with time may be expected. Sampling plans for soil-water content and infiltration tests are functions of soil type and uniformity. The results of the soil surface thus should be available before the initial irrigation evaluation.

If soil salinity/alkalinity is expected to be a problem (indicated by maps, previous surveys, information from the farmer), analyze samples to determine salinity/alkalinity. Such a problem also may indicate a high water table.

6. Water table: The farmer should have general knowledge of water table conditions in the area. Soil survey results may indicate a high water table. If the water table is high, or expected to fluctuate considerably (i.e., within the maximum potential root zone), monitor the groundwater level through the irrigation season with a series or grid of observation wells.

A high water table can limit crop growth through waterlogging. The groundwater quality also can seriously affect crop growth and should be measured.

Crop water use from the capillary fringe or the water table is possible. Estimates of crop consumptive use by evapotranspiration modeling techniques will not correspond with measured soil-water deficits (by soil-water content sampling) when the crop uses groundwater. This assumes both methods are yielding accurate results. This is significant if the water table rises during the season due to early overirrigation. Water table fluctuations due to overirrigation also may contribute to crop consumptive use and can affect root zone expansion.

ON THE DAY BEFORE IRRIGATION

Infiltration Data

When the field has a uniform soil, conduct blocked furrow infiltration tests in at least four locations along the irrigated run. When non-uniform soils are present, conduct a minimum of three test replications on each soil type. Enough labor should be available so each infiltrometer (Figure 1) is manned throughout the test. The tests should not last less than seven to eight hours, and in some cases, as long as the duration of irrigation. Garcia (1978) presents procedures for assembly and operation of the infiltrometers. Infiltration tests must be in furrows that will be irrigated. The tests are not necessary in furrows in which advance/recession data will be collected.

Preirrigation Soil-Water Content Data

Garcia (1978) presents procedures for the collection and analysis of soil samples to determine soil-water content by the gravimetric method. In furrow irrigation, it is difficult to determine average water contents in the soil profile because water does not cover the entire soil surface during irrigation; there may be significant channel movement of water in the soil. In all instances, take samples from each of several layers of the measured or expected maximum rooting depth of the crop (i.e., for a 1.2 m root zone, sample each 30 cm layer, and in the top 30 cm layer, collect samples from each 15 cm increment).

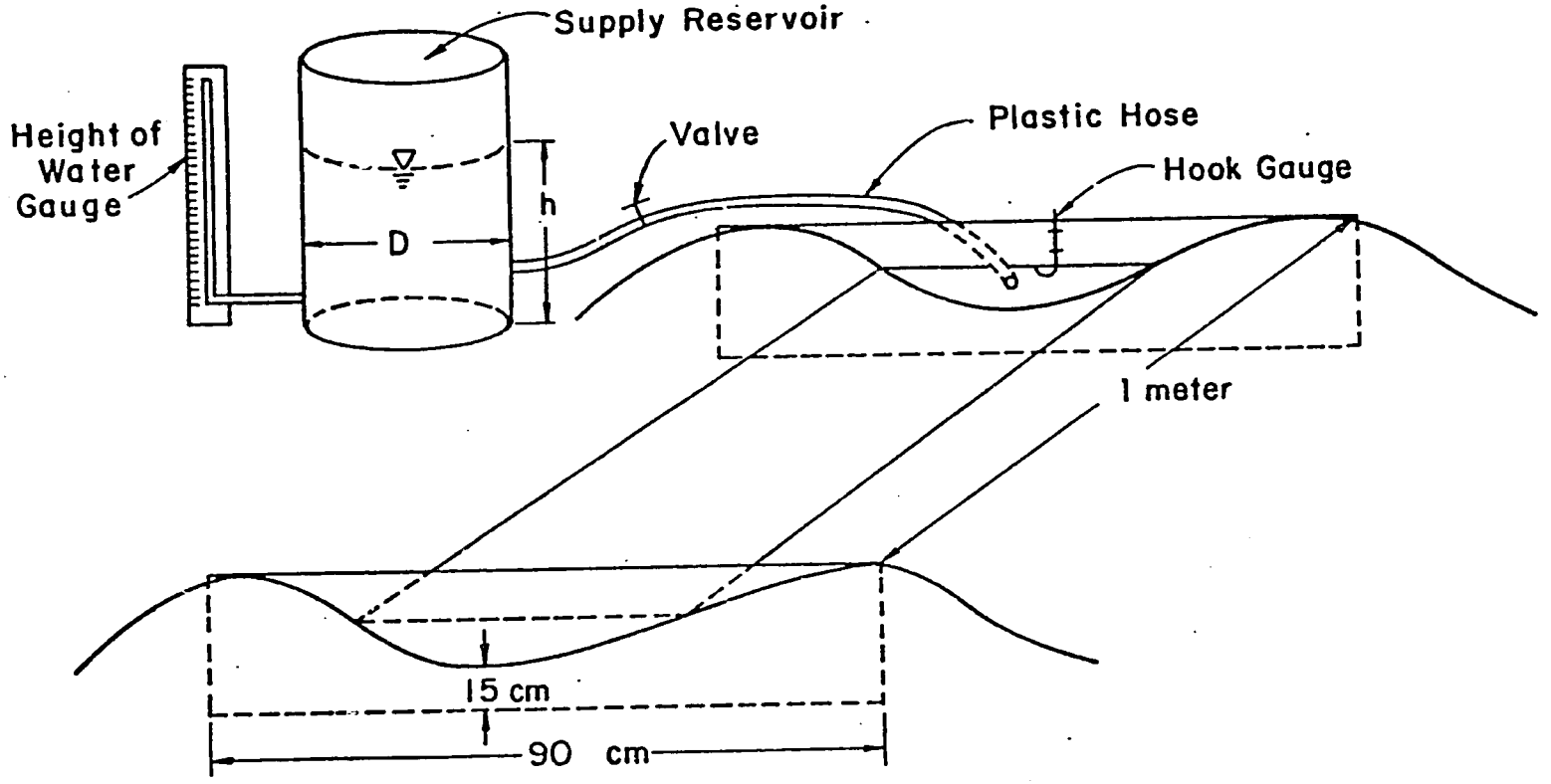


Figure 1. Block Furrow Infiltrometer

If the water table is higher or near the expected maximum rooting depth, collect samples near the water table. Each sample should be 150 grams or more. A problem arises in determining where to sample at each location. When every furrow is irrigated, take samples from the bottom of the wet furrow and the middle of the furrow ridge (plant row) between furrows to get a representative average (Figure 2a). When alternate furrows are irrigated, take samples from the bottom of the irrigated furrow, the middle of the furrow ridge (plant row), and from the bottom of the non-irrigated furrow, to get a representative average of the water content below the ground surface and between wet furrows (Figure 2b). In the example, an average water content for each layer sampled could be defined as:

$$P_{w,avg} = \frac{P_{w,1} + 2P_{w,2} + P_{w,3}}{4} \qquad (1)$$

where,

$P_{w,avg}$ = average water content for the layer,

$P_{w,1}$ = water content for the layer in area 1 (see Figure 2b),

$P_{w,2}$ = water content for the layer in area 2 (see Figure 2b),

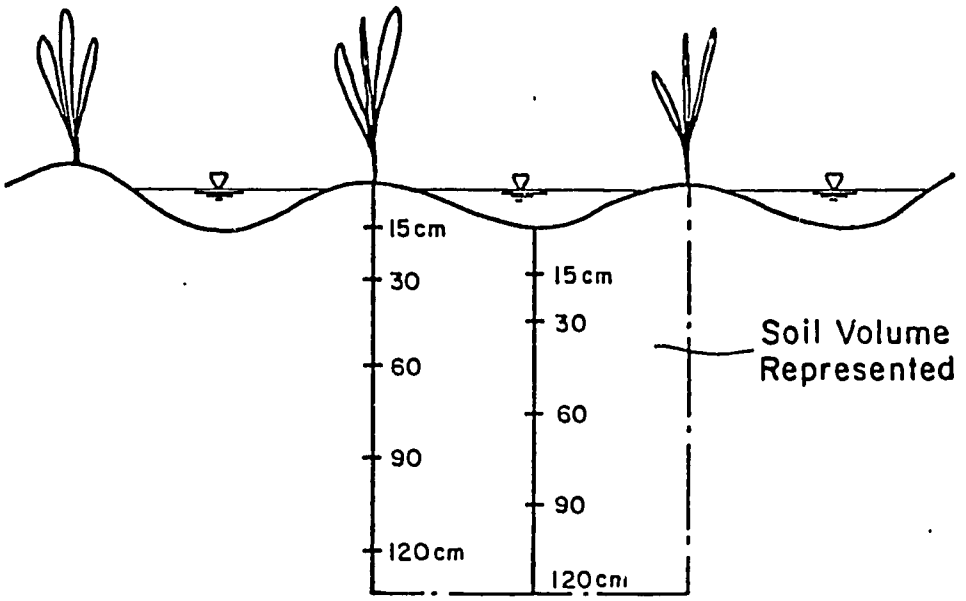
$P_{w,3}$ = water content for the layer in area 3 (see Figure 2b),

Note that Area 2 in Figure 2b receives twice the weight of the others in computing the average because that area occurs twice in the soil volume represented.

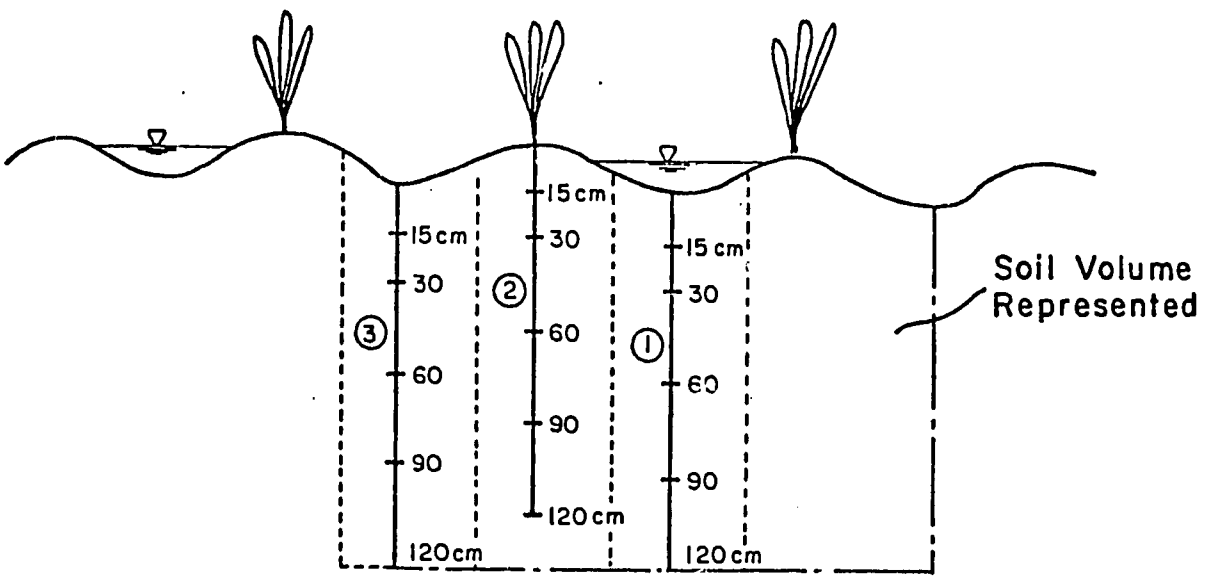
Soil sampling locations in the field are determined by the results of the soil survey. If soils in the field are found to be uniform, select a minimum of three sampling locations in different parts of the field (along the furrow) to obtain an average for the field. If soils are non-uniform or if non-uniform water applications are expected, a minimum of three replications of samples in each representative area are necessary for computing an average. For instance, the distribution of applied water in many fields is non-uniform. A sampling scheme to delineate the differences along the length might be three replications of samples at the head, middle and tail ends of a field.

Evaluation Data

Evaluation data (inflow/runoff, advance/recession, and so forth) should be collected on a minimum of three furrows. Install flumes or other flow measuring devices at the head and tail ends of each furrow to be evaluated. Take



A. Suggested Sample Holes When Every Furrow is Irrigated



B. Suggested Sample Holes When Alternate Furrows are Irrigated

Figure 2. Suggested Soil Water Sampling Locations Across An Irrigated Furrow Spacing

care to ensure that flumes (if used) are level, have no leaks around them, and that furrow sides are built up in the approach to the flume to prevent overtopping. The flume (being a critical depth flow measurement device requiring a loss of head) may cause water in the approach section of the furrow to back up. This effect is more pronounced on smaller slopes than on steeper ones. Install flow measuring devices the day before irrigation.

ON THE DAY OF IRRIGATION

The following data are taken on a minimum of three furrows as the irrigation progresses. Record the clock time when water is introduced to each furrow studied.

1. Advance Data--Record the clock time at which the water arrives at each station (i.e., every 25 m) as the waterfront moves down the furrow.

2. Inflow Data--Periodically record the clock time or elapsed time from the beginning of irrigation and the reading for each inflow rate measuring device.

3. Runoff Data--Record the clock time when water reaches the point (usually near end of field) where the runoff rate measuring devices are located. Collect runoff data at 30 sec, 1 min, 2 min, 4 min, 8 min, 15 min, 30 min and then every 1/2-hour from the time when runoff begins.

4. Recession Data--Toward the end of irrigation, remove the flow measuring devices from the furrows. Record the clock time when water is shut-off. Record the clock time at which water recedes from each station. The receding water edge is hard to define. Recession at a particular point is assumed to occur when approximately two-thirds of the furrow wetted perimeter is free of water. Very shallow flow conditions exist during recession. Small puddles and ripples in the furrow bottom compound the problem. Consistency is of prime importance when taking recession data.

Note: Check all flow measuring devices during the irrigation for leaks and proper operating conditions. During the evaluation, note any unusual factors or conditions. For instance, cracks in the soil significantly affect advance rate. Note any erosion, sedimentation and crop conditions (e.g., relative size, color, stand, wilting,) throughout the section of the field being irrigated. Stunted growth may indicate salinity problems, poor infiltration rates (i.e., change in soil texture of the plow pan layer that reduces infiltration), or other problems.

AFTER IRRIGATION

Collect soil-water content samples any time from one and a half days to three days after irrigation, depending on soil type and the time required for the soil to drain to field capacity. Garcia (1978) presents a field procedure for estimating when (after wetting) a soil is drained to field capacity. The same collection procedures previously discussed apply.

DISCUSSION AND RECOMMENDATIONS

It is important to explain to the farmer what will be done during the evaluation because the farmer's cooperation is vital. Nothing investigators do before or during evaluation should cause the farmer to deviate from his normal irrigation practices.

Preliminary data collected early in the season must be thorough. A careful, coordinated, determined effort to collect such data saves time and eliminates problems and headaches later in the season. For instance, soil-water content of a field before the initial irrigation of the season generally may be assumed to be uniform. Care in soil sampling and in subsequent collection of additional samples (to increase the precision with which mean soil-water content is estimated) is recommended because establishing the initial condition is the starting point for a root zone soil-water budget.

From the initial condition, water added to the root zone of the crop precipitation (measured by rain gauges set up in several locations at the site) and by irrigation (measured by irrigation evaluations) is known. Crop use is estimated using climate data, crop stage, and growth data in an accurate, calibrated evapotranspiration (ET) model. A soil-water budget for the next zone thus can be calculated through the season. Soil water content data collected at succeeding irrigations of the season are used to check the predicted soil-water status when calibration of the ET model is necessary.

If there is a high water table in the area, crop use from the capillary fringe or the water table itself can be estimated. The difference between calculated crop use and measured (by sampling) soil-water deficit during an irrigation interval is an estimate of crop use from the water table during that interval. If there is no reason to believe the crop uses water from a water table, the computed difference indicates the accuracy of each method and the sampling and/or predictive techniques may need to be improved.

Collecting advance/recession data may not be necessary at each irrigation. A uniform application of water may be expected on a field with shorter lengths of run on a heavier soil. In such cases, the distribution is assumed uniform and all that is required is the water on and water off to determine the water added to the soil. Nevertheless it is advisable to collect advance/recession data when any non-uniformity of water application is suspected due to poor irrigation practices, non-uniform soils, non-uniform field slopes, and so forth, in order to know the distribution of applied water.

During irrigation evaluation, conduct a partial evaluation of the data being collected by processing data as it is collected in the field and interpreting the results. For instance, in evaluating inflow and runoff data, an error is obvious if runoff is greater than inflow. Such data checks eliminate wasted time and effort by avoiding collection of erroneous data.

FIELD DATA ANALYSIS

Field data analysis provides a basis for understanding performance of the irrigation system and how the system is operated. Data may be analyzed through a number of procedures. Those presented here represent the minimum analyses required to understand the system's performance resulting from a particular management scheme.

Infiltration Data

Data collected during blocked furrow infiltration tests are generally of the form: total volume infiltrated per unit length versus elapsed time. Data are plotted on log-log or rectangular grid paper. Garcia (1978) presents methods of analyzing the data so an infiltration relationship of either of the following forms can be determined:

$$z = kt^{a}, \tag{2}$$

or

$$z = Kt^{A} + Ct \tag{3}$$

where

z = cumulative volume infiltrated per unit length (L^3L^{-1}),

t = elapsed time (T),

C = steady-state or large-time infiltration rate ($L^3T^{-1}L^{-1}$),

k, a, K, A = empirical constants.

An infiltration function of either form (Equation 2 or 3) should be found. The function usually is determined for the mean of the infiltration data collected at particular locations in a field. For instance, the mean is determined for infiltration data on each major soil type or for each area where a sampling plan calls for tests.

Soil-Water Content Data

Garcia (1978) presents procedures for determining water content (dry weight basis) of each soil sample collected. The depth of water in the soil profile is found using the following relationship:

$$d_m = \sum_{i=1}^{n} (P_{w,i} \times \gamma_{b,i} \times Y_i) \qquad (4)$$

where

d_m = water depth in the soil profile (L),

$P_{w,i}$ = water content (dry weight basis) of the ith layer of the profile (MM^{-1}),

$\gamma_{b,i}$ = soil bulk density in the ith layer of the profile [$ML^{-3}(ML^{-3})^{-1}$],

Y_i = thickness of the ith layer (L), and

n = number of root zone layers sampled.

The preirrigation water depths at each sampling location (i.e., position in the field) are averaged and compared to the water depth when the soil is at field capacity. Result: an estimate of the amount of water that needs to be applied during irrigation to bring the root zone to field capacity. This method for determining the soil-water deficit at irrigation time is subject to the wide variability observed in soil-water content sampling studies, and may give unreliable results. When reliable crop data and climate data are available, obtain another estimate of soil-water deficit through use of an evapotranspiration modeling procedure and soil-water budgeting as discussed earlier.

Water depths before and after irrigation can be compared to obtain an estimate of the depth of water infiltrated (assuming there is no deep percolation of water past the lowest sampling depth) at each location. This is, of course, subject to the comment made previously concerning the reliability of soil sampling to determine water contents. The temporal and spatial variability in soil properties can be magnitudes and even orders of magnitude in just a small area of a field. Thus, the limitation on the reliability of results is imposed.

Advance/Recession Data

Normally, advance/recession data are plotted on a rectangular grid with time as the ordinate and distance along the furrow as the abscissa (Figure 3). The difference in time between the two curves is the infiltration opportunity time. The infiltration opportunity time at each station along the field should be determined. Often, the surface elevations also are plotted on the same sheet. Non-uniformity of slope along the run usually will show up in the advance and recession curves. A plot of the surface profile may be useful often in explaining variations in advance/recession rates.

Inflow and Runoff Data

Plot hydrographs showing the inflow and runoff data versus time. The inflow hydrograph is plotted up to the time of shut off. Graphical integration of the area under this curve represents the volume of water applied, $W_a(L^3)$. The runoff hydrograph also is plotted up to the time of shut off. After shutoff, the runoff rate is assumed to decrease linearly from the runoff rate at the time of shutoff to zero at the end of recession. Graphical integration of the entire area under this curve represents the total runoff volume, W_u (L^3). The difference between the volume of applied water and volume of runoff (as determined by this method) is the volume of water remaining in the field, or the total volume infiltrated during the irrigation, i.e.,

$$W_i = W_a - W_u \tag{5}$$

where W_i = total volume infiltrated (L^3).

The inflow-runoff method is assumed to be the most accurate for determining total volume of infiltration because 1) it gives the average infiltration for the entire furrow length (as opposed to "point" type measurements from infiltration tests or soil-water data), and 2) flow rates usually can be measured more accurately than infiltration or soil-water content.

