ADVANCING THE BLUE REVOLUTION INITIATIVE

ASSESSING WATER RESOURCES SUSTAINABILITY IN THE HADHRAMOUT IN YEMEN

Advancing the Blue Revolution Initiative
U.S. Agency for International Development
November 2010

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DAI (PRIME CONTRACTOR)

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Aiken Global Environmental Services, LLG
AISDevelopment, LLC
CDM International, Inc.
CDR Associates
Duke University
ECO Consult (Jordan)
Emerging Markets Group
Environmental Quality International (Egypt)
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MASCA (Morocco)
Oregon State University
Overseas for Sustainable Development (Jordan)
Resource Mobilization Advisors
Water Environment Federation (WEF)
Yilma Global Consult (Ethiopia)

COVER PHOTOS

Damage caused by 2008 flood in the Hadhramout	Discussion about flood effect on water table
ABRI team measuring well discharge	ABRI team measuring water level

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ACRONYMS

ABRI	Advancing the Blue Revolution Initiative
BW	Wadi Buwaish
CAMA	Civil Aviation and Meteorological Authority
DAI	Development Alternatives, Inc.
EC	Electrical Conductivity
FW	Wadi Fuwwah
GIS	Geospatial Information System
GOY	Government of Yemen
GPS	Global Positioning System
GPCS	Groundwater and Soil Conservation Project
HDL	Highest Desirable Level
IWRM	Integrated Water Resource Management
LWSSC	Local Water Supply and Sanitation Corporation
MAR	Mean Annual Rainfall
MAI	Ministry of Agriculture and Irrigation
MLA	Ministry of Local Administration
MODFLOW	Groundwater Modeling Software of the US Geological Survey
MPL	Maximum Permissible Level
MSA	Military Survey Authority
MWE	Ministry of Water and the Environment
MWSA	Ministry of Work and Social Affairs
NWRA	National Water Resource Authority
PET	Potential Evapotranspiration
pH	Percent Hydrogen
RFP	Request for Proposal
CD-ROM	Compact Disc – Random Operating Memory
SAR	Sodium Absorption Ratio
TDS	Total Dissolved Solids
TRMM	Tropical Rainfall Measuring Mission
USAID	United States Agency for International Development
USD	United States Dollars
USG	United States Government
USGS	United States Geological Survey
WHO	World Health Organization
WMO	World Meteorological Organization

EXECUTIVE SUMMARY

Yemen is located in an arid region with no permanent rivers, although the country has extensively developed groundwater resources. In contrast to the rest of the central Middle East, the World Bank estimates that 30 percent of Yemen‘s population lacks access to clean water and 70 percent live without access to sanitation services. Demand for surface water in Yemen exceeds its availability, with deficits often reduced by pumping nonrenewable storage from deep aquifers. This, in turn, has resulted in major groundwater depletion in a number of regions of the country. For example, the decline in water level in the Sana’a Basin has been found to be between two to six meters per year.

The severity of this water crisis has spurred the Yemeni government to invest in water resource management. With a primary focus on groundwater management, the discussions between the Advancing the Blue Revolution Initiative (ABRI) and the National Water Resource Authority (NWRA) prioritized the Hadhramout Basin, with particular attention given to sub-basins Wadi Buwaish and Wadi Fuwwah.

Recent assessments of the two sub-basins identify two substantial information gaps that must be bridged before a regional water resources management plan can be adequately prepared. The main information gaps are not related to the quantity of information, but to the quality and distribution of information. With regard to the two sub-basins, these gaps were mainly a result of complete or partial absence of hydrological and hydrogeological data and information. Based on these identified gaps, the ABRI team developed four tasks to collect the required information to prepare a water resources management plan in Hadhramout Basin: consolidate information in a database, catalogue wells and springs, establish a new well monitoring network, and conduct groundwater modeling.

Following its research, the ABRI team recommended the following measures be taken: relocate well fields to no less than four kilometers from the sea with the distance between any two no less than 250 meters; change pumping patterns to no greater than 16,500 cubic meters per day in Wadi Buwaish and 1,500 cubic meters per day in Wadi Fuwwah; never drill bore wells in areas where the water level is less than ten meters above sea level; drill observation wells in those areas where the water head is less than seven meters above sea level; protect the water supply from sewage caused by sewage and fertilizers; and increase groundwater recharge by constructing downstream diversion barriers and forbidding upstream dams.

1 BACKGROUND

1.1 Introduction

Many changes have occurred during recent years in Yemen with respect to water resources development and use. Increased water use in agriculture and in industry has raised the economic output significantly. It is clear that the newly established public water supply systems are a major contributor to the general well-being of the population. The benefits obtained thus far are motivating forces behind the further expansion of water resources development.

