COMPUTER MODELING OF WATER DISTRIBUTION SYSTEM PERSONNEL TRAINING AND RECOMMENDATIONS FOR IMPROVEMENTS NOVOKUZNETSK, RUSSIA

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Executive Summary

Engineers from Vodokanal of Novokuznetsk were trained in every aspect of state-of-the-art computer modeling and computer design of water distribution systems. Three weeks of training occurred at Colorado State University in Fort Collins, Colorado and three weeks occurred in Novokuznetsk, Russia. Much of the training was centered around the Kuznetsk District. A computer model of the district was setup, calibrated and then used to model and optimize system improvements. Vodokanal personnel were involved in every aspect of the modeling process and are now well familiar with the use of the software WADISO SA to model and design system improvements.

The existing conditions of the water distribution system in the Kuznetsk District were carefully assessed. Under normal load conditions, the system currently fails to meet the desired minimum pressure of 30 m at many locations for reasons such as partially or fully closed gate valves, and excessive leakage. Redundancy was frequently lost by breaking pipe loops.

In cooperation with Vodokanal personnel low cost system improvements were identified that will result in improved pressure conditions, a reduction in annual pumping costs, and an increase of flow into the next districts by about 16%.

1.0 INTRODUCTION

One component of the ENVIRONMENTAL POLICY AND TECHNOLOGY PROJECT (EPT), a USAID Project Consortium led by CH2MHill, is to provide training in the computer modeling and design of water distribution systems to the water utility of Novokuznetsk, Vodokanal. Computer models of water distribution systems are used for short and long-term planning and management. The model is also used to simulate changes to a system to be assured of feasibility prior to implementation. CH2MHill, through CID, subcontracted with Colorado State University to provide the necessary training and expert advice to Vodokanal.

1.1 Project Objective

The first objective of the project was to train two engineers from Vodokanal in state-of-the-art technology related to the analysis and design of water distribution systems, using the computer software WADISO SA. The second objective of the project was to demonstrate to the Vodokanal personnel how the technology could be applied to their water distribution system. The initial training of how to use the software occurred at Colorado State University. Application of this technology to the needs of Vodokanal was accomplished during a visit of Johannes Gessler and Daniel Gessler, both from Colorado State University, to Novokuznetsk.

1.2 Report Organization

This report is organized into five chapters and three appendices. The five chapters are intended to provide a general description of the work accomplished with little detail about the technical aspects of the computer model of the networks. Detailed discussions of certain aspects of

computer modeling and application of the technology to part of the Novokuznetsk network are included in appendices. They are intended for the benefit of reader interested in such details and Vodokanal personnel. Chapter one gives an introduction to the project and describes the project objectives. Chapter two describes how the project was executed, while chapter three describes how the training and technology was applied to the city of Novokuznetsk. Chapter four presents some conclusions and recommendations about the portion of the system that was modeled and the entire network. Chapter five gives a summary of the report.

2.0 PROJECT EXECUTION

Project execution can be broken down into three segments: selection of the software, training at Colorado State University, and on site training and technology application in Novokuznetsk. Each of the three segments is discussed in the following text.

2.1 Software Selection

A large number of computer programs for modeling pipe networks are commercially available in the United States. The capabilities of the various programs varies greatly. The software selected for this project was WADISO SA. As part of the contract, Vodokanal obtained a copy of the software. The selection of this software was based on the following points:

1) Both team members have extensive experience with WADISO SA. One of the team members provided the lead in the early development of the software;

2) WADISO SA is the only software which provides for a systematic optimization of selected designs. Designs are optimized for both cost and system performance. Financial resources in Russia are very limited, therefore, the optimization capability of WADISO SA is of great importance.

3) WADISO SA has been extensively applied in South Africa to optimize system improvements under economic conditions similar to the ones in Novokuznetsk.

4) WADISO SA in various version has existed for over ten years. The program is based on the WADISO program developed by the U.S. Army Corps of Engineers and is known to be very robust.

2.2 Training at Colorado State University

Johannes Gessler and Daniel Gessler worked with two representatives from Vodokanal (the Novokuznetsk Water Utility) during a three week period in July 1995, with the assistance of two very capable translators. The purpose of the representatives' visit to Colorado State was to provide training in the use of the computer software WADISO SA for the design of water distribution systems and their optimization. Though the emphasis at the time was on training, the system data for the Kuznetsk District, a sub-district of the greater distribution system of Novokuznetsk, was entered into WADISO SA and some general computations were done on pressure and flow distribution.

At the end of the visit, the engineers from Vodokanal had gained considerable experience in all major components of the software: definition of water distribution systems, steady state simulation, extended time simulation and design optimization. In the process, present design philosophies were discussed as well as problems specific to Novokuznetsk.

Preliminary computations on the system of the Kuznetsk District indicated considerable discrepancies between computed and observed data. Discussions at that time indicated that there was probably significant uncertainty regarding load distribution and connectivity. Such aspects were to be investigated and resolved during the visit to Novokuznetsk.

During part of this visit, Randy Hoffman, a representative from the Environmental Policy and

Technology Project, was also present.

2.3 On Site Training in Novokuznetsk

Originally, the site visit was planned for the first three weeks in August 1995. Due to limitations in man power at Vodokanal during this time of the year, it was decided to postpone the visit. Based on discussions with the representatives from the district and the time schedules of Johannes Gessler and Daniel Gessler, it was decided to plan the visit for March/April 1996. At this time, snow conditions and temperatures in Novokuznetsk are in general such that flow tests are possible, though field conditions might at best be described as 'muddy'.

The team from Colorado State University arrived in Novokuznetsk on Monday, March 25, 1996 and left again on Saturday, April 13, 1996. A preliminary work plan had been sent to Vodokanal beforehand and was discussed with Randy Hoffman from CH2MHill. The preliminary work plan is included in Appendix A. In general, it was found that relatively little progress was made on the model during the eight month period between visits. The most significant accomplishment may have been the translation of the entire WADISO SA manual into Russian.