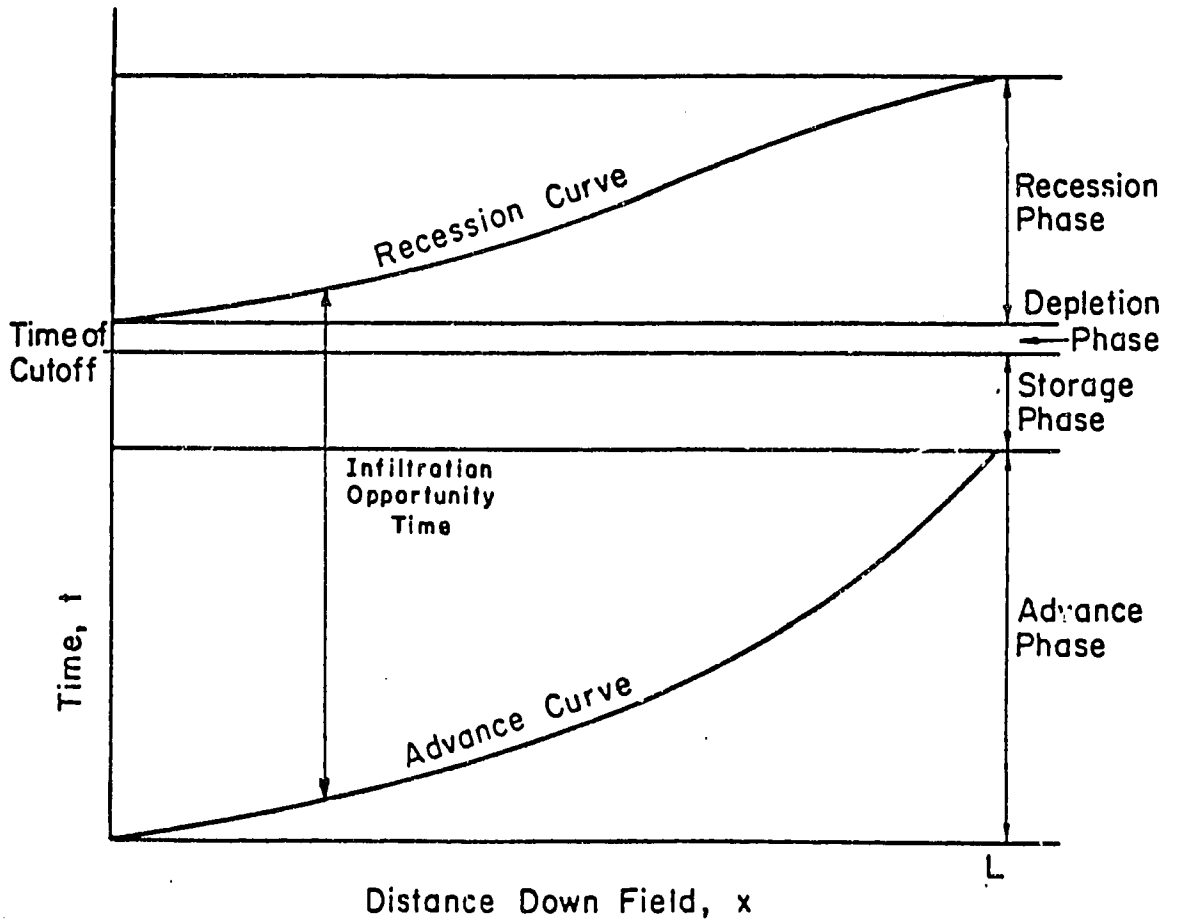


Figure 3. Simplified Representation of Advance and Recession Curves and Phases of Irrigation

Subsurface Distribution of Applied Water

The subsurface distribution of applied water in furrow irrigation can be determined when the following information is known.

1. A representative infiltration function(s) as determined above.

2. Infiltration opportunity times along the irrigated run, i.e., advance/recession times at points along the run.

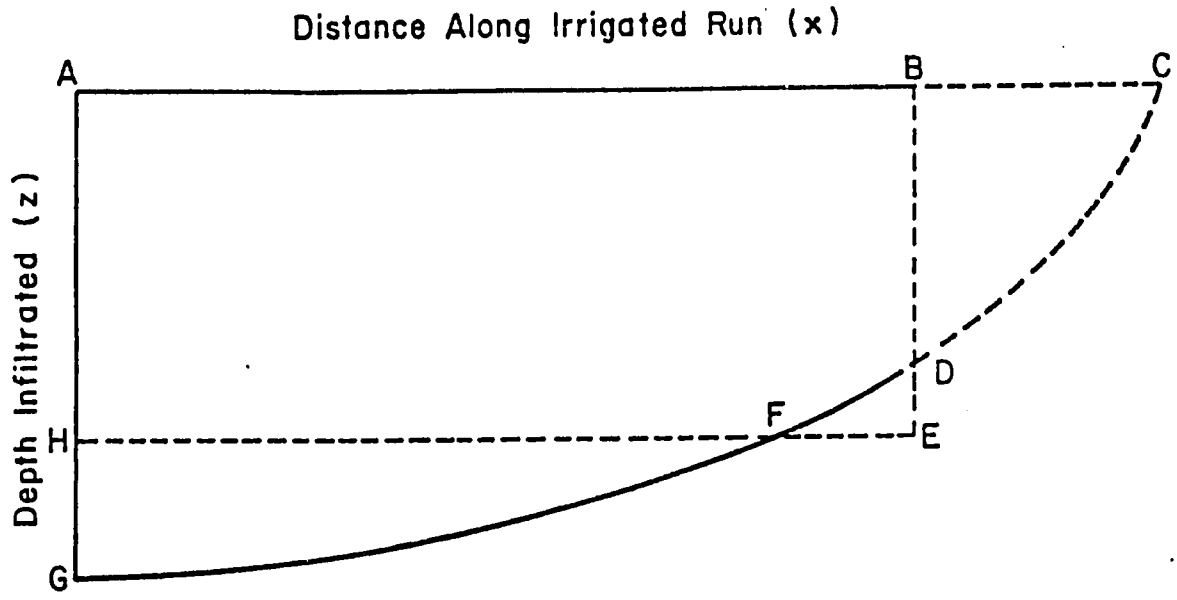
After the subsurface profile is constructed, it is possible to characterize the performance of a particular irrigation. However, before irrigation performance parameters are defined, it is necessary to define several related quantities upon which they depend.

Figure 4 represents an idealized profile of infiltrated water as a result of a furrow irrigation. The distance AB is the field length and the line DFG is the boundary of the infiltrated water. If the downstream boundary condition is one of free outfall, runoff water from the field can be assumed to extend to the imaginary field length C, and to infiltrate according to the profile CD. The water requirement depth at the time of irrigation is assumed uniform along the field length and is represented by line EFH. With these concepts in mind, the following quantities with appropriate units (shown in Figure 4) are defined.

1. Total volume of applied water, W_a (area ACDGA), which is the total volume of water introduced per furrow.

2. Total volume of water required in the root zone to reach field capacity, W_r (area ABEHA), which is the volumetric soil-water deficit.

3. Total volume of water stored in the root zone, W_{rz} (area ABDFHA), which depends on the field capacity of the soil and the available storage at the time of irrigation. The total volume of water available for plant use after the irrigation and drainage period equals the difference between the field capacity (FC) and the permanent wilting point (PWP) of the soil, assuming the root zone is filled completely from the permanent wilting point to field capacity during irrigation [i.e., the total available water expressed as a depth, TAW = (FC - PWP) x (bulk density of the soil) x (rooting depth).



AB	length of furrow (L)
ACDGA	total volume of applied water per furrow, $W_a(L^3)$
ABEHA	total volume of requirement per furrow, $W_r(L^3)$
ABDFHA	total volume of actual root zone storage per furrow, $W_{rz}(L^3)$
FGHF	total volume of deep percolation per furrow, $W_p(L^3)$
BCDB	total volume of runoff water per furrow, $W_u(L^3)$
DEFD	total volume of root zone deficit after irrigation per furrow, $W_{df}(L^3)$

Figure 4. Idealized Subsurface Profile of Applied Water in Furrow Irrigation

4. Total volume of deep percolation, W_p (area FGHF). The volume of water which infiltrates past the lower boundary of the root zone. W_p may equal zero in some cases.

5. Total volume of tailwater or runoff, W_u (area BCDB). The volume of water which runs off the end of the field if free outfall conditions exist.

6. Total volume of root zone deficit after irrigation, W_{df} (area DEFD). W_{df} equals zero if the root zone is completely filled.

The infiltration relationship(s) as determined from infiltration tests and the infiltration opportunity times from advance/recession data are used to plot the subsurface distribution. The total infiltrated volume as predicted by the infiltration function(s) should be determined from this plot. Comparison of the total infiltrated volume with the value determined by the inflow/runoff hydrograph analysis is a check on the adequacy of the infiltration function(s) in predicting the total infiltrated volume. If there is significant deviation, the multiplicative constants of the infiltration function(s) are adjusted by a trial and error volume balance procedure until the two values coincide. Then the subsurface distribution, as predicted by the "adjusted" infiltration function(s), is plotted. The soil-water deficit, as estimated through soil-water content analyses or evapotranspiration studies, also is plotted on the same sheet.

Graphical integration of each representative area of the subsurface distribution is used to find each of the volumes previously mentioned. Values of volume applied, volume infiltrated, and volume of runoff as determined by both the inflow/runoff analyses and by the subsurface distribution should correspond (assuming the infiltration function used to construct the subsurface profile is representative, i.e., yields good prediction of total infiltration water volume).

PERFORMANCE PARAMETERS

Four irrigation performance parameters are defined as follows:

1. Water application efficiency, E_a, is the percent of the amount of water applied that is stored in the root zone for future use.

$$E_a = \frac{W_{rz}}{W_a} \times 100 \qquad (6)$$

where

$$W_{rz} = W_i - W_p \quad (7a)$$

$$= W_r - W_{df} \quad (7b)$$

2. Water requirement efficiency, E_r, indicates the percent of the amount of water required to refill the root zone that is supplied by an irrigation.

$$E_r = \frac{W_{rz}}{W_r} \times 100 \quad (8)$$

3. Runoff (or tailwater) ratio, R_t, represents the fraction of the total amount applied that is lost as runoff from the end of the field.

$$R_t = \frac{W_u}{W_a} \quad (9)$$

4. Deep percolation ratio, R_p, represents the fraction of the total amount applied that is lost as deep percolation past the bottom of the root zone.

$$R_p = \frac{W_p}{W_a} \quad (10)$$

The sum of the deep percolation ratio, the runoff ratio, and the water application efficiency (expressed as a fraction) is unity. Each of the above volumes can be treated as average depths when divided by the product of furrow length and irrigated furrow spacing.

AN EXAMPLE OF SYSTEM EVALUATION

Following are the results of an evaluated furrowed irrigation system using the procedures just discussed. A design of the field was formulated using the SCS furrow irrigation design procedure (USDA, 1978 draft). The results are presented in a separate analysis of the design procedure (Ley and Clyma, 1980). Thus, it is possible to compare the current system operation and performance with the suggested design operation and performance. Ultimately, that enables possible changes to the system design and management thereby improving its performance. Recommended design parameters are repeated here.

Q = 0.57 - 0.76 lps/furrow (9-12 gpm/furrow)

T_1 = 720 min

irrigated furrow spacing = 1.12 m (3.67 ft)

design depth = 61 mm (2.4 in)

The irrigated crop was sugarbeets planted on a 0.56 m (1.84 ft) row spacing. Soil-water content samples both before and after irrigation were collected. However, analysis proved them to be inadequate. At any rate, an average evapotranspiration rate for sugar beets was determined to be near 6 mm/day (0.24 in/day) in the general area. The elapsed time from the previous irrigation (when the root zone was last completely filled) to the time of the irrigation being evaluated was 12 days. The soil-water deficit thus was estimated to be approximately 72 mm (2.8 in).

The farmer irrigated the furrows from a concrete-lined head ditch using 1-1/4 inch siphon tubes. Every other furrow was irrigated so the irrigated furrow spacing was 1.12 m. The average furrow grade is 0.0098 m/m. The furrow length is 365 m. Inflow and runoff measurements were taken at the head of the furrow and at x = 350 m, respectively. Soils were found to be uniform, although there was some variation in texture with depth.

Five blocked furrow infiltration tests were conducted the day before irrigation at five locations along the length of run. The data, reduced to the form of volume infiltrated per unit length versus time, are plotted in Figure 5. The mean infiltrated volume per unit length versus time was found and also is plotted in Figure 5. A least squares regression procedure, outlined in Garcia (1978) determined an empirical infiltration function of the form of Equation (3) for the mean:

$$z = 2369.4\ t^{0.37} + 70\ t \qquad (11)$$

where

z = cumulative volume infiltrated (cm^3/m),

t = time (min).

This function also is plotted in Figure 5.

Advance and recession data and surface elevation data are plotted in Figure 6. Infiltration opportunity times at stations along the furrow are included. The time of advance to the runoff measuring device (x = 350 m) was 180 minutes. The plot of the surface profile slope (Figure 6) indicates the uniformity of slope is acceptable.

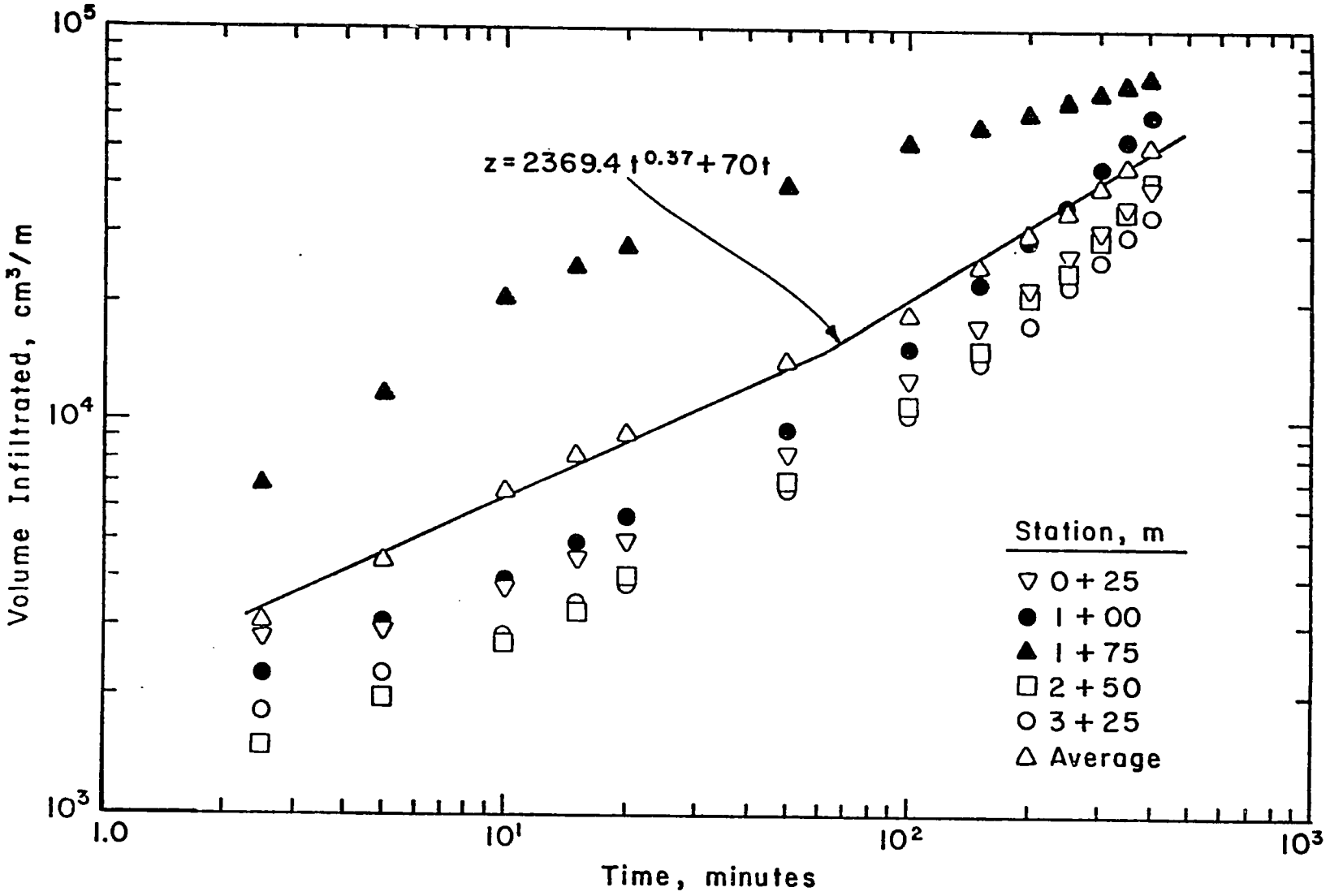
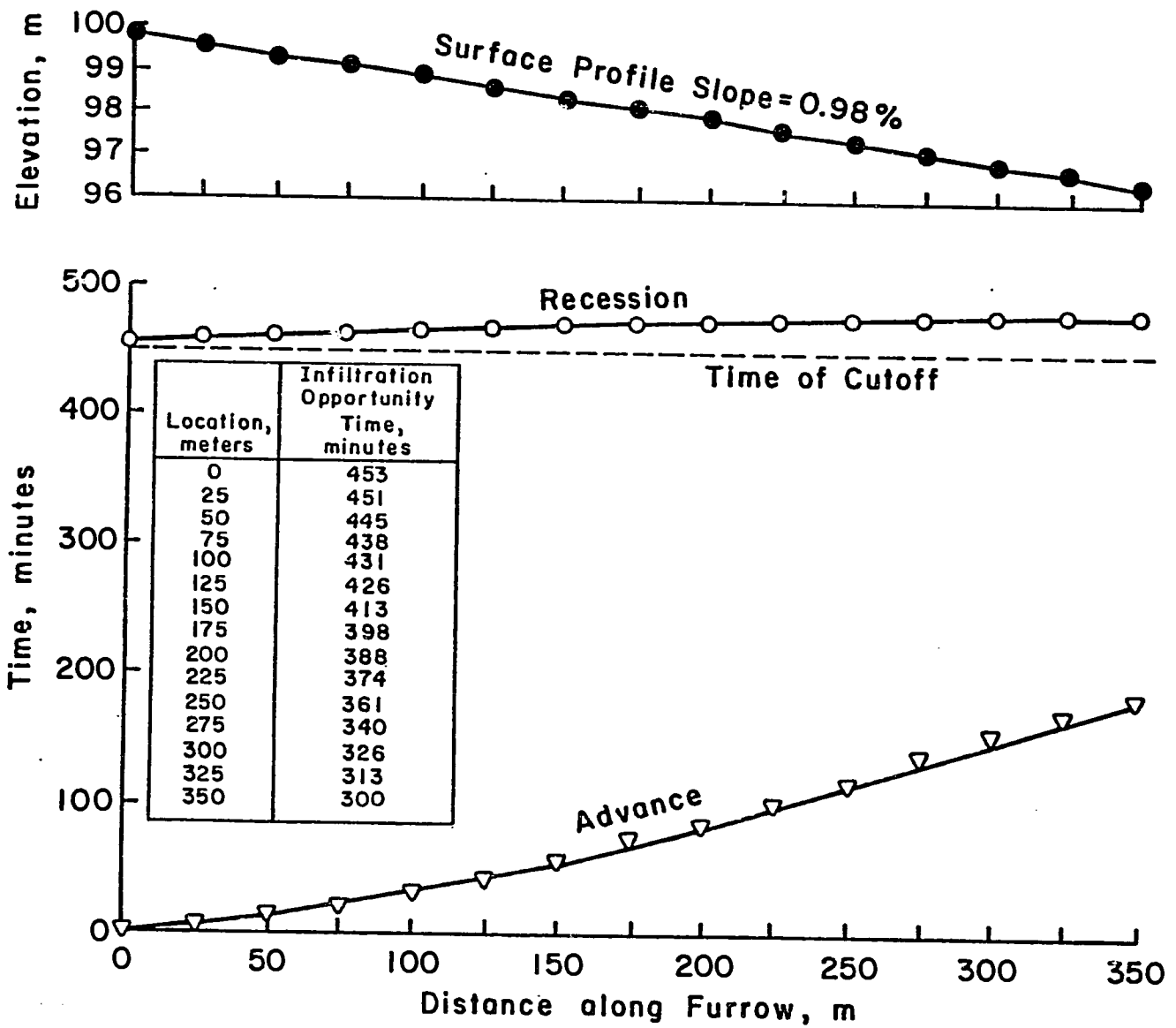


Figure 5. Blocked Furrow Infiltration Test Data



Location, meters	Infiltration Opportunity Time, minutes
0	453
25	451
50	445
75	438
100	431
125	426
150	413
175	398
200	388
225	374
250	361
275	340
300	326
325	313
350	300

Figure 6. Advance/Recession Curves, Subsurface Profile Slope and Infiltration Opportunity Times

Normally, the farmer uses a 12 hour inflow or set time. For this irrigation, however, a power failure caused pump shutdown and interrupted irrigation. The inflow time over which measurements were taken was 7.5 hour. Inflow and runoff data for that time period are plotted in Figure 7. Graphical integration of the area enclosed by each curve resulted in the following volumes:

$$\text{Total volume applied, } W_a = 22.86 \text{ m}^3$$

$$\text{Total runoff volume, } W_u = 6.68 \text{ m}^3$$

$$\text{Total infiltrated volume, } W_i = W_a - W_u = 16.18 \text{ m}^3$$

An average infiltrated depth can be found by dividing by the furrow length and irrigated furrow spacing. In this case, a furrow length of 350 m is used because that is the distance over which infiltration occurred. The average infiltrated depth is:

$$\frac{16.18 \text{ m}^3}{(350 \text{ m})(1.12 \text{ m})} \left(\frac{1000 \text{ mm}}{\text{m}}\right) = 41.3 \text{ mm}$$

Infiltration opportunity times (from Figure 7) are used in Equation (11) to plot the subsurface distribution (Figure 8). The ordinate in Figure 8 is an average infiltration depth in centimeters obtained by converting values obtained in Equation (11) from cm^3/m to m^3/m, then by dividing by the irrigated furrow spacing (m) and multiplying by 100 to obtain cm. Graphical integration of the area enclosed by this curve results in an estimate of total volume infiltrated per unit width as predicted by the blocked furrow infiltration function (Equation 11). The estimate is:

$$W_i')_{pred.} = 15.19 \text{ m}^3/\text{m of width}$$

where

$W_i')_{pred.}$ = estimated total volume infiltrated per unit width ($L^3 L^{-1}$).