But after the initial enthusiasm fed by the short-term benefits of the new water development activities, many problems threaten successful and sustainable exploitation of the water resources. Recognizing these problems, making a correct diagnosis, and implementing appropriate solutions are indispensable steps to ensure sustainability of precious water resources. As Yemen is and will remain an arid country, the limited availability of water and combines with its rather high population density to create water scarcity.

The most serious and obvious problem is the rapid depletion of groundwater resources. Many studies and inventories carried out in recent years have revealed that almost all important groundwater systems in Yemen are being overexploited at alarming rates. Continuing groundwater monitoring confirms predictions made during many assessment studies. To control this problem the government promulgated the 2002 Water Law which provides the legal basis for controlling groundwater abstraction in Yemen. It includes measures for licensing and registration of wells and drilling rigs, and control regimes in water stressed catchments. The law also support decentralization, by encouraging the formation of basin committees and requires working closely with local councils in implementation of water management measures.

The Government of Yemen, supported by many donors, currently is undertaking a USD 380 million Water Sector Support Program. Some of the funds have been directed to support the National Water Resources Authority (NWRA) in basin planning in up to five critical basins.

ABRI and Yemeni government officials discussed several possible activities for water management assistance. This was undertaken through a series of visits started in early December 2007 and through subsequent research. NWRA primary focus was directed to ground and surface water assessments of Hadhramout basin with particular attention to Wadi Buwaish and Wadi Fuwwah. Both are located at Hadhramout Governorate at the south of Yemen close to the Arabian Sea. A review of the available studies made by NWRA about the two sub basins suggested that substantial information gaps remain which must be bridged in order to prepare a regional water resources management plan. The main information gaps were not related to the quantity of information, but to the quality and distribution of information in space and time. With regard to the two basins, these gaps mainly referred to complete or partial

absence of hydrological and hydrogeological data and information. These gaps mainly referred to complete or partial absence of data on:

- Total area of irrigated land;
- Spatial distribution of rainfall and other meteorological data;
- Reliable and continuous data on surface water;
- Data on chemical composition of rain and surface water;
- Type of aquifer and variation in thickness;
- Hydraulic parameters of aquifers;
- A lack of continuous level measurements in wells, ground-control;
- Well and spring inventory, monitoring program;
- Reliable recharge estimates;
- Reliable figures on abstractions/discharge;
- Historical trend about abstractions;
- Interference of groundwater aquifer layers in horizontal and vertical directions;
- Climate and annual rainfall; and
- Surface waters, catchments area, characteristics and principal drainage basin.

Based on the above gaps the following studies are needed to collect the information required to support the preparation of a water resources management plan in Wadi Buwaish and Wadi Fuwwah sub-basins:

- Review and consolidation of information and database;
- Well inventory;
- Select and establish a new wells monitoring network; and
- Groundwater model.

1.2 Well Monitoring Network at Wadi Buwaish and Wadi Fuwwah

Reliable data are an essential element for evaluation of water resources and preparation of a water management plan. Over the years a number of studies related to the geology, hydrology and hydrogeology of Wadi Buwaish and Wadi Fuwwah sub basins have been carried out. However, the data on water resources are incomplete and are scattered among several institutions. Different procedures were used during the data collection and different units were used for measured or interpreted values. The location of the sampling points and topographical parameters are often poorly documented. A proper storage of data and quality control is required in order to evaluate the suitability of historical data for the assessment of trends in water availability and to avoid duplication.

<u>Objectives</u>

- Gather all relevant information on water resources in the area;
- Facilitate a proper storage and manipulation of hydrometric, geological and hydrogeological data and water use data;
- Indicate data gaps; and
- Screen and document the data.

Scope

- Collect all relevant water resources information available at various offices in Sana'a and Abyan governorates. Special attention should be given to availability of hydrological and hydrogeological data;
- Review tabulated data, relevant for water resources management, which were collected during previous studies and during monitoring activities;
- Check and standardize the data according to the NWRA database system;
- Develop or adapt a database;
- Input available data;
- Carry out the quality control of data and dispose all unreliable data; and
- Describe the results of the study.

Deliverables

- A database system compatible with the main NWRA database system. The same system will be used for storage and management of additional information collected during studies described in this request for proposal (RFP); and

- All historical data screened, documented and available within the database.

Output Format

- Data files consistent with NWRA database system;
- Tables and figures with checked information; and
- Report describing the results of the study.