In general terms the following tasks were to be accomplished during the site visit;

1) Review the original training at Colorado State and answer remaining questions;
2) Review work done between the work session at Colorado State and the visit to Novokuznetsk;
3) Gain an understanding of the local water distribution system;
4) Discuss the general philosophy of using flow tests for the calibration of system models;
5) Plan specific flow tests for the Kuznetsk District to provide optimal information;

6) Perform the flow tests;

7) Use existing and new pressure and flow information under normal and flow test conditions to attempt a calibration;

8) Discuss means available to find inconsistencies in the collected data;

9) Plan follow-up flow tests to resolve inconsistencies which developed during the calibration process;

10) Review strategies for short term system improvements at low cost; and

11) Review strategies for long term system improvements with emphasis on optimal solutions and the staging of the work.

Throughout completion of these tasks, special emphasis was to be placed on the training of the personnel of Vodokanal. The water utility of Novokuznetsk serves a much larger area than just the Kuznetsk District. For the Kuznetsk District, however, considerable data was already available. It made for an excellent example for training purposes.

The objectives of the visit to Novokuznetsk did not change substantially during the visit, though the emphasis among various tasks and the amount of time per task deviated considerably from the original work plan. A more detailed description of the work accomplished on the Kuznetsk District is provided in the following section.

3.0 KUZNETSK DISTRICT

The Kuznetsk District comprises approximately 15 to 20 percent of the total water distribution system of Novokuznetsk. Vodokanal personnel compiled sufficient data to model the district on the computer. The computer model was used for training purposes and it provided valuable insight to the authors about the general condition of the water distribution system. The existing condition of the Kuznetsk District was assessed, a computer model was setup and calibrated, and recommendations for improvements to the system were made utilizing the calibrated computer model. Vodokanal personnel were an integral part of all three steps. The following text presents the work accomplished by the team from Colorado State University and Vodokanal.

3.1 Assessment of Water System

The Kuznetsk District is operated as a single pressure zone. This means that water can flow in both directions through all pipes; there are no check valves or pressure reducing valves. Water for the district is taken from three large supply lines that provided water to the entire city. A booster pump station for the three supply lines is located in the district. Approximately ten percent of the water for the district is taken from the supply lines upstream of the pump station. A gate valve can be used to closed this connection. The remaining 90 percent of the water is diverted into the district downstream of the pumps. A flow meter measures the amount of pumped water going to the district.

Discussions with district personnel indicated that substantial problems in the district were attributed to water pressures too high for the relatively old and not very well maintained system. Such problems were felt to have resulted in pipe breaks and increased system leakage. Historically,

district personnel have routinely reduced pressures in parts of the district to minimize such problems. Such pressure reductions are accomplished through the partial or total closure of existing gate valves. Approximately 30 percent (20 meters) of the head imparted to the water by the pumps is destroyed immediately downstream of the pumps with a gate valve. Discussions with district personnel yielded the following additional observations about the system:

1) Over the past ten years, substantial changes in personnel have occurred, in part due to the recent privatization of the water utility. There is little 'institutional memory'. There are no systematic records available on the age of pipes in various parts of the district. Most of the available (but limited) information has been collected by the present district personnel.

2) Available maps of the district show pipe lengths and diameters and the location of valves and connections. Length and diameter information are assumed to be reliable. All valves are located in maintenance holes and provide for easy verification of pipe diameter. Valve setting can be verified if the valves are functional.

3) In many of the maintenance holes the pipes have been tapped to allow for pressure readings. Pressure measurements can also be obtained at fire hydrants. Due to the relatively small (less than 10 percent) demand variations during the day, it is not essential that pressure readings be collected simultaneously. Consequently, it is possible to get substantial pressure information with relatively little effort.

4) The network probably has a substantial leakage problem. This conclusion was arrived at for the following reasons: (a) in general the system has not been well maintained in the past; (b) the peak flow was measured to be about 10 percent greater than the average flow. A more realistic 15 percent variation would imply a leakage of approximately 30 percent; (c) district personnel have frequently closed off or reduced pressure in some pipe sections, presumably because they were considered 'problem areas', i.e. areas with frequent pipe breaks and assumed large leakage. There also might be water lost due to leaking appliances in the apartments.

5) The relatively low pressures in large parts of the network are probably reducing the peak demand. The partially closed valves in the streets plus the restrictions at the connections to the buildings limit the amount of water a user can obtain.

6) All of the closed valves lead to changes in the system connectivity, and cut the loops in the system which provided redundancy. System redundancy is very important in case of pipe breaks and avoiding that sections of the district are temporarily disconnected while repair work is performed.

3.2 Computer Model

The purpose of computer modeling is to predict system behavior under new loading patterns and/or to predict system behavior after some major modifications. Such predictions are only valid if the computer model is well calibrated. In general, calibration addresses the following questions:

1) Is the data representing the physical characteristics of the network correct, i.e. correct pipe length, pipe diameters and node coordinates;

2) Is the system connectivity correct;

3) Are the assumed valve setting correct;

4) Are the assumed internal pipe roughness characteristics reasonable (verification of friction factors); and

5) Are demand magnitude and distribution correct.

It is of paramount importance to make every possible effort to verify all of these aspects. The first item listed above is easy to verify, though it requires substantial time. No particular training of personnel performing verification is needed. The remaining aspects are much more difficult to verify because the distribution system is buried in the ground. In general, one uses pressure measurements under normal and flow tests conditions to systematically approach such verification. In the calibration effort one attempts to match the observed pressure distribution with pressure distribution predicted by the computer model. Discrepancies are to be explained by wrong connectivity, missing or extra pipes, wrong pipe sizes, wrong friction characteristics, and/or wrong demand characteristics. By carefully selecting test conditions, it is frequently possible to exclude some reasons or have results point to likely explanations.