Multiplying by the furrow spacing (1.12 m) yields an estimate of total volume infiltrated. Hence,

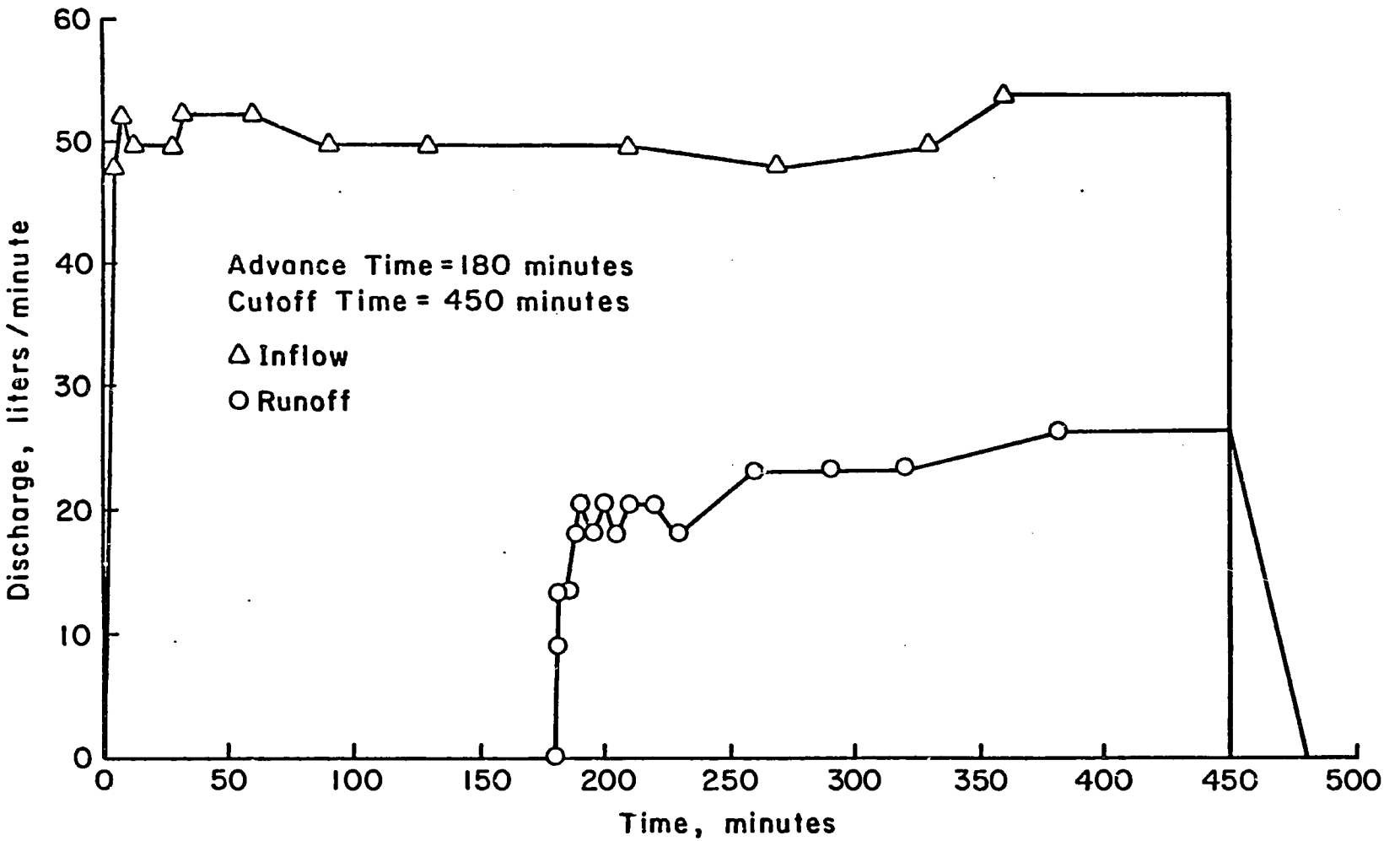


Figure 7. Inflow and Runoff Hydrographs

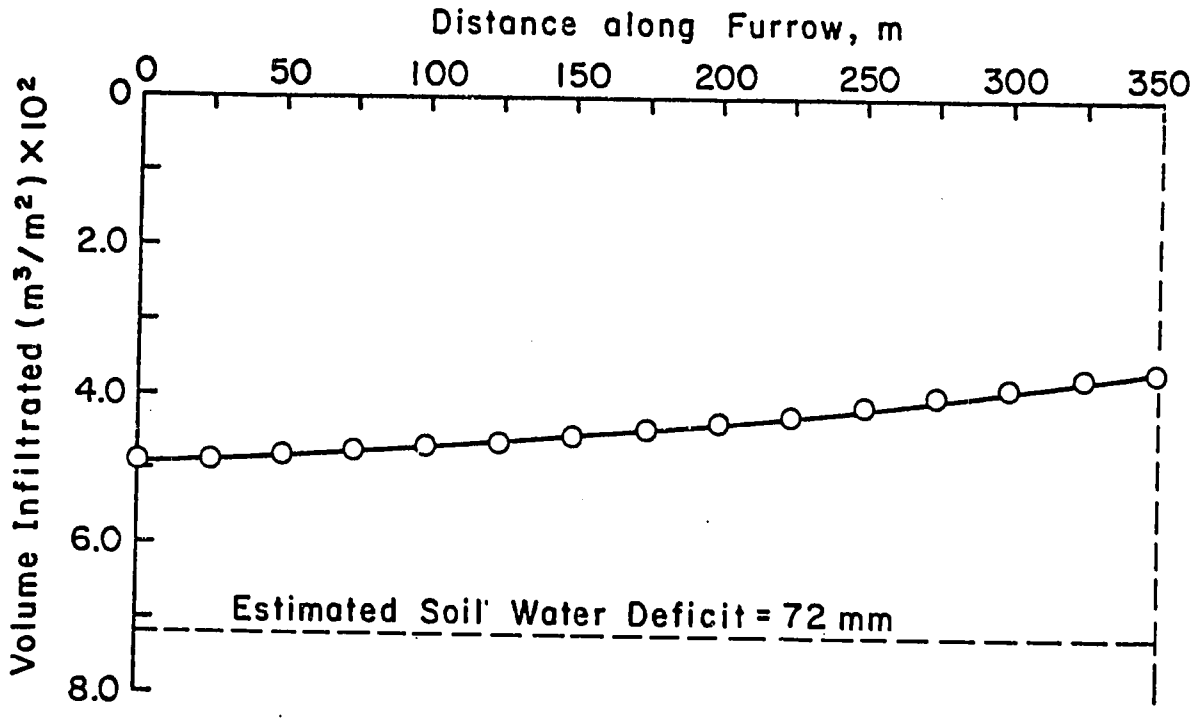


Figure 8. Subsurface Distribution of Applied Water Estimated from Blocked Furrow Infiltration Function, $z = 2369.4t^{0.37} + 70.0t$ (z - cm^3/m, t-min)

$$W_i)_{pred} = W_i')_{pred.} \times 1.12$$
$$= (15.15)(1.12)$$
$$= 17.02\ m^3$$

where

$W_i)_{pred.}$ = estimate of total infiltrated volume (L^3).

An estimate of the average infiltrated depth as predicted by the blocked furrow infiltration function is:

$$\frac{17.02\ m^3}{(350\ m)(1.12\ m)} \quad \frac{1000\ mm}{m} = 43.4\ mm$$

Comparison of the prediction of total infiltrated volume as obtained using the blocked furrow infiltration function with the value obtained by inflow/runoff hydrograph analysis shows the following deviation:

$$\frac{17.02 - 16.18}{16.18} \quad 100 = +5.2\%$$

This deviation is acceptable, considering the accuracy with which data can be collected in the field. Had the deviation been unacceptable (i.e., greater than 10-15 percent), an adjustment of the multiplicative constants in the infiltration function would be necessary by a volume balance trial and error procedure or graphical procedure (Ley and Clyma, 1980) until the deviation was within an acceptable range.

Results

Each of the volumes associated with performance parameters can be determined with the results of the inflow/runoff hydrograph analysis and the subsurface distribution plot. For this case, the inflow/runoff hydrograph results are used. The volumes are as follows:

Total volume applied, W_a = 2[illegible].86 m^3

Total runoff volume, W_u = 6.68 m^3

Total volume infiltrated, W_i = 16.18 m^3

Total volume required, W_r = $(72\ mm)\left(\frac{1\ m}{1000\ mm}\right)(350\ m)\ (1.12\ m)$

$$= 28.22\ m^3$$

Total volume stored, $W_{rz} = 16.18\ m^3$

Total volume deep percolation, $W_p = 0.0\ m^3$

Total deficit volume, $W_{df} = 28.22 - 16.18$

$= 12.04\ m^3$

Each volume can be converted to an average depth by dividing by the product of furrow length and irrigated furrow spacing. The performance parameters for this irrigation are determined using Equations (6) through (10).

Water application efficiency, $E_a = \frac{W_{rz}}{W_a} \times 100$ (6)

$= \frac{16.18}{22.86} \times 100$

$= 70.8\%$

Water requirement efficiency, $E_r = \frac{W_{rz}}{W_r} \times 100$ (8)

$= \frac{16.18}{28.22} \times 100$

$= 57.3\%$

Tailwater ratio, $R_t = \frac{W_u}{W_a}$

$= \frac{6.68}{22.86}$

$= 0.292$

$$\text{Deep percolation ratio, } R_p = \frac{W_p}{W_a} \tag{10}$$

$$= \frac{0.0}{22.86}$$

$$= 0.0$$

Because the irrigation was interrupted by a power failure, it is not possible to compare the design with the results of this evaluation. However, it is known that the farmer normally uses a 12 hour set time and that he makes no adjustment to the furrow inflow rate once the siphon tubes are set. Hence, referring again to Figure 7, it is possible to estimate what the volumes for a 12 hour inflow time would have been by extrapolating both the inflow and runoff curves out to 720 minutes at a discharge rate equal to their averages for the last half of the 450 minute irrigation. Changes will occur in W_a, W_u, W_i, W_{rz} and possibly W_p. Estimates of what the volumes and performance parameters for the 12 hour set might have been are as follows:

W_a = 36.40 m^3

W_u = 13.32 m^3

W_i = 23.08 m^3

W_{rz} = 23.08 m^3

W_p = 0.0 m^3

E_a = 63.4%

E_r = 81.8%

R_t = 0.366

R_p = 0.00

Table 1 provides a summary of the evaluation and a comparison with the design.

Table 1. Summary of Evaluation and Comparison with Design

Parameter	Evaluation (measured)	Evaluation (estimated)	Design*
Inflow time, min	450	720	720
Average furrow inflow rate, l/s	0.847	0.843	0.57-0.76 (9-12 g/m)
Design depth or requirement, mm	72	72	61 (2.4 in.)
Average depth applied, mm	58.4	93.0	70.0 (2.76 in.)
Average infiltrated depth, mm	41.4	58.9	56.5 (2.22 in.)
Water application efficiency, %	70.8	63.4	81.4
Water requirement efficiency, %	57.3	81.8	92.7
Tailwater ratio, dec.	0.292	0.366	0.186
Deep percolation ratio, dec.	0.00	0.00	0.00

*Values for average depth applied, average depth infiltrated and design performance parameters are averages for the 0.57-0.76 lps (9-12 g/m) range of furrow inflow rates.

Conclusions

1. The interrupted irrigation was inadequate. The uniformity of application was good.

2. Extrapolation of flow rates on the inflow/runoff hydrographs (to 720 min) yields an estimate of what the system's performance normally would be under the farmer's current (12 hour set) operation. Assuming the results valid, the farmer is doing only a fair job of replenishing the needed soil-water balance and has a large runoff loss. Comparison with the suggested design parameters indicates why this happens. First, the farmer's average furrow inflow rate for the irrigation is well above the suggested range. This is a major reason for the high runoff losses as compared to design. Second, the farmer irrigates at a higher soil-water deficit than suggested by

design analyses. This factor contributes to the under-irrigation which occurs with his current management.

3. The initial design for the field was formulated for a design depth of 72 mm (2.8 in.), the approximate operating soil-water deficit for the farmer. Only marginally acceptable levels of design performance could be obtained for these design conditions. Iterations of the design procedure for smaller design depths were carried out and a feasible design determined for a design depth of 61 mm (2.4 in.). The farmer can significantly improve system performance by altering his system management to apply a smaller amount (61 mm) on a more frequent basis, i.e., reducing the design depth from 72 mm (2.8 in.) to 61 mm (2.4 in.) shortens the irrigation interval by 1 to 2 days.

Recommendations

1. The farmer should alter his system management to the smaller design application depth as discussed. Given the range of furrow inflow rates suggested from the design, 0.57 to 0.76 l/s (9 to 12 g/m), acceptable levels of system performance can be achieved.

2. Further evaluations of the irrigation system are necessary. If the farmer accepts the above design parameters, an evaluation of the new design and management is desired. Seasonal changes in factors and conditions that affect the system performance also must be evaluated so an efficient operation can be implemented throughout the season.

MORE DETAILED EVALUATION

When it is desirable to obtain more detailed information on the physical operating aspects of an irrigation system, make the following measurements in sequence with the procedures described previously.

Furrow Cross Section Data

Obtain an estimate of the furrow cross-sectional area by using the device shown in Figure 9. Place the furrow profilometer in the furrow with the sliding rods just resting on the furrow bottom. Place an identification marker of the location next to the profilometer and take a photograph of them. Place the markers in several (at least three) preselected points along each furrow in which other measurements are made (for example, advance/recession, inflow/runoff). Collect furrow cross section data before and after the irrigation at the same time soil

water content samples are collected. Exercise care and good judgment so the profilometer is placed in a representative section of the furrow without disturbing the soil.

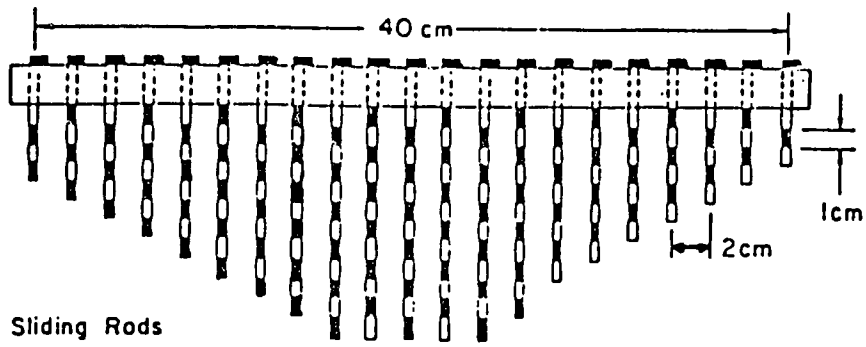


Figure 9. Furrow Profilometer

Flow Depth and Top Width Data

Measure the flow depth and top width in each furrow in which inflow/runoff and advance/recession data are taken. Take measurements at several points along the furrows several times during the irrigation at approximately the same location each time. When the data are collected, make the measurements as often as possible during the advance, and at 30 to 60 minute intervals during the rest of the irrigation.

Furrow Infiltration Data

Another method for determining infiltration during furrow irrigation is the inflow-outflow method presented by Criddle, et al. (1956). Place small flumes or other flow measuring devices in the furrow at spacing anywhere from 25 m to 75 m. Record 1) the inflow and outflow rates versus time and 2) the flow depth and top width measurements for each section. Use a volume balance procedure (discussed shortly) to determine an infiltration relationship. When these data are collected, make the measurements in furrows other than those in which advance/recession data are collected.

DATA ANALYSES

Furrow Profiles and Surface Storage

Once the furrow cross section photographs are ready, transcribe the data on the appropriate data form. The data then is analyzed and, in general, an empirical power relationship between center depth and cross-sectional area found:

$$A_f = ARy^{BR} \tag{12}$$

where

A_f = furrow cross-sectional area (L^2),

y = center depth (L), and

AR, BR = empirical constants.

The constants AR and BR are found using a least squares technique. Usually a mean relationship for the entire furrow length is determined as follows:

1. Graphically estimate the area of each cross section at depths of 1, 2 and 3 cm from the furrow bottom at the furrow centerline.

2. Calculate the mean area for the furrow sections of each furrow at each depth.

3. Perform a logarithmic transformation of Equatio.. (12) and a least squares regression of the transformed variables to determine the constants AR and BR.

Assuming the empirical relationship for the furrow cross-sectional area (as just derived) is valid for the entire furrow length, use flow depth data to find flow areas at each point where flow depth is measured. Because flow depth data are available through the advance phase and the remaining phases of irrigation, an average cross-sectional flow area for the entire furrow length is found for each phase. In turn, an estimate of the total volume of water in the furrow (surface storage) for a particular length is found by multiplying the average flow area by the furrow length being considered. The volume of surface storage may be necessary in certain volume balance analyses.

The cross-sectional flow area relationship and flow depth data also are used in estimating the furrow roughness in a relationship such as Manning's formula:

$$Q = \frac{C_u}{n} S_o^{1/2} R^{2/3} A_f \qquad (13)$$

where:

Q = flow rate at a particular section (L^3T^{-1}),

n = Manning's roughness factor,

S_0 = bed slope ($L\ L^{-1}$),

R = hydraulic radius (L),

A_f = cross-sectional flow area (L^2), and

C_u = constant dependent on units (1.0 for metric, 1.486 for English).

For such an analysis, steady uniform flow in a prismatic channel of uniform slope is assumed. This assumption allows Manning's formula to be used with the energy gradient equal to the furrow bed slope. The condition of steady uniform flow in furrow irrigation is approximated at the time when the soil reaches its basic intake rate. Thus, only flow depth data for about the last half of the irrigation is used. The flow rate at any particular section along a furrow is assumed to decrease linearly from the inflow rate to the runoff rate when the soil is at its basic intake rate. Hence, Equation (13) is solved for Manning's n because the other variables can be estimated (i.e., R and A_f are found from the furrow cross-sectional relation and flow depth data). Point estimates of n result and are averaged to find the mean furrow roughness.

Furrow Infiltration by Inflow-Outflow

Criddle, et al. (1956) present a complete method for analyzing data collected in the inflow-outflow procedure. It involves a volume balance procedure using the inflow-outflow rate measurements to determine the furrow infiltration versus time. Because flow depth data are available for the sections of furrow evaluated, the volume of surface storage for those sections is found as described previously. The estimates of surface storage volume are time distributed as are the inflow rate and outflow rate measurements. A volume balance as follows results in a time distribution of the volume infiltrated.

$$VINF(t) = VIN(t) - [VOUT(t) + VSS(t)] \quad (14)$$

where

VINF(t) = total volume infiltrated at time t, (L^3),

VIN(t) = total volume of inflow to furrow section at time t, (L^3),

VOUT(t) = total volume of outflow from furrow section at time t, (L^3), and

VSS(t) = volume of water in surface storage at time t, (L^3).

In general, a functional relationship for infiltration can be determined for the data: volume infiltrated versus time.

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AUXILIARY SHEET A:

SUGGESTED QUESTIONS FOR INTERVIEWING FARMERS

Farmer operation and management

How does the farmer decide when to irrigate?
What is his irrigation frequency? How does it change during the season?
How does he decide how to irrigate?
How does he decide how much water to apply?
Does the farmer know the total flow rate available to him?
What are the farmer's operating hours?
Does he irrigate at night?
How does he decide how long to irrigate a field?
How long does he irrigate a field?
Does the farmer have any problems with the system?
What are his cultivation and tillage practices?
Does he irrigate every furrow or alternate furrows?
How many furrows does he irrigate in one set?
How many sets does it take to irrigate the field?
Does he try to compact the furrows equally?

Water supply

What are the sources of available water?
Is the delivery station (point of diversion to farm) a problem, i.e., high losses, etc.?
Is the on-farm distribution system a problem (i.e., too many in-field channels, high losses, etc.)?
What is the flow rate of each source of water?
When is each source available and for how long?
Is the frequency of delivery and available head a problem?
What is the water quality?
How is the water delivered to each field?

Crop characteristics

What are the crops grown?
What are the respective planting dates?
What cropping patterns, if any, are followed?
Does the farmer have any major problems in crop production?
What are the major inputs? Potential yield?
What is his expected yield? Average yield in area?
Any obvious physical symptoms of problems?

Physical characteristics

Does the farmer know the field dimensions?
Does he know the slope and cross-slope (if any)?
Is the field leveled to a uniform slope?
If yes, when? If no, why not?
What provisions, if any, are made for surface runoff?
Does runoff leave the farm or is it used again somewhere on the farm?
What is the border spacing and how did the farmer decide on that spacing?
What is the furrow spacing?
What is the method of diverting water into each furrow?

Soil survey

Does the farmer know the soils on his farm?
Does he know of any trouble spots (i.e., very light or heavy soils or salinity problems)?

Water table

Does the farmer know the groundwater level?
Does he think it is a problem?
Is surface/subsurface drainage provided? If so, where?