1.3 Review and Design of a Monitoring Network

The collection of hydrologic, hydrometeorological and hydrogeological data is the basis of any water assessment program. Without timely and correct information it is not possible to assess the available resources in terms of quantity and quality. Field data should be processed and interpreted in the way that suits the requirements for the assessment of the quantity and quality of the water resources. Properly interpreted data are necessary to help establish a general water balance for the area and subsequently to contribute to the recharge estimates, required for the assessment of the groundwater resources. Trends in groundwater level changes can be observed and related to both natural and artificial events.

Currently, there could be only one or two meteorological stations under operation. Next to these daily measurements, total rainfall on monthly basis is collected from numbers of existing stations. The Water Monitoring Unit monitored some wells in the areas. Surface and groundwater levels and conductivity were recorded monthly. Due to various problems, the monitoring program is irregularly and only partly executed.

Objectives

- Review the existing network and the historical data and to operate the existing network for meteorological parameters, surface water and groundwater; and
- Design a new monitoring network.

Scope

- Assess suitability of current existing of relevant data, taking into account the logistics of operations;
- Select new sites and assess the required equipment for network enhancement and make arrangements for installation;
- Develop standard procedures for the monitoring and output data format consistent with NWRA database system;
- Process the collected data and asses the quality of the information;
- Assess the flow volumes in the gauged catchments and extrapolate the results to ungauged catchments;
- Establish a general water balance for each of the wadis and main watershed;
- Establish statistically significant trends in the groundwater levels and groundwater quality, using also historical data; and
- Describe the results of the study.

Deliverables

- An operational network allowing for the collection of hydrological, climatological, surface and groundwater data according to well-established standards;
- Assess quantity and quality of surface and groundwater resources in project area; and
- Evaluation of significant trends in the groundwater levels and groundwater quality.

Output Format:

- Schedule for execution of hydrological fieldwork;
- Data files consistent with NWRA database system;
- Surface water availability (quantity and quality) map scale 1:100,000 or larger as may be available;
- Well hydrographs;
- Graphs showing changes in groundwater quality; and
- Report describing the results of the study.

1.4 Well and Spring Inventory

Wells are the main sources of quantitative information on aquifer type, aquifer productivity, groundwater levels, abstraction, and groundwater chemistry.

Objectives

- Obtain information on the groundwater occurrence, quality and use;
- Obtain information about location of springs together with quantity and quality of water available from these springs; and
- Assess spatial variation in groundwater availability.

Scope

- Review previous well inventories;
- Carry out well inventory according to the NWRA guidelines;
- Obtain a groundwater level measurements from the surveyed wells, whenever possible, as well as measurements of the conductivity, pH, and temperature;
- Store data in a database system. The current well inventory should be carried out in coordination with the previous activity in order to derive benefits of existing possible suitable monitoring wells;
- Process collected data;
- Visualize and interpret the results of inventory on maps and graphs; and
- Describe and evaluate the results.

Deliverables

- Geographical position of all wells and springs in the area defined in Figure 1;
- Process and checked data on all wells according to the NWRA guidelines; and
- A piezometric map.

Output Format

- Filled and checked well inventory forms, according to the NWRA standards;
- Filled and checked spring inventory forms, according to NWRA standards;
- Data files according to the format;
- Groundwater quality map, based on electric conductivity, scale 1:100,000 or larger as may be available;
- Groundwater abstraction map, scale 1:100,000 or larger as may be available;
- Graphs and figures showing the statistics and trends of all relevant parameters, interpreted from collected data; and
- Report describing the results of the inventory.

1.5 Groundwater Modeling

Groundwater modeling is a tool, which aims to predict movement of groundwater and dissolved compounds under natural and artificial conditions. Outcomes of the model can be used to estimate future changes in groundwater, salinity or pollution and eventually to examine the broader implications of various groundwater management strategies. As for any other mathematical model, the output of a groundwater model is highly sensitive to the uncertainties of input parameters.

Objectives

- Using results of hydro-geological investigations and assessments, refined aquifer characteristic values and abstraction estimates with a view to have a better understanding of the groundwater flow regime in the area;

- Improve estimates of recharge, discharge and abstractions; and

- Forecast the changes in water availability and subsequent simulation of current and potential future aquifer use scenarios, based on the results of hydro-geological investigations and assessment, refined aquifer characteristic values and abstraction estimates with a view to predict the behaviour of the aquifers when subjected to various stresses.

Scope

- Update the estimates on annual recharge and discharge, using information from 4 above or use an alternative approach for the estimates;

- Providing details of the models developed (MODFLOW code) are available review the adopted numerical algorithms;

- Make predictions for groundwater table changes and simulate the variations of aquifer water levels in future, under the present abstraction rates as well as simulated abstraction rates. By keeping fixed the water level values, estimate the maximum abstraction rate to avoid groundwater levels depletion;

- Assess the general flow direction of groundwater;

- Examine the possibility of interference of groundwater aquifers layers in horizontal and vertical directions; and

- Describe the results of the study.