Three flow tests were conducted with Vodokanal personnel to train the personnel and help calibrate the model. In addition, extensive pressure measurements were made under normal load conditions throughout the system to help calibrate the model. A more detailed discussion of the calibration process is included in Appendix B. No systematic records are available on totally closed

or partially closed valves. This made calibration very tedious because the true connectivity of the model was not known. It was reasonable to assume that leakage and domestic consumption are both proportional to pipe length. Therefore, leakage is included in the domestic load and does not affect the calibration process.

It is tempting to systematically open all partially closed valves (and perhaps open some totally closed valves) in order to facilitate calibration and re-establish desirable redundancy. However, this will lead to some very substantial pressure increases in the system, re-exposing the network to conditions which may have caused difficulties. Breakages or excessive leakages are most likely to occur at the connections.

3.3 Suggested Improvements

None of the problems described above can be eliminated or minimized at no or little cost. In addition, elimination of some of the restrictions may lead to increased peak demand (more demand variation). Since systems should be designed for peak conditions some components presently judged as 'adequate' may become inadequate due to increased instantaneous demand, even if average demand remains constant. However, some low cost system improvements were modeled and the following suggestions are made. A more detailed description of these improvements is included in Appendix C.

Vodokanal personnel suggested that the minimum pressure requirement at each node during peak demand be 30 meters. The three major supply lines have a pressure that varries from 30 to 35 meters. Much of the Kuznetsk District is physically at an elevation substantially less than that of the supply lines. Consequently, it should be possible to provide water to much of the Kuznetsk District

without pumping and still meet the pressure requirements. A scheme was developed in which the Kuznetsk District is divided into two pressure zones. The lower pressure zone is served directly from the supply lines at two points. The upper pressure zone is served from the supply line downstream of the pump station. The amount of pumped water in the Kuznetsk District is decreased thereby decreasing the cost of supplying water to the district. The lower pressure zone is connected to the upper pressure zone through a pressure reducing valve (PRV). If the pressure in the lower zone at the location of the PRV should drop below the pressure setting (ca 30 meters,) the PRV will open and allow water to flow from the upper zone to the lower zone. Also, over a wide range of operational conditions, the PRV will stabilize the pressure. The scheme is designed such that the valve is mostly closed under normal operating conditions.

The water in the upper pressure zone is pumped using the existing pumps. But it would have more pressure than the system can probably accept without pipe failures (more than 100 m in some places). A second PRV must be installed where the pumped water enters the upper pressure zone.

Presently, there are numerous broken loops in the network. Many of the broken loops should be closed again. All of the partially closed gate valves must be completely opened for the system to operate properly. These measures guarantee satisfactory performance over a wide range of conditions, including many emergency situations.

The cost of the suggested improvements should be minimal. No new pipeline is required. The only costs will be for closing the broken loops, connecting some existing pipes to each other, and the two pressure reducing valves. Any broken gate valves must also be repaired. In return it should be possible to maintain a minimum pressure of about 30 m throughout the system. An additional fire load of 20 l/s at any node will cause only slight additional pressure drops. Pressure

would remain well above the 10 m minimum the fire department would like to specify.

These improvements were developed in cooperation with Vodokanal personnel. They were tested, using the calibrated compter model. In addition, this example was used to demonstrate how, in the improved system, one can locate those pipe which would bring the most significant additional improvements at minimum cost. This analysis was performed using the optimization routine of WADISO SA.

4.0 CONCLUSIONS AND RECOMMENDATIONS

A number of conclusions can be drawn and recommendations can be made. The objective of the project was to train engineers from Vodokanal of Novokuznetsk in every aspect of computer modeling water distribution systems. Training was very successful and Vodokanal personnel can now setup and calibrate water distribution system models. In addition, they know how to use the model for the design and optimization of system improvements.

The Kuznetsk District was modeled and based on the computer model suggestions for improvements were made. The recommendations apply to more than just the Kuznetsk District. The lessons learned from working in the Kuznetsk District can be applied to all of the districts in Novokuznetsk:

1) Leakage is a very difficult and expensive problem to solve. While small (less than 15 percent) leakages in systems are normal and cannot be avoided, large (greater than 35 percent) leakages can cause excessive financial losses. In order to assess the magnitude of the leakage problem, it is imperative to have a good estimate of the amount of water leaked from the system, at least with an accuracy of 10%. If indeed the present system losses are 30%, we would like to establish this percentage with a likely error range of 27 to 33%.

   It is recommended that a few large apartment buildings be metered to monitor the consumption (domestic use and in-house leakage) over several 24 hour periods. This will help in establishing the true 24 hour peaking factor for domestic consumption as well as a reasonably reliable per capita consumption. Based on the total population in the district it will then be possible to estimate domestic consumption. If a district has substantial

commercial and/or industrial users, such consumption needs to be estimated as well. In the Kuznetsk District, industrial and commercial users are limited in numbers. Since a large part of the district can be metered at a bulk meter, it is then possible to establish total leakage into the ground. If such leakage is expressed per kilometer of pipe line one can extrapolate to the leakage of the total network.

2) Domestic leakage may be a considerable problem. The magnitude of the problem can be asses by metering a building as described in item 1. A team of plumbers would then be assigned the task of fixing all domestic leakage in the building. The building would then be metered again. The difference in load over a 24 hour period is the total domestic leakage per day for the building. Alternatively, measured consumption in the building between 2:00 am and 3:00 am may be interpreted as predominantly leakage. One method for improving system performance is to decrease total load by decreasing leakage. Locating and repairing leaking pipes in the ground can be expensive. The most cost effective way for Vodokanal to improve system performance, may be to repair domestic leakage. To determine this, a good estimate of the total domestic leakage must be available.

A number of additional, more detailed recommendations were made to Vodokanal personnel. They are included in Appendix D.

5.0 SUMMARY

The objective of the project was to train engineers from Vodokanal of Novokuznetsk in every aspect of state-of-the-art computer modeling and computer design of water distribution systems. Three weeks of training occurred at Colorado State University in Fort Collins, Colorado and three weeks occurred in Novokuznetsk, Russia. Much of the training was centered around the Kuznetsk District. Field data was collected by district personnel and a computer model of the district was setup, calibrated and then used to model and optimize system improvements. Vodokanal personnel were involved in every aspect of the modeling process. The training exercises were very successful and Vodokanal personnel are now well versed in the use of the software WADISO SA to model and design system improvements.