AUXILIARY SHEET B: EQUIPMENT LIST

Following is a list of equipment necessary for the evaluation of three furrows:

1. Six flow measurement devices (i.e., small cutthroat flumes with 1 inch throats);

2. Engineer's level, field rod, chain or tape, orange flagging;

3. Wood stakes and lathe for station markers, crayon for marking, and hatchet for driving them into ground;

4. Soil sampling equipment:

   - soil auger or tube sampler

   - soil sample cans with tight fitting lids (up to 200, 2-inch diameter cans)

   - box for carrying cans;

5. Small carpenter's levels for leveling flumes, etc;

6. Blocked furrow infiltration equipment (up to 10 sets, see Figure 1) plus plastic sheeting;

7. 50 small wire stakes with orange flagging;

8. Bulk density equipment;

9. Instruments for measuring time (stopwatch, wrist watch with second hand);

10. Buckets for hauling water;

11. Shovels, sledge hammers;

12. Soil uniformity box (partitioned box); and

13. Pencils, clipboards and data forms.

For more detailed measurements include:

14. Device for measuring flow depth and top width;

15. Furrow profilometer (see Figure 9);

16. Camera, film and identification marker; and,

17. Small flow measurement devices for furrow infiltration by inflow-outflow method.

EVALUATION OF GRADED BORDER IRRIGATION SYSTEMS*

by T. Ley and W. Clyma

INTRODUCTION

To evaluate grader border irrigation systems it is necessary to collect information on both the physical and managerial aspects. The data collected is used to determine the performance of the irrigation. The calculation procedures are given together with an example.

REQUIRED DATA

Preliminary Data

Evaluation of any irrigation system requires collection and analysis of extensive data, not the least of which is basic preliminary site data that can be obtained through interviews with the farmer and by performing several basic physical measurements. It is desirable to obtain as much information as possible from the farmer concerning his operation and management of the system. (Suggested questions to assist in interviewing the farmer are given in Auxiliary Sheet A.) Each of the following information categories should be addressed. The list is

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not exhaustive and often the farmers answers to some questions lead the trained person to other more site specific questions.

1. Farmer operation and management: Understanding why or how a farmer does certain things in managing and operating the irrigation system is vital. The farmer's general level of knowledge concerning irrigation principles and practices may constrain the performance level. This aspect of evaluating irrigation performance often may be overlooked and results in incomplete knowledge of the irrigation system.

2. Water supply: The farmer knows the available water supply, source, delivery, and frequency. He may have only a general knowledge of the flow rate and quality. Measure flow rate and quality during the course of an evaluation. On-farm conveyance losses may be a big problem. Measure the losses if necessary.

3. Crop characteristics: The cultivated crops and the planting dates must be known. Data in the literature are needed on the crop's seasonal water requirements, rates and stages of growth, maximum potential rooting depths, time from planting to effective cover, and so forth. Use such information and climatic data estimating crop water use through the irrigation season. Measure the crop root zone at each irrigation for crops with expanding root systems. The measured root zone for a perennial crop (such as alfalfa) often can be assumed valid for the entire season unless a fluctuating water table is encountered. The crop root zone at each irrigation determines the available soil-water reservoir and is necessary to determine soil-water deficiency, stress at the time of irrigation, and performance parameters, e.g. water application and water requirement efficiencies.

4. Physical characteristics: Measure and record the field dimensions. Drive stakes into the ground at 25 meters (m) intervals along the length (adjust for size of field as necessary). Measure and record surface elevations at each stake (station) using a field rod and level. Plot the surface profile (elevation versus length). Measure and record cross-slope and border spacing at each station. Determine if a ponded or free outflow boundary condition exists at the downstream end. Determine where and how to measure border inflow and runoff.

5. Soil survey: If available, obtain information on soils in the area (at the farm level) such as maps and classifications from a local or regional office (e.g., USDA Soil Conservation Service or similar governmental agency). Such information aids the design of data

collection procedures. Soil types and textures are known and maps usually depict the variation of surface textures in a field. If this information is not available, a soil survey is necessary to determine the soil types and uniformity in the field studied. Collect soil samples in a minimum of 10 locations in the field (i.e., at five locations along the length and two along the width). Take samples from a minimum of four depths within the expected root zone (i.e., every 30 centimeters (cm) in an expected 1.2 m root zone, adjust as necessary). Analyze the samples to determine soil types.

Once soil types and variations through the field are known, the apparent specific gravity of the soil (bulk density), the field capacity and wilting point of the soil must be determined. Garcia (1978) presents procedures for these measurements. Depending on the results of the soil survey, the sample collection procedure is defined. For a field with uniform soils, collect data on the above soil properties in a minimum of three locations in the field to obtain a good average. For a field with non-uniform soils, the above soil properties must be determined for each major soil type. A minimum of three replications of samples is necessary to obtain an average. In all cases, sample with depth.

Accurate definition of the above soil properties though time consuming is necessary to eliminate having to repeat any sampling. The data are most easily collected before the crop is planted. Some change of apparent specific gravity of the plow layer may be expected with time. Sampling plans for soil-water content and infiltration tests are functions of soil type and uniformity. The results of the soil survey thus should be available before the initial irrigation evaluation.

If soil salinity/alkalinity is expected to be a problem (indicated by maps, previous surveys, information from the farmers), analyze samples to determine the salinity/alkalinity. Such a problem also may indicate a high water table.

6. Water table: The farmer should have general knowledge of water table conditions in the area. Soil survey results may indicate a high water table. If the water table is high or expected to fluctuate considerably (i.e., within the maximum potential root zone), monitor the groundwater level through the irrigation season with a series or grid of observation wells.

A high water table can limit crop growth through waterlogging. The groundwater quality also can seriously affect crop growth and should be measured.

Crop water use from the capillary fringe or the water table is possible. Estimates of crop consumptive use by evapotranspiration modeling techniques will not correspond with measured soil water deficits (by soil-water content sampling) when the crop uses groundwater. This assumes both methods are yielding accurate results. This is significant if the water table rises during the season due to early overirrigation. Water table fluctuations due to overirrigation also may contribute to crop consumptive use and can affect root zone expansion.

ON THE DAY BEFORE IRRIGATION

Preirrigation Soil Water Content Data

Garcia (1978) presents procedures for the collection and analysis of soil samples to determine water content by the gravimetric method. Depending on results of the soil survey (which should be available by this point), devise the sampling plan. If the soil survey results show soils to be uniform, select a minimum of three locations in different parts of the field for sampling to obtain an average for the field. However, if certain variations are expected (e.g., non-uniform water applications) or if soils are non-uniform, collect a minimum of three replications of samples where the non-uniformities are or where variations are expected. For instance, non-uniform water applications along the length of run is common. So, collect a minimum of three replications of samples at a minimum of three representative locations along the length.

In all cases, collect samples from each of several layers of the measured or expected maximum rooting depth of the crop (i.e., for a 1.2 m root zone, sample each 30 cm layer, and in the top 30 cm layer, collect samples from each 15 cm increment). If the water table is higher than expected maximum rooting depth, collect samples to the water table. Each sample should be 150 grams or more.

Make other preparations for evaluation, such as installation of flow measuring devices and cylinder infiltrameters, the day before irrigation. Contact the farmer and determine the time he expects to start irrigating. Arrive in sufficient time to complete all preparations for the evaluation(s), such as preparation of data forms and assignment of duties.

ON THE DAY OF IRRIGATION

Infiltration Data

For uniform soils, conduct at least three, preferably six, cylinder infiltration tests in three locations along the length. For non-uniform soils, make three test replications in each area where a different soil texture exists. If non-uniformity in distribution along the length of run is anticipated, three replications for each representative length of the field are necessary to delineate these differences. During the season, differences in soil-water content accentuate differences in infiltration and distribution of water.

Start the infiltrometer measurements as the water arrives at each infiltrometer and maintain the ponded depth the same as the depth of flow of irrigation water. If the tests cannot be conducted during irrigation, use a buffer ring to conduct them on the day before irrigation. Garcia (1978) presents procedures for installing infiltrometers and conducting the tests.

Inflow/Runoff Data

Properly install flow measurement devices to determine inflow to and runoff from the border before irrigation. Record the clock time* at which water is first introduced to the border. Measure initial inflow rate. Periodically during the irrigation, record inflow rate and clock time of the observation. When water reaches the runoff measurement device, begin runoff rate versus time measurements. To obtain runoff data from the time runoff starts, take a reading at 30 sec, 1 min, 2 min, 4 min, 8 min, 15 min, 30 min, and then every 1/2 hour. Record the clock time when water entering the border is terminated.

Advance/Recession Data

Observe and record the rate of waterfront advance. When the moving stream front is irregular, record the time when an "average" front reaches each station (see Figure 1). After the inflow is terminated, record the rate of recession. Ideally, this is when water disappears from each station. It is difficult to determine the location of the receding water edge. When water has disappeared from 50 percent of the grid surface area represented by each station, recession is assumed to occur at that station. Consistency is of primary important in taking recession data.

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* Clock times should be on a 24-hour basis (military time).

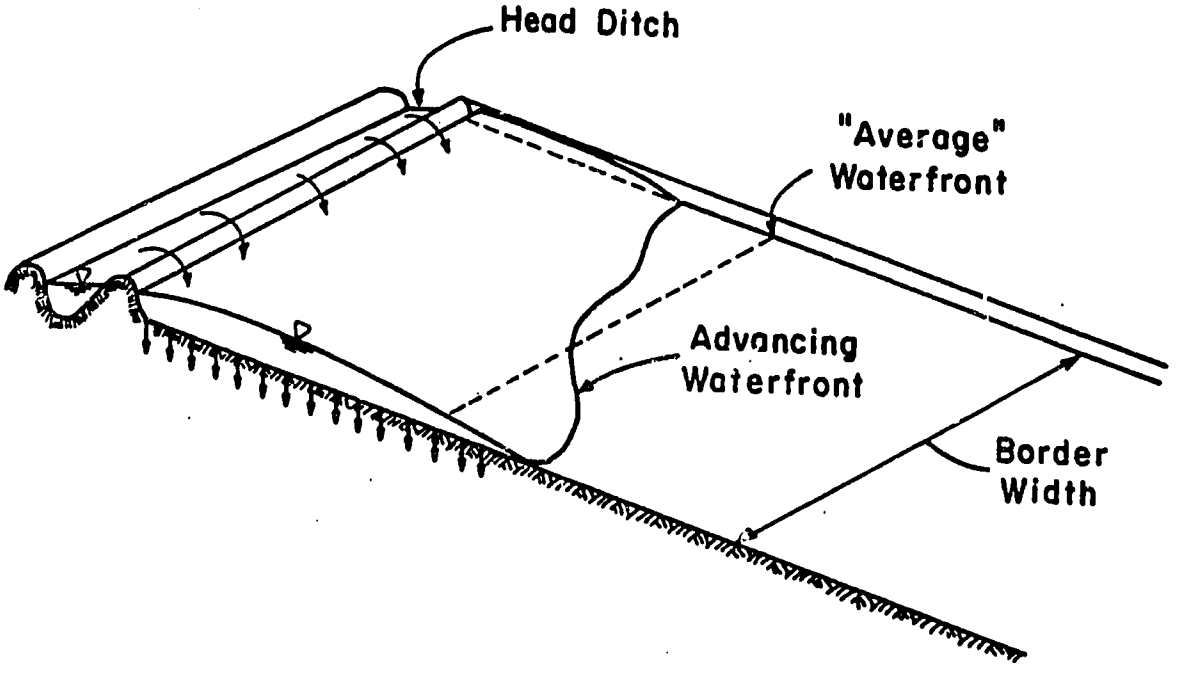


Figure 1. Illustration of Irregular Waterfront Advance and Location of "Average" Waterfront

AFTER IRRIGATION

Collect soil-water content samples one and a half days to three days after irrigation depending on soil type and the time required for soil to drain to field capacity. Garcia (1978) presents a field procedure for estimating when (after wetting) a soil drains to field capacity. Use the same collection procedures as previously discussed.

DISCUSSION AND RECOMMENDATIONS

Describe exactly what will be done to ensure the farmer's cooperation during evaluation. The purpose of evaluation is to determine system performance and evaluate the system operation as the farmer currently manages it. Avoid remarks that may influence his management decisions. Be sure the farmer operates his system as he usually does. Minimize crop damage and soil disturbance.

Preliminary data collected early in the season must be thorough. A careful, coordinated, determined effort saves much time and eliminates problems and headaches later in the season. For instance, soil water content of a field before the initial irrigation of the season generally may be assumed as uniform. Careful soil sampling and collection of more samples (to increase the precision with which mean soil-water content is estimated) is recommended because establishing the initial condition is the starting point for a soil-water budget for a root zone.

From the initial condition, water added to the root zone of the crop by precipitation (measured by rain gauges set up in several locations at the site), and by irrigation (measured by irrigation evaluations) is known. Crop use is estimated using climate data and crop stage and growth data in an accurate, calibrated evapotranspiration (ET) model. A root zone soil-water budget thus can be calculated through the season. Soil-water content data collected at succeeding irrigations of the season are used to check the predicted soil-water status when calibration of the ET model is necessary.

If there is a high water table in the area, crop use from the capillary fringe or the water table itself can be estimated. The difference between calculated crop use and the measured (by sampling) soil-water deficit during an irrigation interval is an estimate of the crop use from the water table during that interval. If there is no reason to believe the crop uses water from a water table, the computed difference indicates the accuracy of each method and the sampling and/or predictive techniques may need to be improved.

Collecting advance/recession data may not be necessary at each irrigation. A uniform application of water may be expected on a field with shorter lengths of run on a heavier soil. In such cases, the distribution is assumed uniform and all that is required is the water on and water off to determine the water added to the soil. Nevertheless, it is advisable to collect advance/recession data when any non-uniformity of water application is suspected due to poor irrigation practices, non-uniform soils, non-uniform field slopes, and so forth, in order to know the distribution of applied water.

During irrigation evaluation, conduct a partial evaluation of the data being collected. This is best accomplished by processing data as it is collected in the field and interpreting the results. For instance, it is easy to evaluate inflow and runoff data: an error is obvious if the runoff is greater than the inflow. Such data checks eliminate wasted time and effort by avoiding collection of erroneous data.

FIELD DATA ANALYSIS

Field data analysis provides a basis for understanding performance of the irrigation system and how the system is operated. Data may be analyzed through a number of procedures. Those presented here represent the minimum analyses required to understand the system's performance resulting from a particular management scheme.

Soil-Water Content Data

Soil water content may be estimated by two methods: 1) gravimetric method, and 2) feel method. The soil-water content expressed as a depth of water per unit depth of root zone is estimated using the results of the gravimetric soil-water analyses in the following equation:

$$D_m = \sum_{i=1}^{n} (P_{w,i} \times \gamma_{b,i} \times y_i) \qquad (1)$$

where

d_m = the soil-water content expressed as a depth (L) for the entire depth investigated,

$P_{w,i}$ = dry weight soil-water content for the ith layer of the root zone (MM^{-1}),

$\gamma_{b,i}$ = soil bulk density in the ith layer $[(ML^{-3})(ML^{-3})^{-1}]$

y_i = thickness of the ith soil layer (L), and

n = number of layers in the root zone which were sampled.

Check preirrigation soil-water content data with the soil field capacity to estimate soil-water deficit (available root zone storage) at the time of irrigation. As previously discussed, crop water use and root zone soil-water budgeting also provide a check on soil-water deficit at irrigation time. The soil-water data both before and after irrigation also can be useful in analyzing depths infiltrated and adequacy of irrigation along the border, assuming there is no deep percolation of water below the lowest depths investigated.

The feel method for estimating soil-water content is largely subjective because it depends on visual inspection of certain characteristics of the soil sample. Use the method only when the investigator has extensive experience and, even then, only for a rough estimate of soil-water content.

Advance/Recession Data

Plot advance/recession data on coordinate paper as shown in Figure 2. The advance curve is a plot of the time the waterfront advances along the border versus the length of the border. The recession curve is a plot of the time the waterfront recedes from the surface versus the border length. The intake opportunity time is the difference between the advance and recession time as shown in Figure 2. Intake opportunity times represent the amount of time water has the opportunity to infiltrate at points along the border. Surface elevation data often are plotted on the same graph to aid in explaining variations in advance/recession rates and the effects on infiltration opportunity time.

Infiltration Relationship

Reduce the data from cylinder infiltration rests to the form of cumulative depth of infiltration versus time. Then plot the reduced data on log-log paper (Garcia, 1978). In general, the data plot as straight lines, but may curve slightly and often "dogleg". Some curves steepen after a few minutes, either because of the release of trapped air (usually in sandier soils) or because the cylinders were not driven deeply enough. Soils that have cracks into which water disappears quickly often exhibit curves that are initially steep and then flatten. Plow pans may cause a similar, but usually delayed effect. Compute the average infiltrated depth versus time using data from each area where soil properties are found to be uniform (Merriam and Keller, 1978). Also plot the average infiltrated depth versus time on the

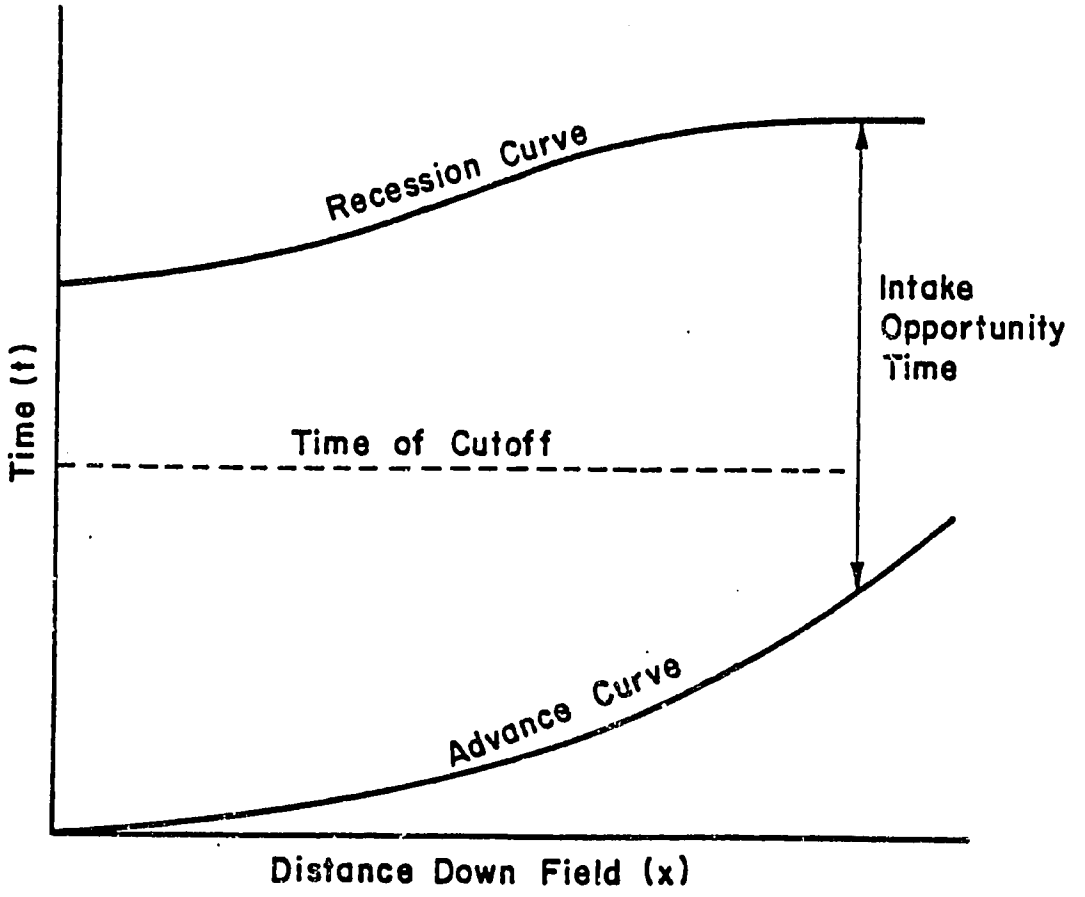


Figure 2. Typical Advance and Recession Curves for Border Irrigation

same log-log graph as the individual data sets for there areas. A least-squares regression technique (see Garcia, 1978) often is used to find an infiltration function of the following form for the average infiltrated depth versus time:

$$z = kt^a \tag{2}$$

where

z = cumulative depth infiltrated (L),

t = time (T), and

k, a = empirical constants.

This type of infiltration function usually is considered representative in border irrigation. In most cases, the infiltration relationship from ring infiltration tests is inadequate in predicting the actual infiltration which occurs during irrigation. Find actual average infiltrated depth by using inflow and runoff data (discussed later) for the irrigation. Use the following procedure to find the predicted average infiltrated depth:

1. Find the predicted infiltrated depth at each station by using intake opportunity times (from advance/recession data) for stations along the border and the infiltration relationship.

2. Determine the average infiltrated depth for each reach (distance between stations) by averaging the predicted infiltrated depths of successive stations.

3. Determine the predicted average infiltrated depth for the entire border by summing the reach averages (found in 2) and dividing by the number of reaches. Remember this value is an estimated or predicted value resulting from the use of the empirical infiltration function.