Deliverables

- Improved estimates on recharge and discharge; and

- Updated groundwater flow models.

Output Format

- Description of methods used for assessing recharge and discharge;

- Model input and output files on CD-ROM; and

- Detailed documentation of modeling procedures, assumptions and results.

1.6 Yemeni Government Participation in Activity Selection and Design

Various government water management entities are involved in surface and groundwater issues in Yemen, especially in rural areas. These entities include: the Ministry of Irrigation and Agriculture (MIA), the Ministry of Water and Environment (MWE), the National Water Resources Authority (NWRA), the Ministry of Local Administration (MLA), Ministry of Work and Social Affairs (MWSA), governors and governorates, district government, and local councils. During the ABRI team's visit to the key ministries and entities, it was clear that NWRA represents the primary body that conducts water studies and planning.

NWRA was founded in 1995 by presidential decree Number 154 to serve as the primary coordinating, policy making, licensing, monitoring, regulatory and public education body for water issues. NWRA is also the primary agency to conduct water studies and planning as is expected to harmonize and coordinate activities in the water sector. NWRA supervises all donor activities relating to the development the Yemeni water sector. On different occasions the ABRI team interviewed Mr. Salem Bashuaib, NWRA chairman, and his technical staff to discuss possible ways of contributing to develop water sector in Yemen. The ABRI team and the authority agreed on Wadi Buwaish and Wadi Fuwwah sub basins for implementing the ABRI activity. Working for years with other donors on similar activities, NWRA developed good technical experience in basin assessments and IWRM plans. Under NWRA supervision, the ABRI team designed this activity and supervised its implementation.

2 MONITORING NETWORK AT WADI BUWAISH AND WADI FUWWAH

2.1 Introduction

The collection of hydrological, hydrometeorological, and hydrogeological data is the basis of any water assessment program. Without timely and correct information it would be very difficult to assess any available water resources in terms of quantity and quality. Field data should be processed and interpreted in a way that suits the requirements for the assessment of the quantity and quality of these resources. Properly interpreted data are necessary to establish a general water balance for the investigated area and subsequently to contribute to the recharge estimates, required for the assessment of the groundwater resources. Trends in groundwater level changes can be observed and related to both natural and artificial events.

With reference to this study, both Wadis Buwaish and Fuwwah are simple in terms of geology and hydrogeology. The reported fluctuation in the level of water table is highly dependent on the annaul change of rainfall in the area. This usually affects the quantity and the quality of the groundwater resource. In the occurrence of fluctuation of groundwater under semi-arid regions, specific measurements are to be taken on parallel with the monitoring of various water quality parameters. This is essential if any suitable water management plan is required to be established for the investigated area.

The objectives of well monitoring were to:

- Evaluate the existing network, review all historical data and possibly to re-operate parts of the network for measuring meteorological parameters, surface water, and groundwater; and

- Design a new monitoring network.