The existing conditions of the water distribution system in the Kuznetsk District were assessed. It was found that under normal load conditions, the system currently fails to meet the desired minimum pressure of 30 m at many locations. Numerous gate valves were identified that are partially closed with the intent to reduce the pressure in the system. The pressure reductions were considered neccessary to reduce system leakage and pipe failures. Based on a measured 24 hour load pattern, it was concluded that there is considerable leakage in the system. Finally, it was found that there are numerous dead-end pipes and broken loops.

In conjunction with training excercises, low cost system improvements were designed that will result in improved system performance, a reduction in annual pumping costs, and increase of flow into the next districts by about 16%. The improvements are described in this report. The suggested improvements include reccomendations to close several loops and open all partially closed valves.

It is imparative that the pipe networks of the other districts in the city be computer modeled. It will be extremely difficult to make any cost effective improvements to the remaining districts until the computer models are setup and calibrated. Setting up the computer models and calibrating them requires considerable time and should be started immediately. Optimum system improvements can then be selected from several alternatives which were carefully modeled and designed. Low cost system improvements can be identified and implemented immediately. More expensive system improvements can be constructed when funds become available.

Acknowledgments

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them last, because this gives us the opportunity to single them out to a greater degree. They were available at all times, sometimes well into the evening hours and during weekends. Their services were of exceptional quality and we enjoyed their company during the many hours we spent together.

Appendix A: Original Work Plan

USAID PROJECT
NOVOKUZNETSK, RUSSIA

Project Schedule for Field Visit March/April 1996

Week 1 (4 days)

Project Status Update

1) Have people working with computer model present overall status of modeling effort, including any data collection.
2) Review the status of the computer model.
3) Look at any additional modeling which may have been done since July 1995.

Answer Software and Model Related Questions

1) Brief review of material covered during July 1995 visit to Colorado State University.
2) Answer any questions about modeling the system

Discuss Flow Test Procedures

1) Discuss equipment required for flow test. Insure this equipment is available.
2) Have system operators and managers relate problems or concerns they may have about the tests.
3) Discuss how to determine number of hydrants to be opened.
4) Discuss how to determine where to measure pressure in system.
5) Review the impact of the flow tests.

Major Detailed Briefing on Water System

1) Have system operators and managers give their assessment of the overall state of the system.
2) Look at maps of entire area served by utility.
3) Look at regional topography.
4) Look at water and pressure availability over 24 hour period throughout system.
5) Review available information regarding pipe age, material, and reliability.

Week 2

Field Inspection of System

1) Have system operators and managers show us any problem areas they would like to have looked at.
2) Visit all of the major system components and appurtenances. This includes any pump stations, bulk meters, pressure gauges, storage tanks, etc.
3) Source of water supply.

Review Available System Data

1) Any available flow and pressure information will be used to make a first pass at calibrating the system.

Discuss and Determine Flow Test Locations

1) Use computer model of the system to model flow tests and predict results.
2) Use computer model to help determine number of hydrants to be opened and where to measure pressure throughout system.

Discuss Flow Test Timing

1) Discuss how to minimize impacts on flow test results by other demands on water system.

Conduct Flow Tests

1) Conduct flow tests.

NOTE:

Flow tests are frequently conducted at night. A typical testing pattern is to spend 2 to 4 hours running flow tests and collecting data. Approximately 2 to 4 tests can be run per night. The results of the tests are assessed the following day and used to plan flow tests for that night. As many flow tests as possible will be run during week 2 and 3.

Week 3

Assess Results from Flow Tests and Calibrate Model

1) Flow test results are used to adjust the friction factors and pipe diameters of the pipes until the model predicts the observed results.
2) Flow test results can also be used to locate anomalies in the model, such as closed valves, or unmapped cross connections.

Discuss Short-Term/Low Cost System Improvements

1) Have system operators and managers present information regarding their highest operating expenses and system improvement priorities.
2) Discuss methods for improving the overall system efficiency at a minimal cost and effort.
3) Show how the computer model can be used to model the system improvements, and test their viability.

Discuss Long-Term System Improvements

1) Have the system managers present their long-term goals and objectives for the system.
2) Discuss with them how best to achieve these goals.
3) Discuss how WADISO SA can be used to minimize the long-term cost of the necessary improvements, including minimizing power cost and pipe cost combined.
4) Discuss methods for financing the system improvements.

Appendix B: Kuznetsk District Model Calibration

The water system of the City of Novokuznetsk is subdivided into five districts. A detailed computer model of the pipe network in the Kuznetsk District was developed using WADISO SA. The Kuznetsk District comprises approximately 10 to 20 percent of the total water system. An important aspect of any network model is accurate calibration. The calibration process involves the collection of flow and pressure measurements throughout the network to establish pipe friction factors and flow distribution. A well calibrated model should accurately predict the water pressure throughout the system for any load condition. The following is a description of the calibration process followed for the Kuznetsk model. The same approach can be utilized for other districts.

A computer model is only as accurate as the input data and the data collected for use in the calibration. The input data includes load distribution, node elevations, pipe connectivity and pipe diameters.

Both the temporal and spacial load distribution must be known along with the total load for the district. Accurate load distributions can be very difficult to obtain. In general, it is best to individually meter all large industrial users of water for both total load and their individual 24 hour load pattern. Residential load can be estimated on a per capita basis using the total number of residential units and the estimated occupancy of each unit. Per capita consumption is known to vary with socio-economic conditions. It is therefore recommended that the per capita consumption and 24 hour load pattern be calibrated. For Novokuznetsk, it is recommended that this be done by metering the total usage of two or three large apartment buildings. The cumulative flow over a 48 hour period should be recorded every half hour. Leakage can comprise a considerable percentage

of the load on a water distribution system. In the Kuznetsk District it is estimated to exceed 30 percent of the load. It is generally assumed that leakage has the same spatial distribution as the system load. (i.e. the consumption at each node is increased by a fixed percentage.) Network leakage can be estimated by subtracting the calibrated residential and industrial demand from the total amount of water supplied to the district. It is recommended that bulk meters be used at all locations where water enters the system to help monitor the system leakage.