Inflow and Runoff Data

Inflow and runoff data provide a simple means of determining the actual average infiltrated depth. Construct the inflow and runoff hydrographs on the same rectangular grid by plotting inflow and runoff rates versus time. Estimate the total volume of water applied, $W_a(L^3)$ by graphically integrating the area under the inflow hydrograph. Estimate the total runoff volume, $W_u(L^3)$ by graphically integrating the area under the runoff hydrograph. Estimate the total infiltrated volume, $W_i(L^3)$ by taking the difference as follows:

$$W_i = W_a - W_u \quad (3)$$

Then determine the actual average infiltrated depth by dividing W_i by the product of the border width and length.

Adequacy of Infiltration Relationship

Once the predicted average infiltrated depth and the actual average infiltrated depth are found, compare them to check the adequacy of the empirical infiltration function in predicting the average infiltrated depth. If the two values are not approximately equal (i.e., less than 5 to 10 percent difference), adjust the infiltration relationship accordingly until the predicted value is approximately equal to the actual value. The adjustment procedure is done either graphically or numerically and involves finding a new value for the multiplicative constant in Equation (2) while the value of the exponent remains the same (Merriam and Keller, 1978). For example, on the log-log plot, the slope of the curve remains constant and the curve is either shifted upwards or downwards. Both graphical and numerical procedures are more fully explained in the example evaluation presented later.

Runoff Data Not Available

When runoff data are not available, check the adequacy of the infiltration function using actual average applied depth rather than actual average infiltrated depth (Merriam and Keller, 1978). This method requires extrapolation of advance/recession curves to their intersection to estimate the water applied. The method also estimates how far water spreads if downstream boundary condition at end of the border was an imaginary extended border length. Find the predicted average applied depth by using intake opportunity times in the infiltration relationship as previously discussed. Now, however, opportunity times for the imaginary extended length must be included in the analysis. Find the actual average applied depth by dividing total applied volume by the imaginary wetted area (i.e., the product of border width and total imaginary extended length). Comparison of predicted average and actual average applied depths indicates if adjustment of the infiltration relationship is necessary. This procedure obviously is not as accurate as that used when runoff data are available because errors occur in extrapolation of advance/recession curves.

Subsurface Distribution

The subsurface distribution of applied water in border irrigation can be determined when the following information is known:

- -- A representative infiltration function (as determined above); and
- -- Infiltration opportunity times along the irrigated run, i.e., advance/recession times at points along the run.

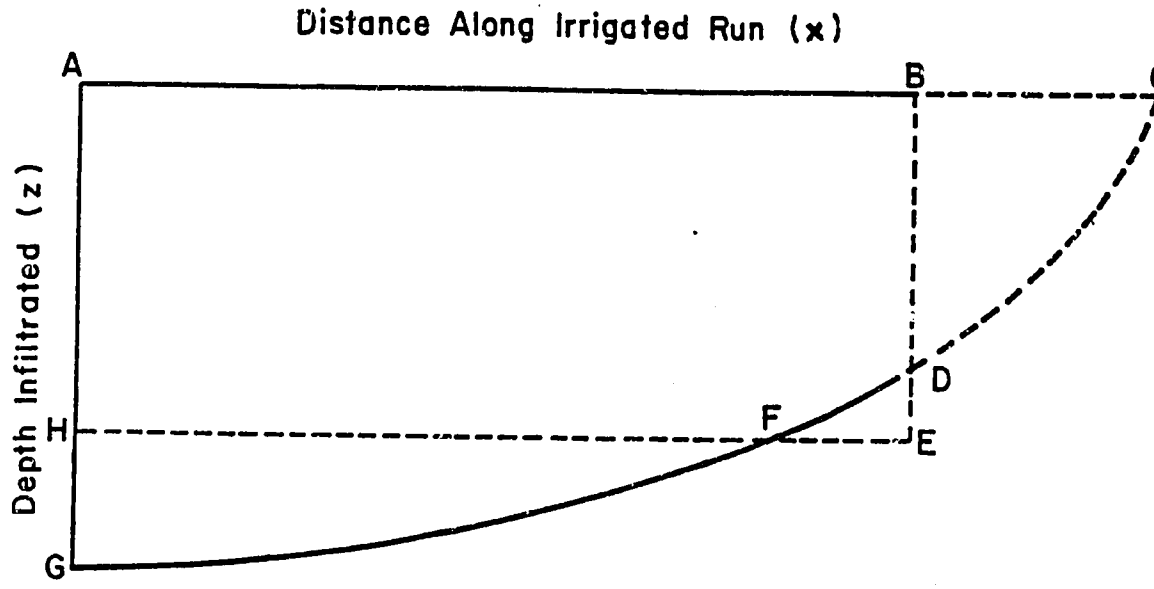
After a subsurface profile is constructed, it is possible to characterize the performance of a particular irrigation. Before irrigation performance parameters are defined, however, it is necessary to define several related quantities upon which they depend.

Figure 3 represents an idealized profile of infiltrated water as a result of border irrigation. The distance AB is the border length; the line DFG is the boundary of the infiltrated water. If the downstream boundary condition is one of free outfall, runoff water from the field can be assumed to extend to the imaginary field length C and to infiltrate according to the profile (N). The water requirement depth at the time of irrigation is assumed uniform along the border length and is represented by line EFH. With these concepts in mind, the following quantities with appropriate units are defined in Figure 3.

1. Total volume of applied water, W_a (area ACDGA) is the total volume of water introduced per unit width of border.

2. Total volume of water required in the root zone to reach field capacity, W_r (area ABEHA) is the volumetric soil water deficiency.

3. Total volume of water stored in the root zone, W_{rz}(area ABDFHA) depends on field capacity of the soil and available storage at the time of irrigation. Total volume of water available for plant use after the irrigation and drainage period equals the difference between field capacity (FC) and permanent wilting point (PWP) of the soil if the root zone is completely filled during irrigation [i.e., the total available water expressed as a depth, TAW = (FC - PWP) x (bulk density of the soil) x (rooting depth)].



AB	length of border (L)
ACDGA	total volume of applied water per unit field width, $W_a(L^3L^{-1})$
ABEHA	total volume of requirement per unit field width, $W_r(L^3L^{-1})$
ABDFHA	total volume of actual root zone storage per unit field width, $W_{rz}(L^3L^{-1})$
FGHF	total volume of deep percolation per unit field width, $W_r(L^3L^{-1})$
BCDB	total volume of runoff water per unit field width, $W_u(L^3L^{-1})$
DEFD	total volume of root zone deficit after irrigation per unit field width, $W_{df}(L^3L^{-1})$

Figure 3. Idealized Subsurface Profile/Applied Water in Border Irrigation

4. Total volume of deep percolation, W_p (area FGHF) is volume of water which infiltrates past the lower boundary of the root zone. W_p may equal zero in some cases.

5. Total volume of tailwater or runoff, W_u (area BCDB) is volume of water that runs off the end of the field if free outfall conditions exist.

6. Total volume of root zone deficit after irrigation, W_{df} (area DEFD). W_{df} equals zero if the root zone is completely filled.

When the data are available, cross-check total volume of water applied and total volume of runoff with the hydrograph analyses discussed earlier. Convert volumes to average depths by dividing by the product of border width and border length.

IRRIGATION PERFORMANCE PARAMETERS

Four irrigation performance parameters are discussed and may be defined using either volumes or depths.

1. Water application efficiency, E_a, is the percent of water applied that is stored in the root zone for future use. It is a measure of the effectiveness of the irrigation in storing water.

$$E_a = \frac{W_{rz}}{W_a} \times 100 = \frac{D_{au}}{D_a} \times 100 \qquad (4)$$

where W_{rz} and W_a are as defined previously, and D_{au} and D_a are the corresponding average depths (L) associated with these volumes, respectively.

2. Water requirement efficiency, E_r, indicates the percent of the amount of water required to refill the root zone supplied by an irrigation. It is a measure of the effectiveness of the irrigation in meeting the crop requirement.

$$E_r = \frac{W_{rz}}{W_r} \times 100 = \frac{D_{au}}{D_u} \times 100 \qquad (5)$$

where W_{rz} and W_r are as defined previously, and D_{au} and D_u are the corresponding average depths (L) associated with these volumes, respectively.

3. Tailwater ratio, R_t, represents the fraction of the total amount applied that is lost as tailwater or runoff from the end of the border.

$$R_t = \frac{W_u}{W_a} \tag{6}$$

where W_u and W_a are volumes (L^3) as previously defined.

4. Deep percolation ratio, R_p, represents the fraction of the total amount applied that is lost as deep percolation past the bottom of the root zone.

$$R_p = \frac{W_p}{W_a} \tag{7}$$

where W_p is as previously defined.

The sum of water application efficiency (expressed as a fraction), tailwater ratio, and deep percolation ratio is unity.

Uniformity of spatial distribution describes the uniformity of water application. It may not be unnecessary to determine this parameter if a plot of the subsurface distribution of applied water (as discussed earlier) is available. Several techniques for characterizing the spatial distribution of infiltrated water were developed. One common and easily calculated parameter is UCH, the Hawaiian Sugar Planter's Association uniformity coefficient (Hart, 1961):

$$UCH = 1 - \frac{2}{\sqrt{\pi}} \frac{s}{\bar{x}} = 1 - 0.798 \frac{s}{\bar{x}} \tag{8}$$

where

$\bar{x}$ = the mean infiltrated depth (determined from several observations), and

s = the standard deviation of the observations.

AN EXAMPLE OF SYSTEM EVALUATION

The following results of an evaluation of a graded border irrigation system, taken from Merriam and Keller (1978), show the value of being able to 1) to describe system operation and performance through an evaluation and 2) to compare results with an appropriate design. A design for the field was formulated using the SCS border irrigation design procedure (USDA, 1974). Design results are presented in a separate analysis of the design procedure (Clyma, 1980). Changes in system operation and

management for improved water application are recognized more easily when compared to the design.

Unfortunately, for this evaluation, runoff data and soil-water content data following irrigation were not available. The soil-water status prior to irrigation was evaluated using the feel method previously discussed. Recommended design parameters are repeated here for the reader's convenience.

Q_u = 4.31 lps/m (0.0464 cfs/ft)

T_a = 118 min

strip width = 7.9 m (26 ft)

design depth = 114 mm (4.5 in)

The farmer operated the system using the full available stream of 34 l/s (1.2 cfs) on a border strip width of only 7 m (23 ft) and border length of 210 m (700 cfs) to give a unit width stream of 4.83 l/s/m (0.052 cfs/ft) (which is larger than the design value due to smaller border width). Due to harvest operations, the farmer scheduled a more frequent water application. Application time was 88 minutes and soil-water deficit at irrigation was estimated to be 74 mm (2.9 in).

Four cylinder infiltration tests were conducted during evaluation in four locations along the length because the soil was fairly uniform. These data, in the form of cumulative depth infiltrated versus time, are plotted in Figure 4. A wide range of initial intake rates is observed. However, after approximately 30 minutes, the data curves have nearly the same slope. The average cumulative intake versus time was determined from the four sets of data and also is plotted in Figure 4 (as the curve labeled "average"). A significant dogleg occurs in the curve (Merriam and Keller, 1978). Because all data plots exhibit nearly the same slope after 30 minutes, it was decided a straight line typical of this condition (but also typical of the wide range of initial rates) was most representative. Result: the curve labeled "typical". The "typical" curve is considered to provide adequate representation of intake data and is easy to describe functionally. The infiltration function defining the "typical" curve is:

$$z = 4.27\ t^{0.64} \tag{9}$$

where

z = depth infiltrated (mm), and

t = intake opportunity time (min).

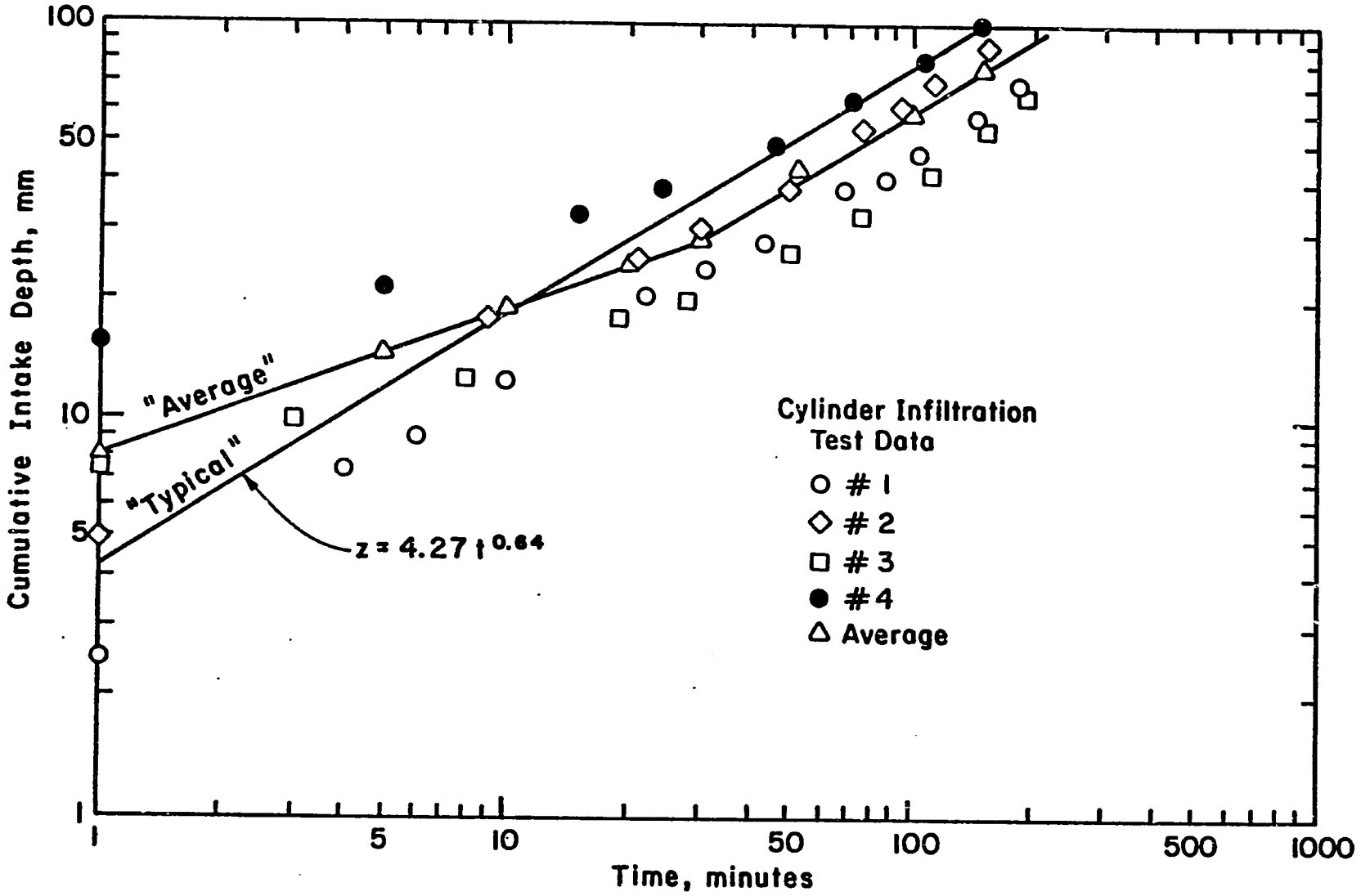


Figure 4. Cylinder Intake Data

Equation (9) also was used to develop the initial design results presented earlier.

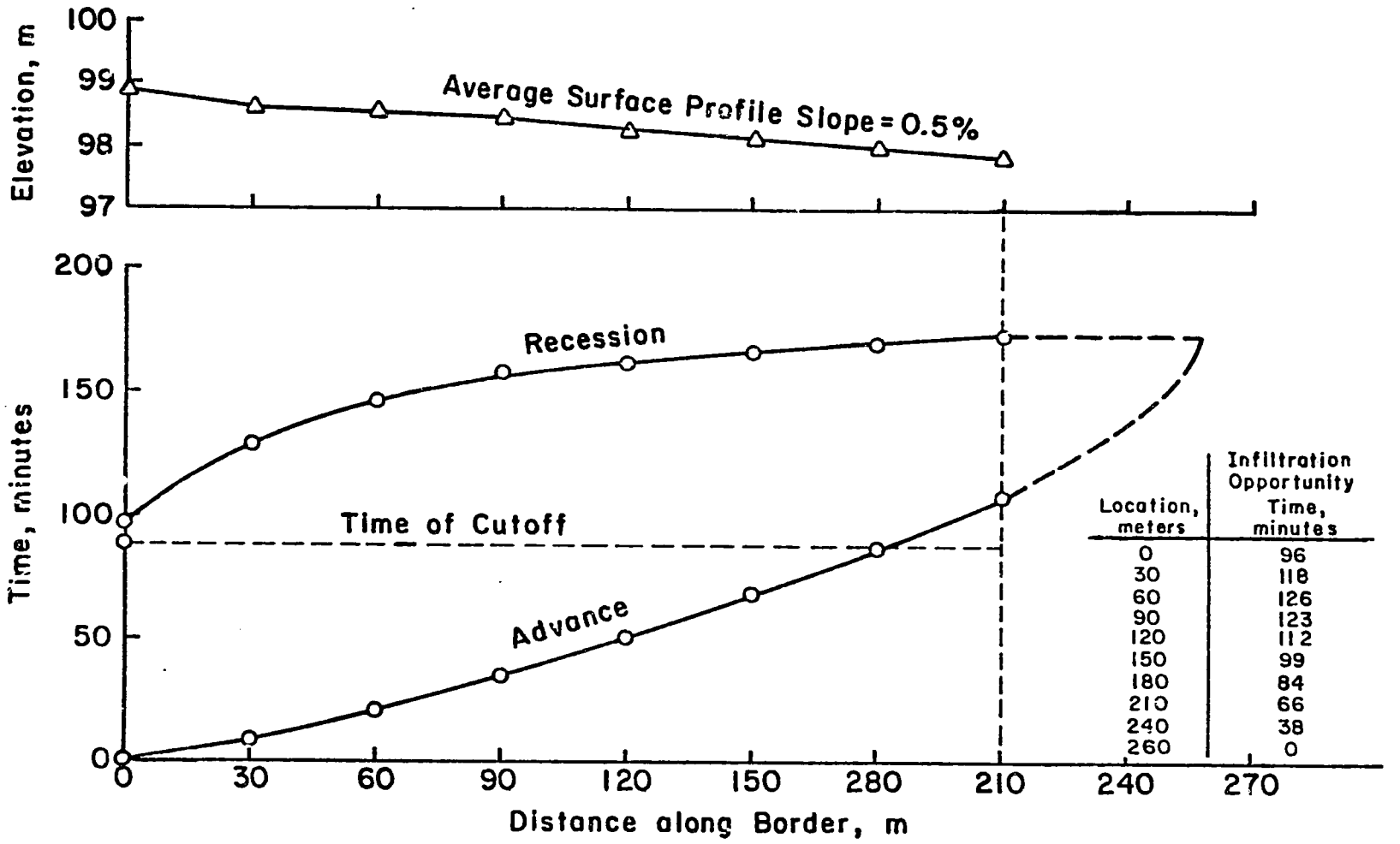
Advance/recession data were collected at 30 m stations along the irrigated run. These data, with infiltration opportunity times and surface profile slope, are presented in Figure 5. Because runoff data are not available, advance and recession curves were extrapolated to their intersection in Figure 5. The imaginary extended length is about 260 m. Intake opportunity times for the imaginary extended length are included. An estimate of the actual average applied depth now can be determined. The inflow rate of 34 l/s (1.2 cfs) was constant for the entire 88 minute duration. Therefore:

$$D_a = \frac{W_a}{WL} = \frac{QT}{WL} \qquad (10)$$

$$D_a = \frac{(34\ \text{lps})(88\ \text{min})(60\ \text{x/min})(\frac{1\ m^3}{1000\ l})}{(7\ m)\ (260\ m)}(\frac{1000\ mm}{1\ m})$$

$$D_a = 99\ \text{mm}$$

This value was used as a checkpoint to test the adequacy of the infiltration function previously determined in predicting average applied depth. The procedure is illustrated in Table 1. Equation (9) and infiltration opportunity times from Figure 6 were used to find infiltrated depths at stations along the run (actual plus extended length). The average depth for each 30 m reach was found. The last reach was only 15 m, thus the average depth was determined proportionately to length. The average applied depth for the entire wetted length as predicted by Equation (9) is calculated as 76.9 mm. That does not correspond with the actual average depth applied of 99 mm found earlier, so it was necessary to adjust the infiltration function. The procedure is illustrated in Figure 6. The "typical" curve represented by Equation (9) is shifted upward in Figure 6 to keep the slope of the curve constant. The "adjusted" curve should have a slope equal to the "typical" curve and should pass through the point where depth equals 99 mm and time equals the time at which the "typical" curve has a depth of 76.9 mm infiltrated. The time (using Equation (9)) is approximately 92 minutes. The intercept at unit time for the adjusted curve is approximately 92 minutes. The intercept at unit time for the adjusted curve is approximately 5.48 mm. A numerical procedure for determining the functional relationship of the "adjusted" curve involves finding a new value for k in Equation (2), such that with a = 0.64 and t = 92 min, z will equal 99 mm:



Location, meters	Infiltration Opportunity Time, minutes
0	96
30	118
60	126
90	123
120	112
150	99
180	84
210	66
240	38
260	0

Figure 5. Advance/Recession, Surface Profile Curves and Infiltration Opportunity Times