2.2 Existing Well Monitoring Network

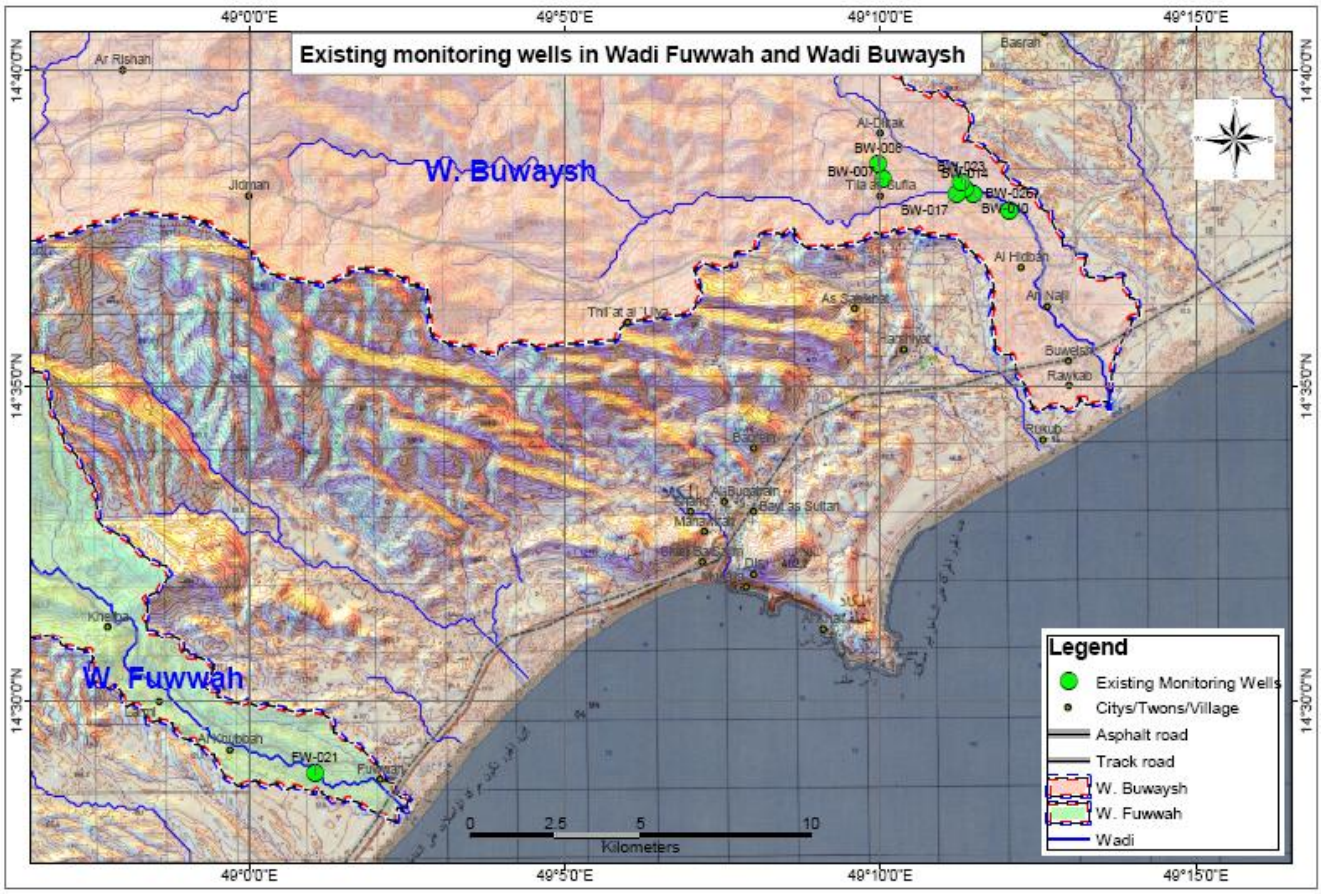
There are no existing well monitoring networks in Wadis Buwaish and Fuwwah. The visit of ABRI technical team revealed that the Hadhramout branch of NWRA possesses no wells for monitoring purposes. The team’s only findings were some water level measurement undertaken by the Local Water Supply and Sanitation Corporation (LWSSC) at Al-Mukalla. Seven water supply LWSSC's wells were being monitored by LWSSC within the two wadis. Data collection started in late 2006 and the gathered data were ground water level, percent hydrogen (pH), and electrical conductivity (EC). Out of seven wells, six are located within the Wadi Buwaish and seventh is in Wadi Fuwwah.

Having in mind that the area of Wadi Buwaish is 650 square kilometers and that of Wadi Fuwwah is 450 square kilometers, it becomes clear that the above number of wells is not enough. The locations of those wells are not along wadi streams and hence their readings are not of a significant value. Also, it appears that dynamic water level were measured where the static water level were required for monitoring purposes. The locations of presently

monitored wells within the two wadis are given in Figure 1. Lately, it is reported that LWSSC has stopped the monitoring.

Figure 1 shows the locations of the seven wells in the two wadis. It can also be noticed that in Wadi Buwaish all observatory wells are located very close to each other and only one well is located in Wadi Fuwwah.

Figure 1: Location of Existing Monitoring Well



2.3 Selection of Monitoring Wells

Many bore holes have been observed in the region. They were used for monitoring the fluctuation in the level of the ground water and its quality. Despite the fact that all types of wells within the two wadis have been used for monitoring additional wells specially drilled for monitoring are definitely required.

In general, the criteria for establishing new monitoring wells shall comply with the following conditions:

- Well shall be constructed with minimum disturbance of geological formation;
- Well shall be located at the places which are compatible with general anticipated geology of the region;
- Adequately seal the well with materials that will not interfere with the collection of representative water quality samples; and
- Sufficiently develop the wells to remove any additives associated with drilling and provide unobstructed flow through the well.

In addition to appropriate construction details, the monitoring well must be designed in concert with the overall goals of the monitoring program. Key factors that must be considered include:

- Intended purpose of the wells;
- Placement of the well to achieve accurate water levels and/or representative water quality samples;
- Adequate well diameter to accommodate appropriate tools for well development, aquifer testing equipments and water quality sampling device; and
- Surface protection to assure no alteration of the structure or impairment of the data collected from the well.