It is generally assumed that node elevations and pipe diameters can be collected very accurately. Node elevations should be known within one half meter and pipe diameters are assumed to be correct since pipes can be inspected in the maintenance holes. Pipe connectivity is initially determined from maps and construction drawings of the network. Over time, modifications and maintenance to the system is necessary. Frequently, modifications to the system are poorly documented, and the locations of closed valves and dead-end pipes are unknown. A major aspect of the calibration of the model is to verify connectivity of the system through extensive pressure measurements and conversations with system operators. An incorrectly connected model can sometimes be calibrated, but only for a single load condition. If the flow conditions are changed the error in connectivity should become apparent.

A pipe's resistance to flow (friction factor) typically increases over time. By measuring the pressure at various locations in the network during a known load condition, the friction factor of the pipes can be determined. The higher the water velocity in the pipe, the more reliable the computed friction factor is. It may be desirable to change the network connectivity or load to increase the flow rate in a specific pipe and improve the reliability of the computed friction factor. By opening or closing valves in the system, the flow rate through individual pipes can be changed substancially.

This can also be accomplished by opening fire hydrants, measuring the hydrant discharge and the pressure at various points in the system that should be affected by the change in load. The change in connectivity or load is modeled on the computer and predicted pressures are compared to measured pressures. Pipe friction factors are adjusted until the model accurately predicts the pressure under the various load and connectivity conditions. When discharging water from a fire hydrant (flow test) it can be difficult to accurately measure the discharge, especially when flow rates are less than 20 liters per second. This may be a limiting factor in the usefulness of flow tests in calibration.

In the Kuznetsk District, calibration of the model was accomplished in the following manner: There are two sources of water for the district, one of the pipes is equipped with a cumulative flow meter, the other one was disconnected for a 24 hour period. The total flow was plotted over the 24 hour period to determine temporal variation of the demand. The flow rate was also computed as a percentage of the average flow rate. During the 24 hour period, the pressure was measured at 21 locations throughout the district at three times during the day. Measurements were taken between 10 and 11 am, 3:30 and 4:30 pm and 7 and 8 pm. Since the demand on the system varied by less than five percent at the three times, the average pressure and average load was used for calibration. To calibrate the model, one works away from the source of water. Starting at the source and moving progressively further into the network, the friction factors are adjusted such that predicted pressures up to a certain distance from the source match the measured pressures. The friction factors in these pipes are then assumed to be correct and one moves further away from the source. In this manner, the entire model is calibrated. The process may need to be repeated several times.

In addition to the calibration of the model at normal load conditions, flow tests were used to

verify the friction factor in individual pipes. In the Kuznetsk District, the reliability of flow tests is questioned. Relatively low system pressures result in the ability to discharge only small amounts of water, typically less than 20 liters per second.

Much of the effort in the calibration of the Kuznetsk District model was focused on locating unknown dead-ends, closed valves and partially closed valves. The partially closed valves may be broken, or they may have been deliberately partially closed such that they reduce pressure. Partially closed valves can be difficult to differentiate from pipes with high friction factors. If sufficient pressure measurements are made along the pipe line, they can be found by the discontinuity in the energy grade line along the pipe.

Appendix C: Detailed Description of Kuznetsk District Improvements

The following description demonstrates the methodology used in developing system improvements and refinement of the proposal, using the software WADISO SA.

Concept

Pressure Zones: Past operational procedures centered around the concept of keeping the pressure throughout the district as low as possible in order to minimize problems related to high pressures (leakage, pipe breaks). The district shows considerable elevation changes, therefore, it is logical to consider the establishment of two or three pressure zones.

Water Supply to the Pressure Zones: In the past, almost all water used in the Kuznetsk District was first pumped through a head of about 65 m in a pumping station primarily used for moving water into the next district. This made for a convenient supply of high pressure water. But the pressure was too high and was subsequently reduced through the use of gate valves to an acceptable level. With various pressure zones it becomes possible to supply the lowest parts of the District with water from the suction pipe of the pump (no pumping). The intermediate pressure zone can be supplied with water, pumped through a lower head pump, and only the highest pressure zone may remain connected to the discharge side of the existing pump station.

Use of Pressure Reducing Valves: In the process of creating pressure zones much redundancy will be lost. This can be avoided through the installation of pressure reducing valves between the

pressure zones. Such valves also help in sustaining good pressures during periods of high demands by supplying additional water at high pressure to the next lower pressure zone.

Implementation

Design I: Originally, the improvements consisted of creating three pressure zones. The low pressure zone was connected to the 900 mm supply line at node 2002, connecting to node 45. The medium pressure zone was supplied with water by a new low head (20 m) pump at the existing pump station, feeding into the zone at node 14. The high pressure zone was supplied with water from the discharge side of the existing pump station, connecting to node 1001.

A pressure reducing valve was to be installed between the high and medium pressure zones, between nodes 48 and 44. The low pressure zone was connected with the medium pressure zone with pressure reducing valves between nodes 27 and 151 and between nodes 44 and 43.

Design II: When this system was tested it was observed that the pressures in the low and medium pressure zones did not substantially differ. It was consequently decided to combine the low and medium pressure zones into a single zone, to be supplied at node 2002 and node 14 (without the use of the low head pump). The two pressure reducing valves between low and medium pressure zones were eliminated.

Also the high pressure zone showed pressures at times exceeding 100 m. In order to avoid such high pressures a pressure reducing valve was installed into the high pressure supply line between nodes 1001 and 96.

Fine tuning of the system resulted in suggested settings for the pressure reducing valves as

follows: the valve between 1001 and 96 at 27 m, and the valve between nodes 48 and 44 at 32.5 m.