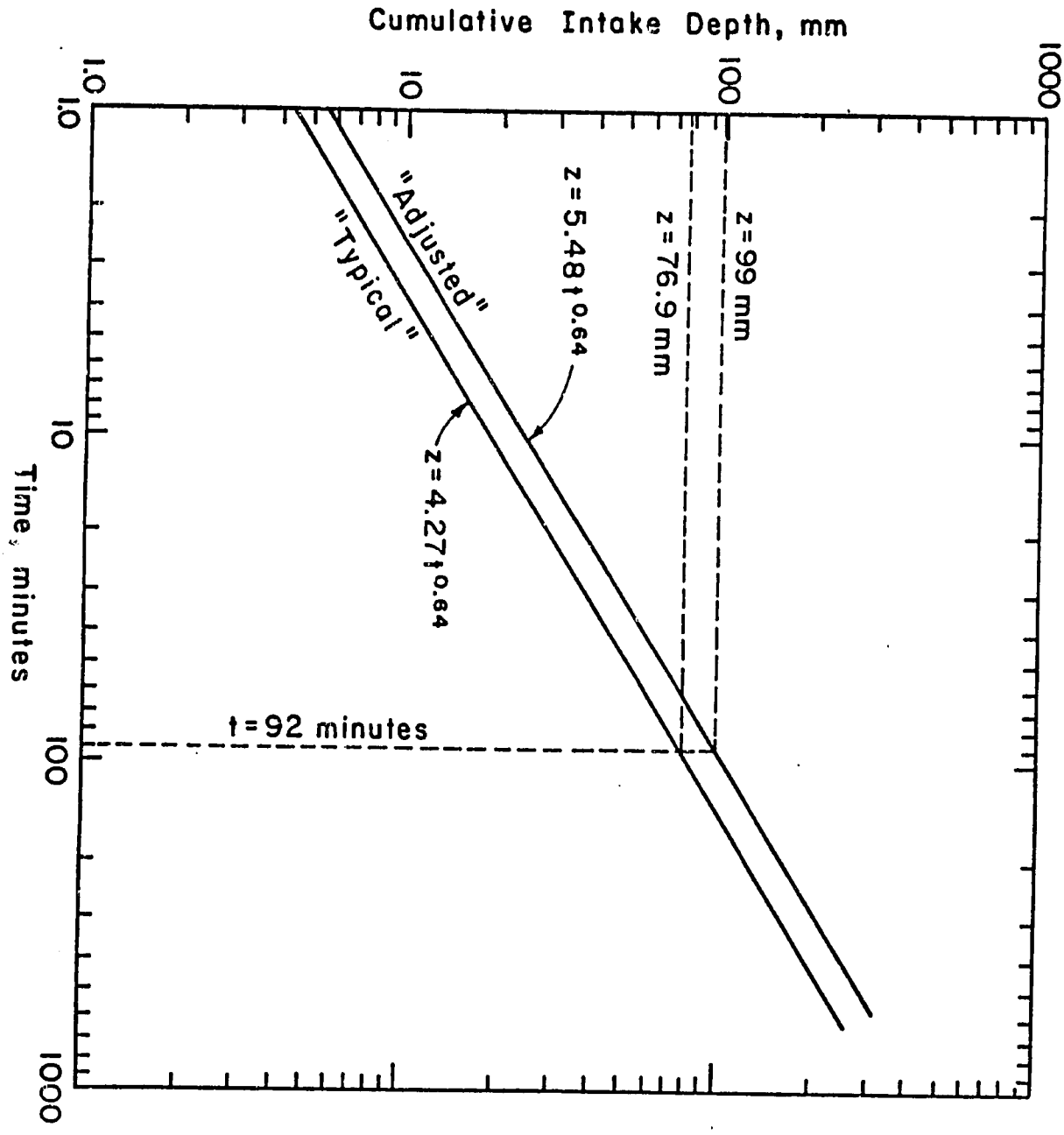


Figure 6. Illustration of Adjustment of Infiltration Function

$$k = z \div t^{a}$$

$$k = 99 \div 92^{0.64}$$

$$k = 5.48$$

Thus, the "adjusted infiltration curve is represented by:

$$z = 5.48\ t^{0.64} \tag{11}$$

where

z = cumulative infiltrated depth (mm), and

t = time (min).

A check on the adequacy of the "adjusted" curve is provided in the lower section of Table 1 using the same procedure as before. Equation (11) adequately predicts the total average applied depth.

Results

The subsurface distribution of applied water predicted by Equation (11) is plotted in Figure 7.

Each volume associated with Figure 7 (as previously discussed) is found by graphical integration of related areas of Figure 7. On a unit width basis (for border width of 7 m), they are:

Volume applied, W_a = 25.6 m^3/m

Volume runoff, W_u = 2.7 m^3/m

Volume infiltrated, 22.9 m^3/m

Volume required, W_r = 15.7 m^3/m

Volume stored, W_{rz} = 15.7 m^3/m

Volume deep percolated, W_p = 7.2 m^3/m

Volume deficit, W_{df} = 0.0 m^3/m

Each volume is converted to an average depth by dividing by the border length of 240 m. Using the above volumes, performance parameters for this irrigation are determined using Equations (4) through (7).

Table 1. Check On Infiltrated Depths and Total Applied Depth Predicted by "Typical" Infiltration Function and "Adjusted" Infiltration Function (After Merriam and Keller, 1978)

Station (m)	0	30	60	90	120	150	180	210	240	260
Opportunity Time (min)	96	118	126	123	112	99	84	66	38	0
					Infiltration Depths /using Equation (9)/					
Depth (mm)	79.3	90.5	94.3	92.9	87.5	80.8	72.8	62.4	43.8	0.0
Average Depth (mm)	84.9	92.4	93.6	90.2	84.2	76.8	67.6	53.1	0.5	(21.9)
Average Depth on 260 mm = 653.7/8.5 - 76.9 mm										
					Infiltration Depths /using Equation (11)/					
Depth (mm)	101.7	116.1	121.1	119.2	112.3	103.7	93.4	80.0	56.2	0.0
Average Depth (mm)	108.9	118.6	120.2	115.8	108.0	98.6	86.7	68.1	0.5	(28.1)
Average Depth on 260 mm = 838.8/8.5 = 98.7 mm										

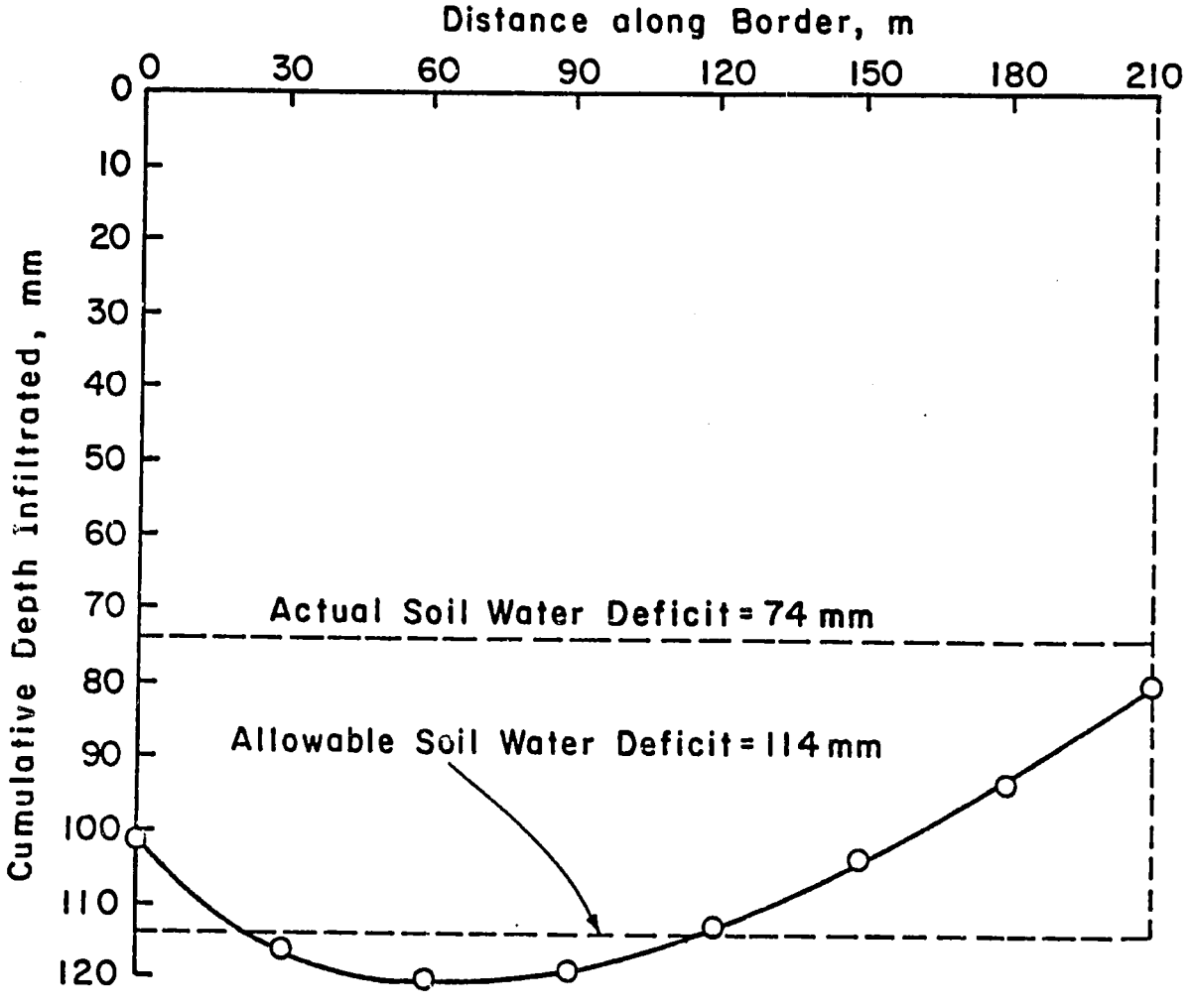


Figure 7. Subsurface Distribution of Applied Water

Water application efficiency, (4)

$$E_a = \frac{W_{rz}}{W_a} \times 100$$

$$= \frac{15.7}{25.6} \times 100$$

$$= 61.4\%$$

Water requirement efficiency, (5)

$$E_r = \frac{W_{rz}}{W_r} \times 100$$

$$= \frac{15.7}{15.7} \times 100$$

$$= 100\%$$

Tailwater ratio, (6)

$$R_t = \frac{W_u}{W_a}$$

$$= \frac{2.7}{25.6}$$

$$= 0.11$$

Deep percolation ratio, (7)

$$R_p = \frac{W_p}{W_a}$$

$$= \frac{7.2}{25.6}$$

$$= 0.28$$

The uniformity of water application is illustrated in Figure 7.

Table 2 compares the suggested design with the system as it was operated for this irrigation. The expected runoff and deep percolation for the design are not available.

Table 2. Comparison of Design and Current Operation

Parameter	Design	Current Operation
Unit width stream, lps/m	4.31 (0.0464 cfs/ft)	4.83
Time of application, min	118.0	88.00
Border strip width, m	7.9 (26.0 ft)	7.00
Design depth or requirement, mm	114.0 (4.5 in)	74.00
Average depth applied, mm	142.5 (5.61 in)	119.90
Water application efficiency, %	80.0	61.40
Water requirement efficiency, %	---	100
Tailwater ratio, dec.	---	0.11
Deep percolation ratio, dec.	---	0.28

Conclusions

Comparing the results of the evaluation with the suggested design yields the following comparisons:

1. The farmer irrigated too soon, i.e., at a smaller requirement than suggested. Although he was aware of this and tried to apply a lighter amount of water, he still over-irrigated the entire field.

2. By using the entire available flow on a smaller strip width, the farmer used a larger unit width stream. The smaller application time used must be an attempt at reducing the amount applied. At 80% design efficiency and a requirement of 74 mm (2.9 in), design equations yield an application time of approximately 68 minutes for the larger unit width stream. This may be too short for the given field length because the distance of advance for this time is about 150 m (Figure 5). Poor distribution and underirrigation of the lower end would probably result.

3. The anticipated advance curve for the design should be only slightly steeper than in Figure 5 because of the offsetting effects of greater application time, but higher initial intake rate of the drier soil. The anticipated recession curve should be slightly steeper at the lower end and shifted upward by an amount equal to the increase of application time, compared to Figure 5. Thus, if the system were operated according to design, the expected result would be a more uniform application of water, with the upper end being slightly overirrigated and the lower end being slightly underirrigated.

4. For the border strip width in use, the farmer could use the larger unit width stream and decrease the application time to around 106 minutes and expect a value of E_a near 80%. The resulting irrigation, however, most likely would be less uniform.

5. The non-uniformity in slope for the first 90 m probably causes the recession curve to be steeper in that section. The first 30 m, being much steeper, would cause a short lag time; and the next, flatter 60 m section would cause the recession to slow. The advance also is slowed in the 30 m station to 90 m station section (see Figure 5). If this section were graded to the slope of the remainder of the field, the advance/recession curves should be more "parallel" and the amount of overirrigation in that section reduced.

6. The extensive deep percolation is caused by irrigating too soon. The amount of runoff is about right, however, indicating the farmer had about the correct inflow time. An efficient irrigation most likely would be impossible for the 210 m border, the given soil-water deficit and the available stream. Either a non-uniform irrigation would result with the requirement at the upper end just being met, or a large runoff on what would have to be very narrow borders (so the unit width stream would be large enough for the desired advance time).

Recommendations

1. The farmer should adhere to an irrigation schedule in which the design depth of 114 mm (4.5 in) is applied at each irrigation. Obviously, however, seasonal changes in crop requirement and infiltration rate have to be considered.

2. Land leveling to obtain a more uniform grade in the direction of irrigation will increase uniformity of water application. In particular, overirrigation at the upper end of the border will be reduced.

3. The combined effects of the first two recommendations will yield high values for E_a and E_r. Runoff losses from the border also could be effectively reduced through use of a tailwater reuse system.

4. The farmer should not deviate from an irrigation schedule in which he applied 114 mm (4.5 in) at each irrigation. Operating at lower values of design depth for the given available flow rate and border dimensions reduces efficiency and uniformity of water application. Increased flexibility in timing and rate of water delivery is necessary to obtain a specific unit width stream for a particular design depth, design efficiency, and application time.

5. Using the 7 m (23 ft) width borders rather than the design recommend 7.9 m (26 ft) width results in a larger unit width stream when the full available flow is used. That reduces application efficiency. Assuming other design parameters were used with this unit width stream, a reduction in efficiency from the design efficiency is expected. The farmer could use a slightly smaller application in time than in the design and still achieve good results because the deviation in border widths was small. The best choices are to reduce the supply rate to the field or to increase the width to 7.9 meters.

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AUXILIARY SHEET A :

SUGGESTED QUESTIONS FOR INTERVIEWING FARMERS

Farmer operation and management

How does the farmer decide when to irrigate?
What is his irrigation frequency? How does it change during the season?
How does he decide how to irrigate?
How does he decide how much water to apply?
Does the farmer know the total flow rate available to him?
What are the farmer's operating hours?
Does he irrigate at night?
How does he decide how long to irrigate a field?
How long does he irrigate a field?
Does the farmer have any problems with the system?
What are his cultivation and tillage practices?
Does he irrigate every furrow or alternate furrows?
How many furrows does he irrigate in one set?
How many sets does it take to irrigate the field?
Does he try to compact the furrows equally?

Water supply

What are the sources of available water?
Is the delivery station (point of diversion to farm) a problem, i.e., high losses, etc.?
Is the on-farm distribution system a problem (i.e., too many in-field channels, high losses, etc.)?
What is the flow rate of each source of water?
When is each source available and for how long?
Is the frequency of delivery and available head a problem?
What is the water quality?
How is the water delivered to each field?

Crop characteristics

What are the crops grown?
What are the respective planting dates?
What cropping patterns, if any, are followed?
Does the farmer have any major problems in crop production?
What are the major inputs? Potential yield?
What is his expected yield? Average yield in area?
Any obvious physical symptoms of problems?

Physical characteristics

Does the farmer know the field dimensions?
Does he know the slope and cross-slope (if any)?
Is the field leveled to a uniform slope?
If yes, when? If no, why not?
What provisions, if any, are made for surface runoff?
Does runoff leave the farm or is it used again somewhere on the farm?
What is the border spacing and how did the farmer decide on that spacing?
What is the furrow spacing?
What is the method of diverting water into each furrow?

Soil survey

Does the farmer know the soils on his farm?
Does he know of any trouble spots (i.e., very light or heavy soils or salinity problems)?

Water table

Does the farmer know the groundwater level?
Does he think it is a problem?
Is surface/subsurface drainage provided? If so, where?

IRRIGATION EVALUATION PROCEDURE FOR FLOODED RICE CROPS*

by A. Early

INTRODUCTION

The objective of an irrigation evaluation is to determine the water use efficiency of the irrigation. Irrigation efficiency is a useful measure of how water is being used and can be helpful in identifying specific problem areas where water losses may be reduced.

Farmers generally do not know how much water should be given to their rice fields. They just irrigate so that the fields are ponded with the full supply of water. In this way, much water is wasted due to overirrigation. Accurate measurements are important to determine how much water is used in the rice fields and how much could be saved and used for other crops.

This article indicates the procedure for efficiency evaluations for irrigated lowland rice water use and lists the equipment required to complete the evaluation. A blank data form is attached.

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* Modified from an article in The Problem Identification Handbook. (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100. Fort Collins, CO.

METHODOLOGY

Flooded (lowland) rice irrigation evaluations are unlike other (upland) crop water use determinations because the soil moisture reservoir is vastly different. In lowland rice land preparation, the soil is puddled to destroy the soil structure and to decrease the moisture infiltration and transmission rates within the soil. The soil itself remains close to saturated and only under rare circumstances should the moisture content fall as low as field capacity. Thus, the only reservoir considered for the lowland rice evaluation is the water stored on the soil surface.

Because channel moisture movement within the soil as seepage and vertical movement as percolation is minimized by puddling, further uncontrolled losses of seepage and percolation are considered a soil requirement for water and a necessary part of the entire irrigation requirement for lowland rice. The general efficiency concept is the quotient of output (in this case, useful water consumption as evapotranspiration, percolation and seepage) and input (rainfall and irrigation) as

$$E = \frac{\text{output}}{\text{input}} \times 100$$

For lowland flooded rice, the irrigation application efficiency generally is known as the water use efficiency (WUE) and is defined as:

$$WUE = \frac{ET + S\&P}{RN + IR} \times 100$$

where ET is the evapotranspiration of the crop, depth/unit time; S&P is the seepage and percolation of the soil, depth/unit time; RN is the rainfall depth/unit time; and IR is the irrigation depth/unit time.

Flooded rice often is continuously irrigated over the entire season; therefore, the time base for an evaluation is not the usual short term irrigation as for other crops. Water use efficiency generally is expressed on the minimum time period of one week to adequately represent the field conditions. It also is expressed for the two general stages of rice growth: vegetative stage before panicle initiation, and the reproductive stage of growth. Generally, it is not applied to the drying-off stage when irrigation is stopped and drainage of fields is completed as maturation occurs.

In the case of upland crop evaluation, the unit on which measurement and results are expressed is the bunded unit. When the continuous flow irrigation method of lowland rice evaluations and frequent paddy-to-paddy flow occurrence with

attendant difficulty in flow measurement, the basis of the irrigation evaluations generally is a larger block of land from the irrigation inlet to the drainage outlet. It can include any suitably bounded unit from 1 acre to 25 acres, depending on the flow pattern. Suitable boundaries are cultivated or uncultivated land to which flow does not occur, highways, railroad right-of-ways, or irrigation conveyance structures. If drainage occurs to or through any of these boundaries, that flow must be measured and accounted for in the overall moisture balance.

The overall basis on which lowland flooded rice irrigation evaluations are made is the water balance (otherwise known as the continuity relationship). Stated simply, for complete accounting, the inflow minus outflow must equal the change in storage.

Water supplied to lowland rice fields as irrigation and rainfall can be accounted for by evapotranspiration into the atmosphere, by surface drainage from the fields, and by seepage and percolation into the soil as well as a change in water stored on the soil surface. Evapotranspiration cannot be measured easily in the field, but relatively accurate methods have been developed for estimating it from open pan evaporation. Evaporation, water depth change, surface drainage, rainfall and irrigation can be measured readily. Surface drainage can be measured by use of cutthroat flumes (although usually with difficulty).

Water balance accounting allows the estimation of seepage and percolation as a residual weighted average over a larger area. Point measurements of seepage and percolation are useful in finding the effects of local soil or topographical conditions, but they are difficult to integrate into a mean value representative of large areas. Collecting data for the complete water balance is, however, arduous and expensive because one must account for all water entering and leaving a site. The wide and unpredictable fluctuations in the flow of the many lowland irrigation sources and drains make these measurements difficult and inaccurate. Furthermore, seepage and percolation values are sometimes less than 5 percent of the accounted for total water; therefore, inaccuracies in the irrigation or drainage measurement easily could result in individual seepage and percolation values being too high or too low by an order of magnitude.

PROCEDURE

Six components must be considered in estimating the complete water balance for flooded rice crops:

- Irrigation (IR)
- Rain (RN)
- Potential Evapotranspiration (E_{tp})
- Drainage (DR)
- Change in Surface Storage (AS)
- Seepage and Percolation (S&P)

These components are considered sequentially as follows:

1. Irrigation: Irrigation can be measured by various methods. The easiest is by installation of cutthroat flumes at the field entrance of water to measure the irrigation flow.