For the two wadis, all available wells belong to the farmers and to LWSSC. Consequently, there are limitations on the above established criteria of selection of monitoring since NWRA have no control on these wells. In the two wadis, groundwater is abstracted from the alluvial aquifer. Care has been taken in selecting of monitoring wells in order to obtain monitoring data for these aquifers.

During the well inventory survey, the ABRI team noticed that the water level in the wells is mostly dropped during dry season. The reason is attributed to the direct relation with the seasonal rainfall recharge. To avoid the tendency of the shallow wells becoming too dry during any dry year, only bore holes and deep dug wells were selected as monitoring wells from the existing concentrate. Care has been taken in selection of the monitoring wells from “intermittent”, “temporarily use,” and “not in use” wells so that influence of ground water table, as in case of production wells, can be minimized.

Other than the seven water supply wells which were being monitored by LWSSC within the two wadis, there are 61 other wells in the area. These are either intermittent temporarily used or not in use. Currently, only ten are partially utilized while the other 51 are not in use for many different reasons. Only 29 of these are dug wells, twelve in Wadi Fuwwah and seventeen in Wadi Buwaish while the rest are bore holes. The majority of the dug wells are private property. As for the bore holes, they are distributed as seven in Wadi Fuwwah and fifteen in Wadi Buwaish. Twelve are private property and ten belong to LWSSC, they have all been abandoned. In general out of the 51 not in use wells, ten were selected for future monitoring. Table 1 shows the distribution and numbers of dug and bore holes wells in both wadis and Table 2 shows the locations of these wells.

Table 1: Utilization of Dug and Borehole Wells in Wadi Fuwwah and Wadi Buwaish

Number of Wells	Intermittent	Temporarily not in use	Not In Use	Total
Wadi Fuwwah	0	5	12	**17**
Wadi Buwaish	0	2	17	**19**
Sub-Total	0	7	29	**36**

Table 2: Potential Future Monitoring Wells in Wadi Fuwwah and Wadi Buwaish

Number of Dug Wells at	Not In Use
Wadi Fuwwah	12
Wadi Buwaish	17
Sub-Total	29

2.4 Density of Monitoring Wells

With the ten wells that were used for monitoring in the two wadis, the density appeared to be one monitoring well for every 110 square kilometers. In general, the density of monitoring networks generally varies from country to country depending on the purpose for which the observation wells are being set. The coverage of observation wells may range from one per 250 square kilometers to more than five per square kilometer for special network. Normally, the required density of wells in confined aquifers is much less than those in unconfined aquifers which are more open to meteorological and human influences. Taking in consideration the conditions of the two wadis where agriculture and domestic water wells are concentrated in the main wadi stream and where the wadi width which accommodates all agricultural activities is ranging between 30 meters to about 950 meters, the impulse is to reduce the density of the monitoring wells per square kilometer.

The concentration of the wells within small spots in the wadis is also another reason to reduce the density of the monitoring wells per square kilometer. Consequently, it looks that the ten monitoring wells within the two wadis is reasonable number. One limitation though is that the upper part of Wadi Buwaish is not covered partly due to the shortage of "not in use" wells and/or due to unwillingness of the local farmers to volunteer their wells to be part of the monitoring network. NWRA may try to encourage them by offering some incentives to allow the use their wells. Of course, the other option is to dig new monitoring wells in the area which is more expensive option.

2.5 Monitoring and Measuring Devices

A flow meter device has been used by LWSSC for measuring groundwater abstraction rates while manual readings were adopted for groundwater level measurements. Within the last three years, the Ground Water and Soil Conservation Project (GSCP) has installed groundwater monitoring equipment in many wells in Yemen using the automatic water level and water quality recorders under the supervision on NWRA. These equipments were placed on abandoned "not in use" wells changing their function to be as real monitoring wells: wells which are used exclusively for monitoring and are hence not subjected to water pumping. The selection of the monitoring wells is hampered by the fact that existing abandoned wells are also requires owners’ permission. No dedicated monitoring wells are drilled under the GSCP.

Taking in consideration the type of wells selected for monitoring, NWRA guidelines for the recommended measuring devices and data required to be collected, it found that the automatic water level and water quality recorders can be successfully used if the selected wells are “not in use.” It also found that the tape with sensor device has been already

approved and used by NWRA for measuring the water level for regular monitoring of the water level, temperature and the EC. These wells are not monitoring wells, but wells that are monitored. Monitoring of the water level in these wells is not representative for the monitoring objectives of detecting water level changes due to changes in water savings under GSCP.