This system was capable of providing at average load conditions at least 30 m through out the central part of the Kuznetsk District. At peak load of 125% of average load, the 30 m requirement was violated by 1 to 2 m at a few nodes.

Further Refinements: An attempt was then made to further refine the design by determining the most critical pipes, to be replaced with larger pipes, at lowest possible cost. In this part of the design the optimization routine of WADISO SA was used.

The question to be answered was: which pipes need to be replaced to provide pressure increase at the lowest cost.

The new system, as proposed delivered at least 30 m of head throughout the system, at average load. But at peak load of 1.25 the pressure dropped below 30 at several points.

Step 1: Under peak flow conditions the pipes with high velocities, e.g. > 1.5 m/s and also pipes with high pressure gradient (e.g. > 0.03) were determined. These pipes are to be considered for replacement.

The following pipes were identified (with their present diameters):

Pipe	Diameter	Group	Candidate Sizes			
2	150mm	1	150	200	250	
4	250mm	2	250	300	350	
7	250mm	3	250	300	350	
9	200mm	4	200	250	300	
45	200mm	5	]	200	250	300
46	200mm	5	]			
63	150mm	6	150	200	250	
65	100mm	7	100	150	200	
67	150mm	8	150	200	250	
68	150mm	9	150	200	250	

Step 2: Decisions were made on the 'grouping' of the pipes. Pipes in the same group are assigned the same diameter. Grouping is done to avoid arbitrary pipe size changes in adjacent pipes (and it reduces the computational work of the program).

In the example it made sense to put pipes 45 and 46 into the same group. The above table shows the group assignments on the right.

Step 3: Candidate pipe sizes needed to be determined for these pipes. Since these pipes are already in the ground they only would be replaced if larger pipes are needed.

Consequently, the smallest candidate size is the present size. The next two larger sizes were also included for each group. Candidate sizes are listed in the table above.

Step 4: Load and minimum pressure: in 'Loading Pattern 1' the present loads from the simulation are automatically entered.

Minimum pressure to be specified is 30 m. Because there are nodes in the system which are outside of the design area, 30 m were specified for a select group of critical nodes. The final answer will need to be verified to make sure no other nodes drop below 30 m.

The following nodes are selected based on pressures below 30 m under peak load conditions:

13 27 36 48 49 50 51

Step 5: At this point the actual optimization under the parameters as specified can take place. The result indicated that the least expensive way to reach 30 m throughout the system at peak load is to replace three relatively short pieces of pipe (total length 157m) with pipes one size larger:

Pipe #	Length	Old Diameter	New Diameter
7	32.5	250	300
63	81.5	150	200
67	43.0	150	200

Step 6: WADISO SA allows to explore alternative 'Pareto Optimum Solutions' in the vicinity of the solution listed above. Pareto optimum solutions are slightly more expensive solutions which also provide better pressure, or slightly less expensive solutions which violate the pressure requirement by a small amount. There is one possibly attractive solution which at only marginally larger cost provided a minimum pressure about 0.6 m higher than the optimum solution.

Appendix D: Recommendations Discussed with Vodokanal

1) Volumetric calibration of fire hydrant.

2) Develop a maintenance schedule for all valves, and fire hydrant connections.

3) Meter one or two apartment buildings for a 48 hour period with a cumulative flow meter. Read the meter every half hour.

4) Develop 24 hour domestic use load pattern. Compute per capita daily usage.

5) Based on the results from metering the building, estimate the domestic leakage.

6) Based on the results from metering the building, estimate the under-ground leakage.

7) Finish calibration of the Kuznetsk District model.

8) Model variations of the suggested system improvements for the Kuznetsk District. Determine the optimal improvement scheme.

9) Implement improvements developed for the Kuznetsk District

10) Collect data for computer models of other districts.

11) Setup computer models of other districts.

12) Calibrate models for other districts.

13) Analyze other district for possible low cost improvements.

Appendix E: Field Data Collected in Novokuznetsk

KUZNETSK WATER DISTRICT SYSTEM CALIBRATION
24 HOUR WORK PLAN

Hour:	Time:	Activity	
-0:10	8:50	1) Record flow rate through meter at node 13.	
		2) Record flow rate through meter at node 3555.	
		3) Record flow rate through meter at node 3556.	
		4) Record suction side pump pressure at node 2022 and 2023.	
		5) Record discharge side pump pressure at node 2020 and 2021.	
		6) Record pressure at node 60.	
		7) Record pressure between node 55 and valve to be closed.	
0:00	9:00	1) Close valve between node 55 and node 56.	
0:05	9:05	1) Record flow rate through meter at node 13.	
		2) Record flow rate through meter at node 3555.	
		3) Record flow rate through meter at node 3556.	
		4) Record suction side pump pressure at node 2022 and 2023.	
		5) Record discharge side pump pressure at node 2020 and 2021.	
		6) Record pressure at node 60.	
		7) Record pressure between node 55 and closed valve.	
1:00	10:00	1) Record pressure at nodes 77, 9, 10, 7, 4, 6, 20	
	to	2) Record pressure at nodes 28, 29, 36, 39, 38, 5, 43	
2:00	11:00	3) Record pressure at nodes 44, 48, 47, 56, 60, 59, 58	
2:30	11:30	1) Record pressure at nodes 4, 5, 6, 7, 9 ---	|
2:40	11:40	1) Open fire hydrant at node 5	|
2:45	11:45	1) Measure discharge and pressure at node 5	|--- Flow test at node 5
2:45	11:45	1) Record pressure at nodes 4, 6, 7, 9	|
2:50	11:50	1) Close fire hydrant at node 5	|
2:55	11:55	1) Record pressure at nodes 4, 5, 6, 7, 9 ---	|

3:30	12:30	1)	Record pressure at nodes 10, 29, 28, 49, 48 ---	|
3:40	12:40	1)	Open fire hydrant at node 48	|
3:45	12:45	1)	Measure discharge and pressure at node 48	|--- Flow test at node 48
3:45	12:45	1)	Record pressure at nodes 10, 29, 28, 49	|
3:50	12:50	1)	Close fire hydrant at node 48	|
3:55	12:55	1)	Record pressure at nodes 10, 29, 28, 49, 48 ---	|