2. Rain: A non-recording rain gauge can be used at the field site or data from a meteorological center of less than one mile distance can be used only when there is no rain gauge.

3. Potential Evapotranspiration: E_{tp} cannot be measured easily in the field, but relatively accurate methods were developed for estimating E_{tp} from a U.S. Weather Bureau Class A evaporation pan. This can be done by installing an evaporation pan in the field with the difference in daily readings recorded as ET, and a good estimate of E_{tp} of a flooded rice crop, irregardless of the stage of crop growth.

4. Drainage: Drainage can be measured by installing flumes at the outlets of the rice fields from which direct readings are taken periodically. Drainage water outflow is far more variable than the irrigation water inflow and is much more difficult to measure. If drainage is to be measured, hourly readings of flow should be recorded, or flumes with water level recorders should be used to provide a continuous record.

5. Change in Surface Storage: Each paddy included in the block of land should be equipped with a staff gauge for direct reading of the daily water surface elevation, or with a suitably stabilized reference stake from which water surface elevations can be read by means of a standard hook gauge. From the daily elevations and the area of the paddy, the total volume and,

hence, the change in surface storage for the entire area can be calculated (AS).

6. Seepage and Percolation:* Methods of measuring seepage and percolation include laboratory permeability analysis and field pumping analysis to determine hydraulic conductivity, lysimeters, and field water surface level recession. The latter method requires a water level recorder on a stilling well. The stilling well generally is an empty oil drum with both ends open, buried with an open end approximately one foot into the soil. The drum is independently supplied with water from the paddy and the surface recession is recorded continuously.

This total recession includes ET, hence, the pan evaporation rate must be subtracted to provide the estimate of seepage and percolation.

The major problems with the lysimeter and water recession methods are due to: 1) the discontinuities caused by the tank walls, 2) the disturbed and unrepresentative conditions of the soil after filling the tank or permeameter, and 3) the tendency to measure only the percolation, i.e., the vertical water movement to deeper depths. Seepage, i.e., the channel movement of water in the soil, often is more important than percolation, but depends on many environmental factors that are site specific.

The most common field method of estimating seepage and percolation in irrigation evaluations is by use of a water balance. Seepage and percolation then are estimated as the residual after all other factors are accounted for.

EQUIPMENT

The equipment needs for flooded rice irrigation evaluations follows:

1. Irrigation - as many cutthroat flumes as there are inflow sites for the block of land under evaluation. They should be equipped for continuous flow recording of inflow measurements.

2. Rainfall - one standard non-recording rain gauge;

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* If seepage and percolation can be measured adequately by water surface recession, then drainage measurement is not necessary and can be estimated by the residual.

3. Evaporation - one standard U.S. Weather Bureau Class A pan and hook gauge;

4. Drainage - same as for number one;

5. Change in surface storage - as many staff gauges for water surface elevation or hook gauge bases as there are paddies in the area being studied; and

6. Seepage and percolation - lysimeter, water surface recession or residual as discussed earlier

DATA RECORD

The attached data sheet provides the format for detailed accounting of water in the moisture budget and serves as a weekly and fortnightly summary. All measurements are in units of water depth. The water use efficiency results are expressed as a dimensionless percentage.

SUMMARY SHEET FOR FLOODED RICE IRRIGATION EVALUATION*

Location_____ Start Date_____ Finish Date_____

Day	Depth of Irrig. IR	Depth of Rainfall RN	Depth of Drainage DR	Initial Depth of Surface IS	Final Depth of Surface Storage FS	Depth Change of Surface Storage AS + IS-FS	Pan Evaporation Depth ET	Residual† Seepage & Percolation Depth Residual S&P	Water Use Efficiency‡† WUE %
1									
2									
3									
4									
5									
6									
7									
Week Summary									
1									
2									
3									
4									
5									
6									
7									
Week Summary									

* Basic efficiency relationship

$$\text{Eff.} = \frac{\text{output}}{\text{input}}\ 1{,}100$$

†S&P residual calculation

Inflow - outflow = change in storage
Inflow = IR + RN
Outflow = S&P + ET + DR
Change in Storage = IS - FS = AS
IR + RN - S&P - ET - DR = AS
IR + RN - ET - DR - AS = S&P

‡Water use efficiency

$$\left(\frac{ET+S\&P}{IR+RN}\right) 100 = 100 \left(\frac{-DR}{IR+RN}\right) + 100$$

CONSUMPTIVE USE*

by W. Franklin

INTRODUCTION

Total evaporation occurring from soil and plant surfaces and plant transpiration (evaporation from the pareachyma cells through stomatal cells) is called evapotranspiration (ET). In addition to ET, plants use a small amount of water in tissue building. The sum of ET and water use in tissue building is called consumptive use. However, because the water removed in plant tissues is usually very small compared to ET, the terms consumptive use and evapotranspiration are commonly used interchangeably.

When the evapotranspiration rate of a particular crop is not limited by soil-water availability, and when the crop is growing vigorously with full foliage, it is called potential evapotranspiration (E_{tp}). Potential evapotranspiration usually is defined for a "reference" crop and is regarded as a function of climatic factors only.

Evapotranspiration for a crop may be greater or less than that for the reference crop due to various environmental factors. This is referred to as actual

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* Modified from an article in The Problem Identification Handbook. (Draft Copy). 1980. CSU-Pakistan Water Management Project. U.S. Agency for International Development, Contract No. AID/TAC-1100. Fort Collins, CO.

evapotranspiration (Et). The ratio of Et/E_{tp} (when soil water is not a limiting factor) is called the crop coefficient. When soil-water is limiting, evapotranspiration will decrease and a "stress" factor (K_S) term is introduced. An empirical equation to evaluate K_S has been proposed by Kincaid and Heermann (1974).

COMPUTING EVAPOTRANSPIRATION

A review of the alternative approaches to estimating the volume and rates of water evaporated from wet crop and soil surfaces or transpired by the plants can be found in several literature sources (Jensen, 1973; Doorenbos and Pruitt, 1977. As far as this technology is applicable to the management of irrigation return flow quality (through irrigation scheduling), Skogerboe et al. (1974) and Jensen (1975) are good summaries.

Evapotranspiration can be calculated many ways. But the three most common approaches are: 1) the Blaney-Criddle method; 2) the Modified Jensen-Haise method; and 3) the Penman Combination method. These methods represent much of the range in sophistication available today, varying in detail from a temperature dependent analysis (Blaney-Criddle) to an analysis of energy balance and convective transport (Penman). Both the Jensen-Haise and Penman equations are calculated in cal $cm^{-2}t^{-1}$ and can be converted to an equivalent depth of evaporation by dividing by an assumed value for the latent heat of vaporization of 585 cal gm^{-1}, which yields units of length over time. The conversion is:

$$E_{tp} \times 0.0017 \rightarrow cm\ t^{-1}$$

$$E_{tp} \times 0.000673 \rightarrow in\ t^{-1}$$

The Blaney-Criddle Method

The Blaney-Criddle procedure for estimating evapotranspiration has the form (Blaney and Criddle, 1950):

$$E_t = \frac{k_t k_c t\ p}{100} \qquad (1)$$

where:

E_t = monthly evapotranspiration in inches;

k_t = 0.0.173t - 0.134 (2)

k_c = time distributed crop growth stage coefficient;

t = mean monthly temperature in degrees °F; and

p = mean monthly percentage of annual daytime hours.

Crop curves and values for p can be found in Blaney and Criddle (1950) and USDA Soil Conservation Service, Technical Report 21. Estimates of E_t originally were intended on a seasonal basis, but work by numerous individuals shortened this interval by interpolating values for p and k_c.

The Modified Jensen-Haise Method

The Jensen-Haise procedure is a temperature and solar reduction equation adjusted for location and elevation by vapor pressure functions (Jensen and Haise, 1963):

$$E_{tp} = C_t(T - T_x)\ R_s \qquad (3)$$

in which,

E_{tp} = average daily potential evapotranspiration of a well-watered alfalfa crop having 30 to 50 cm of top growth, mm/day;

T = mean daily tempature, °C;

R_s = total daily solar radiation in langleys multiplied by 0.0171 to get mm/day;

T_x = intercept of the temperature axis

$$= -2.5 - 0.14\ (e_2 - e_1)\ °C/mb - elev(m)/550 \qquad (4)$$

e_2, e_1 = saturation vapor pressures at the mean maximum and mean minimum temperature, respectively, for the warmest month of the year, in mb/

C_T = temperature coefficient

$$= \frac{1}{C_1 + C_2\ C_H} \qquad (5)$$

$$C_1 = 38 - (2°C \times elev/(m)/305) \quad (6)$$

$$C_2 = 7.6°C \quad (7)$$

$$C_H = \frac{50\ mb}{(e_2 - e_1)} \quad (8)$$

In order to relate E_{tp} to evapotranspiration values for other crops, a crop growth stage coefficient was defined,

$$k_{co} = E_t/E_{tp} \quad (9)$$

where

k_{co} = crop growth stage coefficient; and

E_t = potential evaporation for the specified crop.

Kincaid and Heermann (1974) present polynomial regression equations for k_{co} based on the table of coefficients presented by Jensen (1973).

The Penman Combination Method

Penman (1948) first derived an equation for the evapotranspiration of a short, well-watered crop (generally assumed to be grass) based on a combination of energy balance at the crop surface and the heat-mass transfer processes due to air movements. The equation which resulted and is used today is written for alfalfa:

$$E_{tp} = [\frac{\Delta}{\Delta+\gamma}(Rn+G)+15.36\frac{\Delta}{\Delta+\gamma}(a+bU_2)(e_z°-e_z)] - 0.0171 \quad (10)$$

in which,

Δ = slope of the saturation vapor pressure curve at a specified temperature, d(mb)/d(°C);

γ = psychrometric constant, mb/°C;

R_n = net radiant energy, Langleys/day (Ly/day);

G = soil heat flux, Ly/day;

U_2 = wind run at a height of 2 meters, km/day;

a, b = empirical regression coefficients requiring local calibration;

e_z° = saturation vapor pressure at the surface of the crop, mb; and

e_z = vapor pressure at the crop surface, mb.

The data available at most irrigated sites employing the Penman approach include solar radiation (R_S), temperature, wind, and relative humidity or dew point temperature. To develop the parameters for Equation (10), a number of empirical functions can be used. In the Grand Valley of western Colorado, the approach used is as follows:

Net radiation, R_n, was determined from relationships presented by both Jensen (1973) and Kincaid and Heermann (1974). The procedure begins by defining solar radiation on a clear, cloudless day by plotting a curve through the long-term maximal values:

$$R_{so} = 760 \exp - \left[\frac{\text{Day}-107}{167}\right]^2 \qquad (11)$$

where

R_{so} = clear day solar radiation, Ly/day; and

Day 1 = March 1.

A more recent review of Equation (11) indicates the coefficient 760 should be increased about 10 percent, but the overall effect is negligible. In a similar view, it is necessary to define the clear day net outgoing longwave radiation:

$$R_{bo} = \varepsilon' \sigma T_k^4 \qquad (12)$$

where

R_{bo} = net clear day outgoing longwave radiation, Ly/day;

$$\varepsilon' = -0.2 + 0.261 \exp \left[-7.77 \times 10^{-4} (273-T_k^2\right] \qquad (13)$$

T_k = temperature in degrees Kelvin (°C + 273)

σ = Stefan-Boltzmann constant =

11.21×10^{-8} Ly/°K

Based on Equations (11) and (12), the longwave radiation occurring on a particular day equals (Jensen, 1973):

$$R_b = [1.2 \frac{R_s}{R_{so}} - 0.2] R_{bo} \quad (14)$$

and

$$R_n = (1-\alpha) R_s - R_b \quad (15)$$

in which α = crop albedo (generally taken to be 0.23).

The exchange in heat from the soil is based on two assumptions: 1) the soil temperature to a depth of 2 meters varies approximately with average air temperature; and 2) the volumetric heat capacity of the soil is 0.5 cal cm^{-3} $°C^{-1}$. The soil heat flux, G, is then written as (Jensen, 1973):

$$G = \frac{\bar{T}_{i-1} - \bar{T}_{i+1}}{t} \times 100 \quad (16)$$

where,

G = soil heat flux, ly/day;

$\bar{T}_{i-1}$ = mean temperature for the previous period, °C;

$\bar{T}_{i+1}$ = mean temperature for the following period, °C; and

Δt = days between the preceding and following periods (period interval).

Kincaid and Heermann (1974) use of comparison of current temperature with the average of the previous three days to calculate G for irrigation scheduling. They also present convenient expressions for $\Delta/\Delta+\gamma$, $\gamma/\Delta+\gamma$, and e_z° as follows:

$$\gamma/\Delta+\gamma = 0.959 - 0.0125T + 0.00004534T^2 \quad (17)$$

$$\Delta/\Delta+\gamma = 1 - (\gamma/\Delta+\gamma) \quad (18)$$

$$e^{\circ}_z = -0.6959 + 0.2946T - 0.005195T^2 + 89 \times 10^{-6}T^{-3} \quad (19)$$

in which T represents the mean daily temperature in °F.

The elevation of the term $(e_z^{\circ} - e_z)$ in the Penman equation can be made in several ways. For the Grand Valley studies, the following expression was used:

$$(e_z^{\circ} - e_z) = \frac{e^{\circ}_2 + e^{\circ}_1}{2} - e^{\circ}_1 \times rh \quad (20)$$

in which,

e_z°, e_1° = saturation vapor pressure at maximum and minimum temperatures, mb; and

rh = maximum relative humidity (usually taken as the 6-8 AM values) expressed as a fraction.

MEASUREMENT OF EVAPOTRANSPIRATION

Consumptive use of water in a water balance computation of an irrigated area is a major component of the budget. It is, therefore, necessary that the consumptive use value be determined as accurately as possible. It is imperative also that the evapotranspiration estimating formulas be calibrated for local conditions. Attempts to base conclusions on uncalibrated consumptive use equations are extremely presumptuous, as is explained later in this section. Tanner (1967) and the World Meteorological Organization (WMO) Technical 1, Note No. 83 (1966) provide a good review of the procedure and methodology used for the measurement of potential evapotranspiration in the field.

Measurement of evapotranspiration should include 1) the means for the actual measurement of consumptive use and, 2) a complete weather station to measure air temperature (plus data, maximum and minimum) dew point temperature, relative humidity, precipitation, wind run, solar and net radiation and evaporation (Class A pan). Doorenbos (1976) presents an excellent discussion on the establishment and operation of a weather station

for agricultural studies and the calibration of empirical ET indexes to actual ET measurements.

Lysimetry

Probably the most accurate measurement of ET is obtained by the use of lysimeters. Lysimetry is the only method of measuring evapotranspiration where the investigator has complete knowledge of all the terms of the water balance equation. Harrold (1966) presents a good review of the use of lysimeters for measuring ET. Horton (1973) compiled an annotated bibliography on Et that includes lysimetry.

A lysimeter is a device that is hydrologically isolated from the surrounding soil. The device contains a volume of soil (which usually is planted to vegetation) and some means to measure the consumptive use (described below). Lysimeters must be representative of the surrounding conditions if they are to provide useful ET measurements. They must be representative of the soil type.

Two types of lysimeters, which work quite well for calibration purposes, are the constant water table lysimeter and hydraulic weighing lysimeters. The constant water table lysimeter usually are planted to grass (such as Kentucky Bluegrass) or other crops with shallow root systems. On the other hand, the hydraulic weighing lysimeters usually are planted in deeper rooted crops such as alfalfa or corn. The reference crops used in the calculations, which are usually planted in lysimeters, are generally considered to be well-watered grass or alfalfa.

Construction of a constant water table lysimeter is shown in Figure 1. Lysimeters usually are about 1 meter square and about 60 cm deep. The amount of water use is calculated by using an area ratio of the lysimeter to the reservoir. The evapotranspiration rate is very sensitive to the depth of the water table in the lysimeter (usually kept at about 15 cm from surface for grass). In addition, the crop must be trimmed periodically to insure vigorous growth, and any vegetative growth extending beyond the sides of the lysimeter should be trimmed back.

Construction of the hydraulic weighing lysimeters are shown in Figure 2, and a typical calibration curve is shown in Figure 3 a short time period does not give complete confidence in the resulting equations because temperature is only one of many climatic factors affecting evapotranspiration. A longer term analysis is needed before proposing a usable function for k beyond that expressed in Equation (2).