It also has been found that monitoring of the groundwater quality using the mentioned recommended automatic water level and water quality recorders cannot be used in most of the wells in the two wadis. The reason is that these wells are not designed as monitoring wells. The water quality under the bore wells will be affected by the rust of the casing if iron and steel pipes are used as a casing in the well. Also, the water quality under the dug wells will be affected by many dead animals, dead animals, and human activities. To overcome the problem of using wells not specifically designed for water quality motoring, ten water samples representing the wells of the two wadis were analyzed to identify the physical and chemical properties. The results of the laboratory testing of these ten samples can be taken as base line scenario of the ground water condition in the two wadis. The water quality monitoring was determined by NWRA Hadhramout Branch and Mukalla LWSSC shall continue testing of water samples from these ten wells. NWRA Hadhramout Branch shall keep pursuing NWRA or any future project to procure the remaining required number of automatic groundwater monitoring devices. These monitoring devices are to be installed in selected wells in discussion with the well owners.

2.6 Frequency of Observation

As a general rule, the monitoring measurements of groundwater quality and manual groundwater level have to be adjusted to the dynamics of the ground water system behavior as well as to the monitoring objectives and required accuracy.

The frequency of observation will have to be adjusted to the highest level of relevant fluctuations. In natural conditions, relevant fluctuations are often the seasonal fluctuations. If the frequency of observation is high enough to assess these seasonal fluctuations, then they are usually sufficient for variations with a longer periods. Variations with a longer period may be variations caused by dry and wet years or long term trends. If seasonal fluctuations are of minor importance, the frequency of observations can be usually limited to one or two measurements per year.

The best strategy of observation is to start with a frequency high enough to observe seasonal fluctuations, if these are expected to relevant. This period of frequent observation should preferably last for some years. After quantifying the magnitude of seasonal fluctuation, the frequency of monitoring can be adjusted to the minimum accuracy requirements, for instance aimed at identifying long term trends. LWSSC may continue their monitoring activity according to the purpose and frequency needed.

For the automatic water level and water quality recorders, the frequency of data collection will have to be adjusted according to battery life, resolution, and number of records per time units.

2.7 Data Analysis and Interpretation

Table 3 shows that out of available data from LWSSC wells, seven wells are exploiting water from alluvial aquifer. The alluvial aquifer is the main aquifer from which water is presently being abstracted in the two wadis. The observed data of seasonal variation of water levels is given in Table 3.

Table 3: Variation of Water Levels in LWSSC Monitoring Wells at Wadi Buwaish

Total Depth	Dynamic Water Level			Dynamic Water Level			Dynamic Water Level			Dynamic Water Level		Dynamic Water Level		
	2007	2008	2009	2007	2008	2009	2007	2008	2009	2008	2009	2007	2008	2009
Jan		50.43	46.32		72.53	64.27		27.74	7.3	29.32	8.5		20.25	5.7
Feb		48.24	46.57		71.19	63.8		27.91	7.72	28.67	8.78		20.18	6.24
Mar		48.28	46.6		71.19	63.79		27.23	9.2	29.7	10.84		21.41	6.39
Apr	53	49.13	47.07	72.85	70.61	64.45	23.96	28.1	10.35	29.6	11.9	17.56	21.85	6.9
May	53.37	48.23	46.12	72.64	71.23	63.63	24.2	27.3	11.08	29.4	12.93	17.51	21.95	7.34
Jun	50.28	48.15	45.95	71.82	71.58	63.8	24.25	30.07		26.23		17.6	20	
Jul	50.45	48.25		73.7	70.15		24.15	27.23		29.7		17.63	20.3	
Aug	50.28	49		73.8	70.45		24.17	28.35		29		17.59	20.12	
Sep	48.95	48.5		72.36	69.5		26.2	28.85		28.9		19.28	21.42	
Oct	50.45	48.17		72.2	68.17		26.58					19.5		
Nov		48.22			67.55		27.14	8.6		10.2		19.79	6.25	
Dec		48.2			65.9			9.9		11.65			6.4	

The graphical representation of seasonal variation of water levels as obtained from the monitoring data is given from Figures 2 through 8.