5:00	14:00	1)	Record pressure at nodes 77, 9, 10, 7, 4, 6, 20
	to	2)	Record pressure at nodes 28, 29, 36, 39, 38, 5, 43
6:00	15:00	3)	Record pressure at nodes 44, 48, 47, 56, 60, 59, 58

10:00	19:00	1)	Record pressure at nodes 77, 9, 10, 7, 4, 6, 20
	to	2)	Record pressure at nodes 28, 29, 36, 39, 38, 5, 43
11:00	20:00	3)	Record pressure at nodes 44, 48, 47, 56, 60, 59, 58

23:50	8:50	1)	Record flow rate through meter at node 13.
		2)	Record flow rate through meter at node 3555.
		3)	Record flow rate through meter at node 3556.
		4)	Record suction side pump pressure at node 2022 and 2023.
		5)	Record discharge side pump pressure at node 2020 and 2021.
		6)	Record pressure at node 60.
		7)	Record pressure between node 55 and valve to be closed.

24:00	9:00	1)	Open valve between node 55 and node 56.

24:05	9:05	1)	Record flow rate through meter at node 13.
		2)	Record flow rate through meter at node 3555.
		3)	Record flow rate through meter at node 3556.
		4)	Record suction side pump pressure at node 2022 and 2023.
		5)	Record discharge side pump pressure at node 2020 and 2021.
		6)	Record pressure at node 60.
		7)	Record pressure between node 55 and closed valve.

Kuznetsk District Calibration Data
March 29, 1996

PRESSURE READINGS WHILE VALVE IN PIPE 74 CLOSED

Node	Reading 1		Reading 2		Reading 3	
	Time	Pressure (m)	Time	Pressure (m)	Time	Pressure (m)
9	10:18	62	16:16	64	19:15	62
10	10:06	44	16:00	56	19:00	60
7	10:24	58	16:22	59	19:20	56
4	10:32	43	16:25	38	19:25	35
6	10:40	40	16:35	39	19:32	34
20	10:50	48	16:40	50	19:40	45
28	10:40	42	15:50	41	19:13	40
29	10:46	40	15:55	38	19:19	35
36	10:34	27	15:44	28	19:07	33
39	11:00	26		28	19:35	27
38	10:15	30	16:10	32	19:30	31
5	10:53	37	16:03	36	19:25	30
43	10:05	25	15:36	25	19:00	30
44	10:00	18	15:42	20	19:25	17
48	10:06	28	15:36	25	19:19	25
47	10:14	12	15:48	15	19:15	14
56	10:17	7	15:53	10	19:08	12
60	10:20	36	15:57	36	19:12	37
59	10:45	34	16:14	34	19:05	30
58	11:15	32	16:20	32	18:58	28
15					19:12	61

Kuznetsk District Calibration Data

March 29, 1996: Pump Station Records

Time of day	Intake Pressure (m)			Output Pressure (m)			Output Flow (m^3/h)			Kuznetsk District		Percent above Avg
	Right	Left	Avg	Right	Left	Avg	Right	Left	Total	Pressure (m)	Flow (m^3/h)	
1.0	29	30	29.5	93	94	93.5	1100	2100	3200	78	720	
2.0	29	30	29.5	94	95	94.5	1050	2050	3100	79	700	
3.0	29	30	29.5	94	95	94.5	1050	2050	3100	79	700	
4.0	29	30	29.5	94	95	94.5	1050	2050	3100	79	700	
5.0	29	30	29.5	93	94	93.5	1100	2100	3200	79	700	
6.0	29	30	29.5	92	94	93	1100	2100	3200	78	740	
7.0	29	30	29.5	92	93	92.5	1100	2100	3200	74	780	
8.0	28	29	28.5	91	92	91.5	1150	2150	3300	70	840	
8.8	29	30	29.5	91	92	91.5	1150	2150	3300	72	820	
9.0	29	30	29.5	91	92	91.5	1150	2150	3300	71	840	
9.2	29	30	29.5	92	93	92.5	1150	2150	3300	73	800	1.02
10.0	30	31	30.5	92	94	93	1150	2150	3300	74	800	1.02
11.0	29	30	29.5	91	93	92	1150	2150	3300	72	840	1.07
12.0	29	30	29.5	92	93	92.5	1150	2150	3300	73	820	1.04
13.0	29	30	29.5	91	93	92	1150	2150	3300	73	800	1.02
14.0	29	30	29.5	92	93	92.5	1150	2150	3300	73	820	1.04
15.0	29	30	29.5	91	93	92	1100	2150	3250	73	820	1.04
16.0	29	30	29.5	92	94	93	1100	2100	3200	73	820	1.04
17.0	29	30	29.5	92	93	92.5	1100	2150	3250	74	800	1.02
18.0	30	31	30.5	92	94	93	1050	2200	3250	74	800	1.02
19.0	30	31	30.5	92	94	93	1050	2200	3250	75	780	0.99
20.0	29	30	29.5	91	92	91.5	1150	2150	3300	71	830	1.06
21.0	29	30	29.5	91	92	91.5	1150	2150	3300	70	830	1.06
22.0	30	31	30.5	91	92	91.5	1150	2150	3300	73	800	1.02
23.0	31	32	31.5	92	94	93	1150	2150	3300	75	770	0.98
24.0	31	32	31.5	92	94	93	1150	2150	3300	76	760	0.97
1.0	31	32	31.5	94	96	95	1100	2100	3200	79	730	0.93
2.0	31	32	31.5	94	96	95	1100	2150	3250	79	730	0.93
3.0	31	32	31.5	94	96	95	1100	2100	3200	79	730	0.93
4.0	31	32	31.5	93	95	94	1100	2100	3200	79	720	0.92
5.0	31	32	31.5	93	95	94	1150	2200	3350	79	720	0.92
6.0	31	32	31.5	93	95	94	1150	2200	3350	79	720	0.92
7.0	31	32	31.5	93	95	94	1150	2150	3300	77	740	0.94
8.0	30	31	30.5	92	94	93	1150	2200	3350	70	860	1.1
9.0	29	30	29.5	91	93	92	1150	2200	3350	71	840	
9.3	29	30	29.5	91	93	92	1150	2150	3300	70	840	
9.5	28	29	28.5	91	93	92	1150	2150	3300	71	830	
10.0	28	29	28.5	91	92	91.5	1150	2150	3300	70	830	