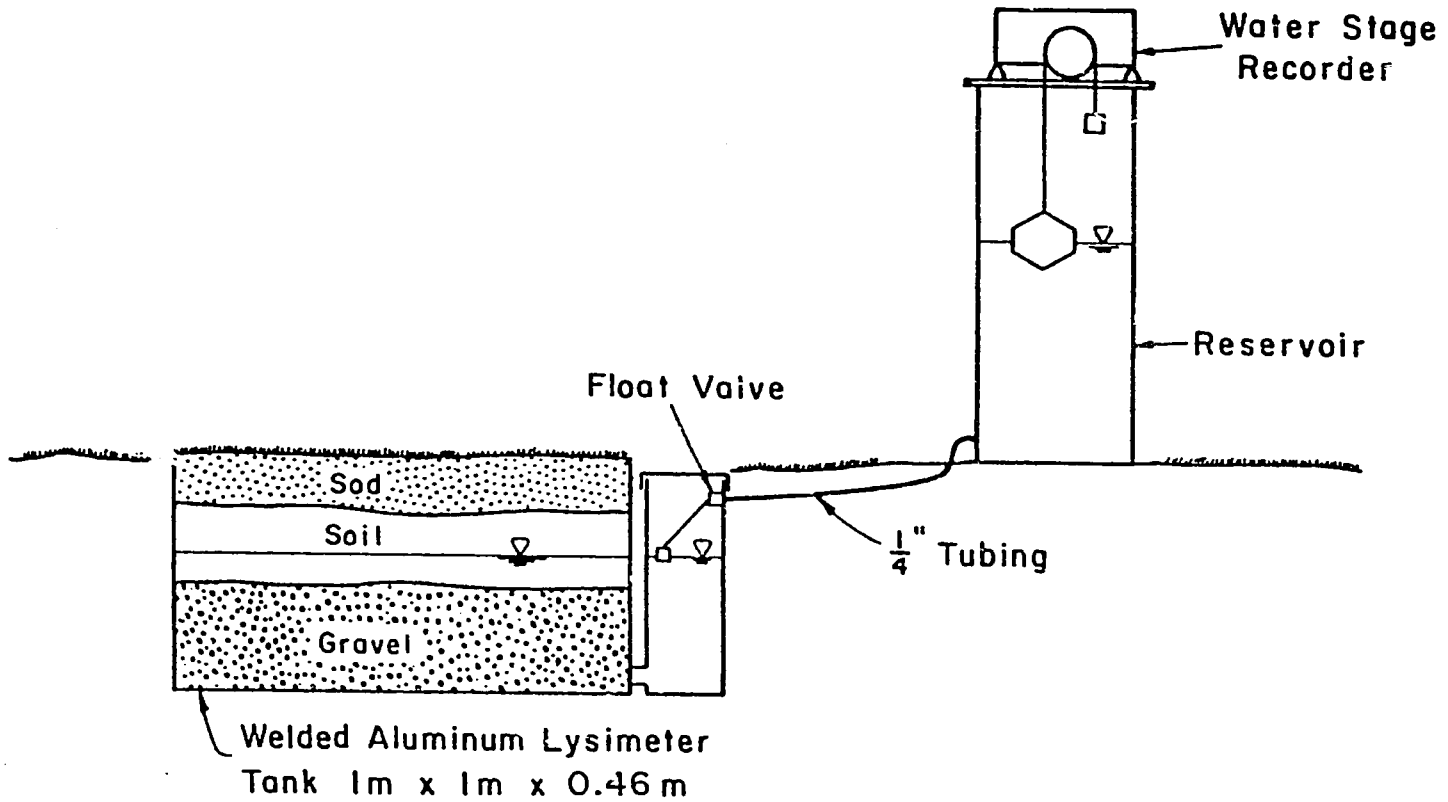

Figure 1. Constant Water Table Lysimeter

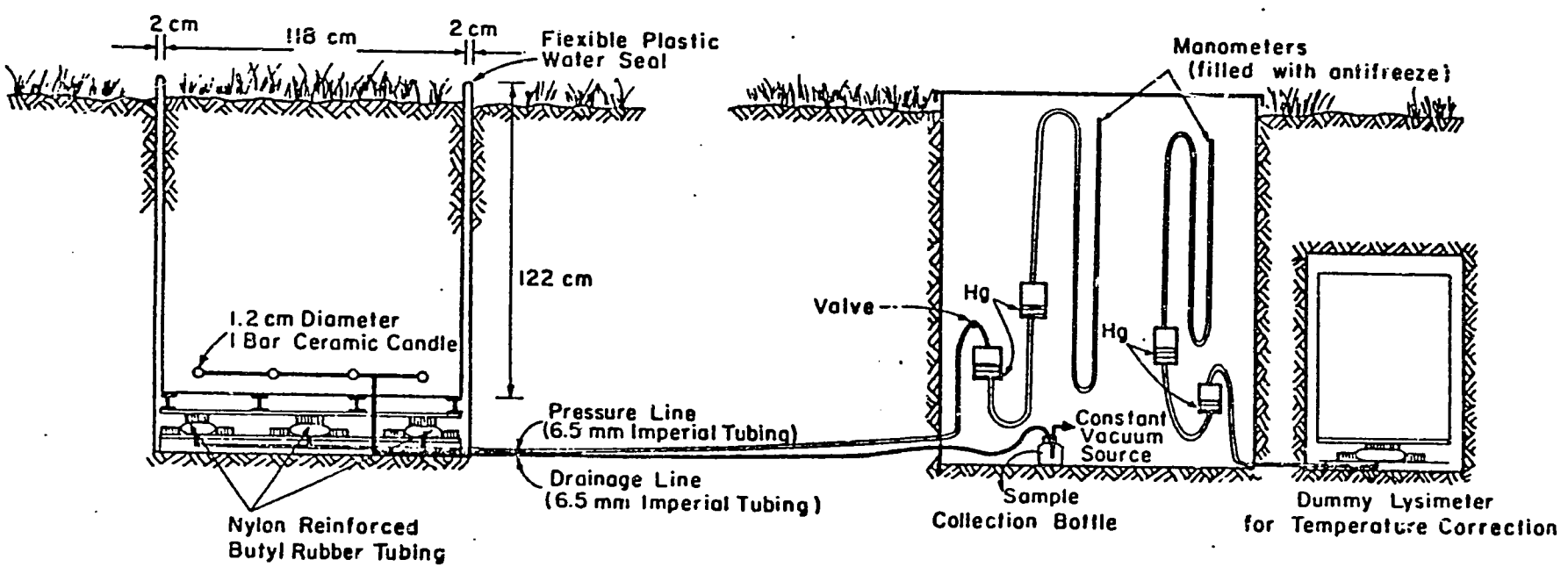

Figure 2. Hydraulic Weighing Lysimeter

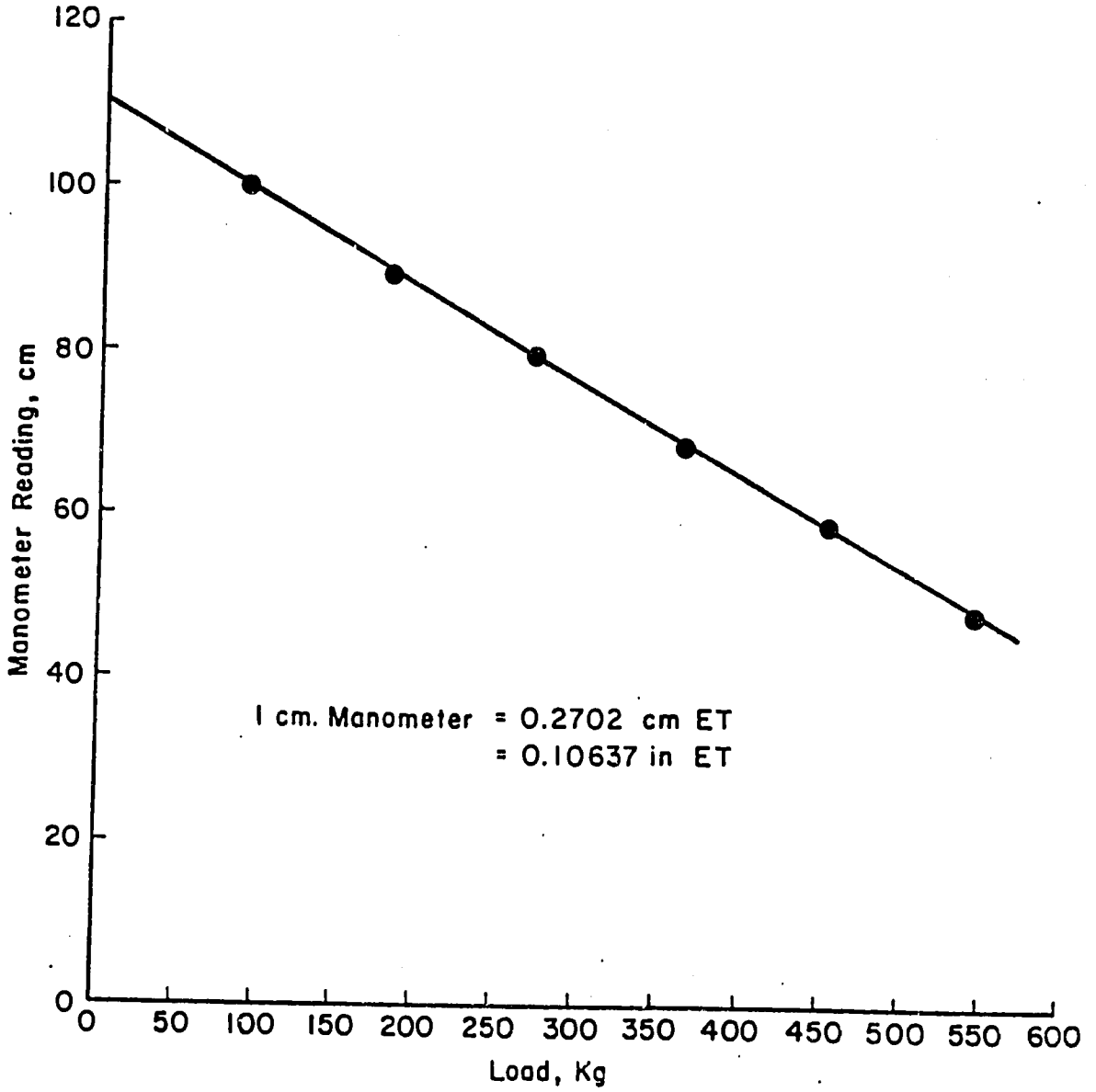

Figure 3. Typical Calibration Curve

Jensen-Haise Calibration

In the Grand Valley, the mean minimum and mean maximum temperatures at the 1,430 meter elevation are 346. °C and 18.1°C, respectively. At these temperatures, e_2 = 55.29 mb and e_1 = 20.58 mb so that C_H = 1.44. The data similarly result in C_T being equal to 0.0255 and T_X= -10.05. The Jensen-Haise equation for the Grand Valley is, therefore (multiplied by 0.0171 to yield mm/day):

$$E_{tp} = 4.36 \times 10^{-4} (T + 10.05) R_s \qquad (23)$$

Equation (23) overestimates evapotranspiration as determined from the grass lysimeters (and divided by 0.87) by 4% to 5% over the accumulated irrigation season. However, during the windy periods of May and June, Equation (23) can underestimate E_{tp} by about 10 to 15%. By solving for C_T and T_x and correlating with the lysimeter data, Equation (23) was slightly modified as indicated below:

$$E_{tp} = 4.75 \times 10^{4} (T + 9.646) R_s \qquad (24)$$

Penman Calculations

The Penman equation has several regression formulas implied in its form as listed in Equation (10). An evaluation of each was made, but the only effective correlation was between the wind term coefficients, a and b. Interestingly, the values determined for alfalfa (a = 0.90 and b = 0.0062) are not significantly different from the values Penman originally suggested for grass (Jensen, 1973). The resulting Penman formula for alfalfa (E_{tp}) is:

$$E_{tp} = 0.0171 [C_1 (R_n+G) + C_2(0.9+0.0062U_2) (e_z^o - e_z)] \qquad (25)$$

Comparison of Methods

The mean monthly measured values of the grass lysimeter evapotranspiration for the Grand Valley are plotted against both the calibrated and original Blaney-Criddle relationships in Figure 4. These data were collected in 1975. The other years do not differ markedly, however. The revised function allows a substantially better monthly estimate of consumptive use than the version suggested by Blaney-Criddle (1950). In fact, over the season the measured and predicted (by the adjusted equation) are identical. The Blaney-Criddle approach is satisfactory for time periods

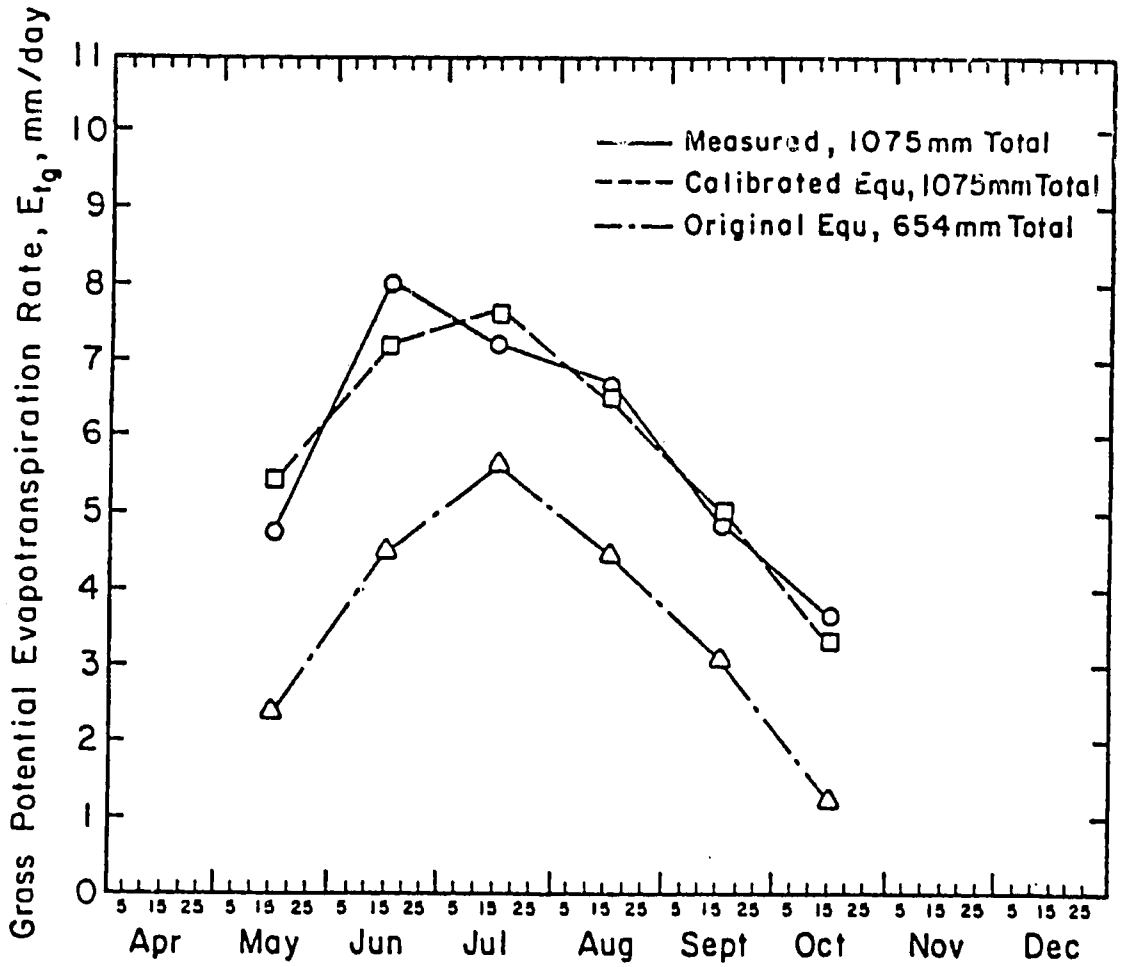

Figure 4. Comparison of Lysimeter Data with the Blaney-Criddle Estimate for Well-watered Grass in 1975

can lead to significant errors if the method is not locally calibrated.

A comparison of the measured and calculated E values during the 1975 irrigation season in Grand Valley, when the Jensen-Haise method was applied, revealed that an error was introduced simply by using the reported function with an altitude correction too small to be significant. However, about a 4 to 5 percent improvement was achieved. The lysimeters are irrigated for the purpose of maintaining a low-tension soil moisture condition. A neutron access tube or other methods are installed to assist in monitoring soil moisture distribution. A method of extracting the surplus water and to provide a leaching mechanism should be installed. One bar ceramic candles connected to a vacuum system work well for this purpose.

CALIBRATING ESTIMATING FORMULAS

Once a reliable measurement of evapotranspiration is obtained, it is then used to calibrate the evapotranspiration estimating formulas for the local conditions. For purposes of illustration, these formulas will be calibrated for conditions encountered in the Grand Valley of Colorado.

Blaney Criddle Calibration

The uncalibrated Blaney-Criddle equation, as described earlier, underestimates E in the Grand Valley by approximately 40 percent. Generally, in the windy months of spring the procedure underestimates E_{tp} by as much as 50%, whereas later results show substantial overestimation. The calibration of Equation (1) involved solving for the k term:

$$at - b = \frac{E_t \times 100}{p \times c \times k_t} \tag{21}$$

In this case, k_t was found to be:

$$k_t = -0.00268 + 1.49 \tag{22}$$

Even so, the month-to-month variations were large (i.e., Equations (1) and (22) overestimate E_{tp} in May, July and September, while it underestimates the values in June and August). It should be noted that calibration of the k_t parameter over so with local calibration. The Jensen-Haise method is often used in conjunction with the Penman equation in many irrigation scheduling services, primarily from July on when wind is less significant. The largest error in the time distributed estimates (5 to 6 day intervals) was less than

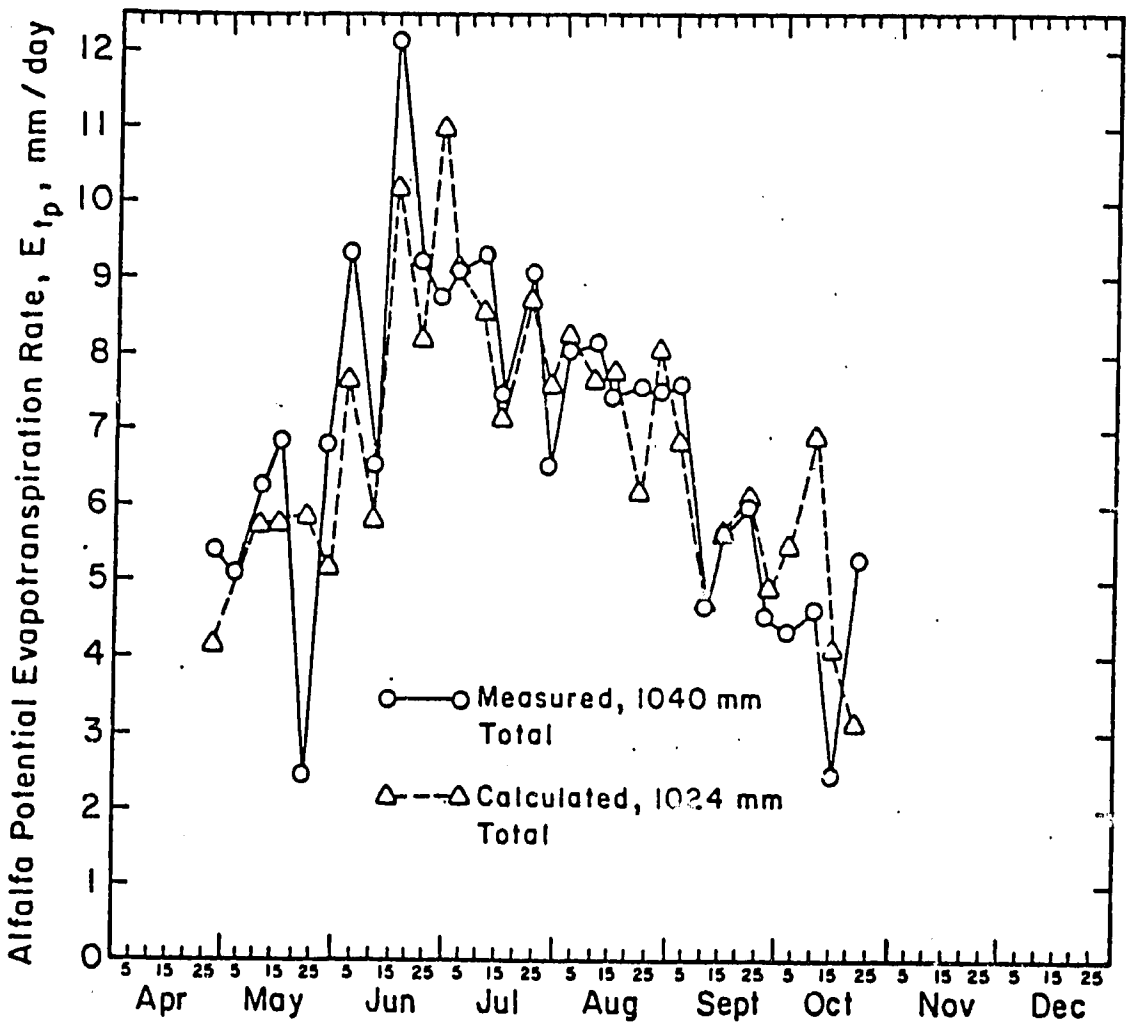

Figure 5. Comparison of Lysimeter Data and the Penman Equation Estimate for Alfalfa in 1975

2 mm per day in the latter part of the Grand Valley's 1975 irrigation season. In June, a 5 mm error is noticeable.

Although the Penman equation shows more seasonal error than the Jensen-Haise approach (Figure 5), it follows the lysimeter data better over the season. In evaluating these results, it appears that time intervals less than 3 to 5 days are not justified by the sensitivity of the approaches. In fact, the correlation between measured and predicted values on a daily basis was less than 70 percent, whereas it was approximately 90 percent for 5 to 6 day periods.

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ERRATA

DIAGNOSTIC ANALYSIS OF
IRRIGATION SYSTEMS

VOLUME 2:
EVALUATION TECHNIQUES

Page

154-155 Should read:

Nutrient solution concentrations for foliar sprays:

N	4% solution of Urea
P	0.3% solution of P
K	0.5% solution of K
Fe	2% solution of $FeSO_4$
Zn	.5 to 1.5% solution of $ZnSO_4$
Mn	.2 to 2% solution of $MnSO_4$ with small amount of lime
Cu	0.5% solution of $CuSO_4$ with small amount of lime
B	0.1 to 0.3% solution of H_3BO_4

171 Should read:

HI - FS = Elev. not, HI + FS = Elev.

207 Should read:

$h_b/h_a = .40/.80 = .50$

not, $h_a/h_b = .40/.80 = .50$

210 Should read:

d = depth applied to field (L)

A = area of field (L^2)

not, d = depth applied to field (L^2)
a = area of field (L)

VOLUME 2, Errata (continued)

Page

334 Should read:

$E_{tp} \times 0.00171 \rightarrow cm\ t^{-1}$

not, $E_{tp} \times 0.0017 \rightarrow cm\ t^{-1}$

Should read:

$k_t = 0.0173t - 0.314$

not, $k_t = 0.0.173t - 0.134$

335 Should read:

$E_{tp} = C_T(T - T_x)\ R_s$

not, $E_{tp} = C_t(T - T_x)\ R_s$

Should read:

$= -2.5 - 0.14\ (e_2 - e_1)$ °C/mb

$- elev(m)/550$

not, $-2.5 - 0.14\ (e_2 - e_1)$

°C/mb $- elev(m)/550$

336 Should read:

$$E_{tp} = [\frac{\Delta}{\Delta+\gamma}\ (R_n+G)+15.36\ \frac{\gamma}{\Delta+\gamma}\ (a+bU_2)(e_z{}^{\circ}-e_z)] \times 0.00171$$

not,

$$E_{tp} = [\frac{\Delta}{\Delta+\gamma}\ (Rn+G)+15.36\ \frac{\Delta}{\Delta+\gamma}\ (a+bU_2)(e_z{}^{\circ}-e_z)] - 0.0171$$

337 Should read:

$\varepsilon' = -0.02 + 0.261\ \exp$

$[-7.77 \times 10^{-4}\ (273-T_k)^2]$

not, $-0.2 + 0.261\ \exp$

$[-7.77 \times 10^{-4}\ (273-T_k{}^2]$

338 Should read:

11.71×10^{-8} Ly $K^{-4}day^{-1}$

not, 11.21×10^{-8} Ly/ K

Should read:

$$R_b = [a \frac{R_s}{R_{so}} - b] R_{bo}$$

in which a = 1.2 in arid regions and 1.0 in humid regions
b = 0.2 in arid regions and 0.0 in humid regions

not, $R_b = [1.2 \frac{R_s}{R_{so}} - 0.2] R_{bo}$

Should read:

$$G = \frac{\overline{T}_{i-1} - \overline{T}_{i+1}}{\Delta t} \times 100$$

not, $G = \frac{\overline{T}_{i-1} - \overline{T}_{i+1}}{t} \times 100$

339 Should read:

for $\Delta(\Delta+\gamma)$, $\gamma(\Delta+\gamma)$ and $e_z°$ as follows:

not, for $\Delta/\Delta+\gamma$, $\gamma/\Delta+\gamma$, and $e_z°$ as follows:

Should read:

$\gamma(\Delta+\gamma) = 0.959 - 0.0125T + 0.00004534T^2$

not, $\gamma/\Delta+\gamma = 0.959 - 0.0125T + 0.00004534T^2$

Should read:

$\Delta(\Delta+\gamma) = 1 - \gamma(\Delta+\gamma)$

not, $\Delta/\Delta+\gamma = 1 - (\gamma/\Delta+\gamma)$

340 Should read:

$E_{tp} = 4.75 \times 10^{-4} (T + 9.646) R_s$

not, $E_{tp} = 4.75 \times 10^{4} (T + 9.646) R_s$

Should read:

$E_{tp} = .00171[C_1(R_n+G) + C_2(0.9+0.0062U_2)$

not, $E_{tp} = 0.0171[C_1 (R_n+G) + C_2(0.9+0.0062U_2)$

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