Kuznetsk District Calibration Data
March 29, 1996

FLOW INTO DISTRICT WHILE VALVE IN PIPE 74 CLOSED

Reading 1		Reading 2		Reading 3	
Time	Flow (m^3/h)	Time	Flow (m^3/h)	Time	Flow (m^3/h)
10:00	800	15:00	820	19:00	780
11:00	840	16:00	820	20:00	830
		17:00	800		
Avg =	820	Avg =	813	Avg =	805

Average flow rate over all three time periods is 813 m^3 /h

Kuznetsk District Calibration Data

March 29, 1996

Time: 12:00 noon to 12:30 pm

System description during data collection:

Flow test at node 5.

Pipe 401 (Valve near node 56 and 60) was closed. The only source of water to the district is through the pump station. Pressure measurements were taken at various points in the system.

Before (m)	During (m)	After (m)	Location Description
35	7	31	Node 5
35	21	37	Node 6
58	53	59	Node 7
64	63	66	Node 9
42	36	36	Node 4

Pitot tube reading during flow test = 3.5 psi to 4.0 psi estimated at 3.8 psi

Computed discharge = 14 l/s

Estimated discharge range = 13.5 to 14.5 l/s

Kuznetsk District Calibration Data

March 29, 1996

Time: 1 pm to 2 pm

System description during data collection:

Flow test at node 48.

Pipe 401 (Valve near node 56 and 60) was closed. The only source of water to the district is through the pump station. Pressure measurements were taken at various points in the system.

Before (m)	During (m)	After (m)	Location Description
24	7	22	Node 48
22	12	24	Node 49
60	57	57	Node 10
46	40	47	Node 28
42	40	41	Node 29

Pitot tube reading during flow test = 4 psi to 5 psi estimated at 4.5 psi

Computed discharge = 15.5 l/s

Estimated discharge range = 14.5 to 16.3 l/s

Kuznetsk District Calibration Data

April 1, 1996

Time: 3:30 pm. To 5:00 pm

System description during data collection:

Pipe 401 (Valve near node 56 and 60) was closed. The only source of water to the district is through the pump station. Pressure measurements were taken at various points in the system.

Pressure at node 550 before closure was 35m and after closure was 13m

Pressure (m)	EGL (m)	Description of Location
25	267	Node 49
27	266	Node 48
43	278 *	Node 28 Pressure not measured right at 28. Add 4 meters to elev. at 28 to correct for difference in ground elev.
39	263 *	Node 27 measured on pipe
29	267 *	Middle of pipe 46
41	272 *	Middle of pipe 45

* Indicates estimated pipe elevation. Actual elevation was not available. Pipes are assumed to be 2.5 m below ground and the slope between adjacent nodes is assumed to be constant.

All Pressures include 3 meters added to account for the distance from the pressure gauge on the hydrant to the water pipe, except node 27.

Kuznetsk District Calibration Data

April 3, 1996

Time: 3:30 pm. To 5:00 pm

System description during data collection:

Pipe 401 (Valve near node 56 and 60) was closed. The only source of water to the district is through the pump station. Pressure measurements were taken at various points in the system.

Pressure at node 550 before closure was 34m and after closure was 10m

Pressure (m)	EGL (m)	Description of Location
51	271	Node 20
39	263	Node 27
29	258	Node 36
18	251 *	Node 44
10	250	Node 550
23	247 *	Between Node 42 & 43 about 1/3 of the way from 42 to 43.
23	245 *	Midway between Node 40 and 42
25	247 *	Node 40
53	270	Node 21

* Indicates estimated pipe elevation. Actual elevation was not available. Pipes are assumed to be 2.5 m below ground and the slope between adjacent nodes is assumed to be constant.

All Pressures include 3 meters added to account for the distance from the pressure gauge on the hydrant to the water pipe.

Pressure gauges were marked in two meter incraments. Pressures are estimated to the closest meter.

Pressure gauges were marked in two meter incraments. Pressures are estimated to the closest meter.

Kuznetsk District Calibration Data

April 4, 1996

Time: 3:30 pm to 4:00 pm

System description during data collection:

Flow test at middle of pipe 45, new node designation 281.

Pipe 401 (Valve near node 56 and 60) was open. Pressure measurements were taken at various points in the system.

Before (m)	During (m)	After (m)	Location Description
41	8		At Flow test location, node 281
45	39	44	Node 28
33	32	35	Node 29
60	58	59	Node 10
53	48	52	Node 20

Pitot tube reading during flow test = 8 psi to 10 psi estimated at 9 psi

Computed discharge = 22 l/s

Estimated discharge range = 20 to 23 l/s

Note: Hydrant failed during flow test. After reading was not possible.

Kuznetsk District Calibration Data

April 4, 1996

Time: 4:15 pm. To 5:00 pm

System description during data collection:

Pressure measurements were taken at various points in the system.

Pressure (m)	EGL (m)	Description of Location
30	265	Node 35
35	255	Node 38
43	263	Node 37
44	264	Node 151

* Indicates estimated pipe elevation. Actual elevation was not available. Pipes are assumed to be 2.5 m below ground and the slope between adjacent nodes is assumed to be constant.

All Pressures include 3 meters added to account for the distance from the pressure gauge on the hydrant to the water pipe.

Pressure gauges were marked in two meter incraments. Pressures are estimated to the closest meter.

Partially closed valve probable between node 35 and 43 in pipe 49.