Figure 2

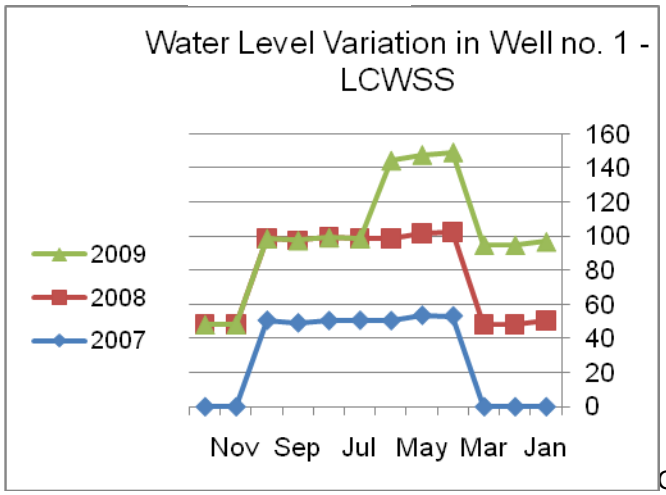


Figure 3

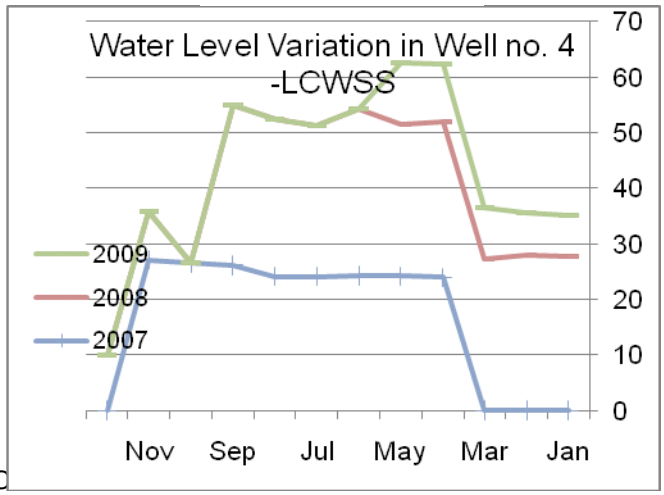


Figure 4

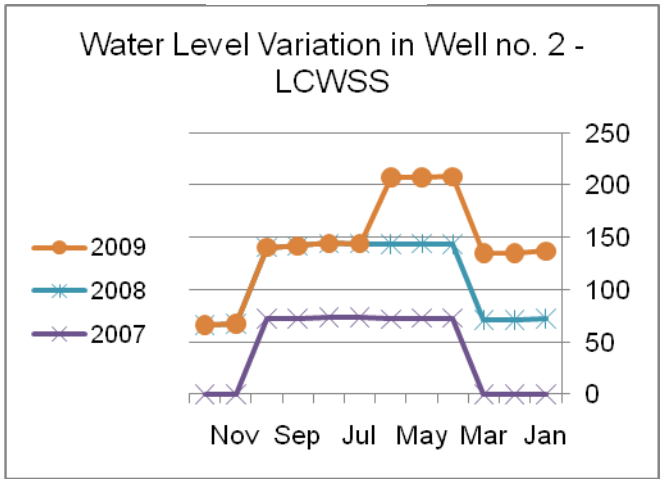


Figure 5

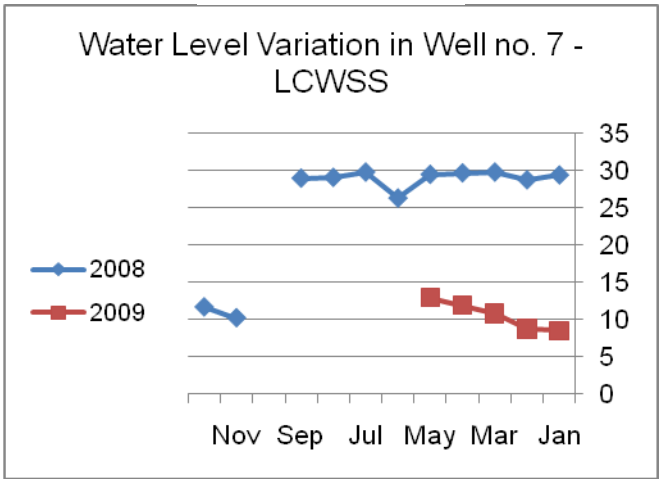


Figure 6

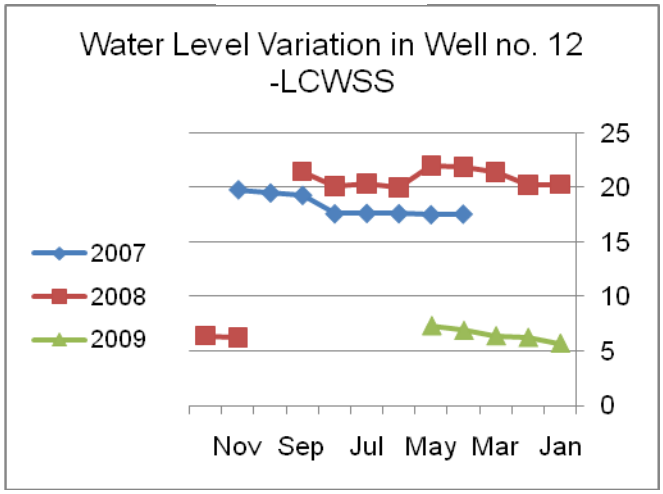


Figure 7

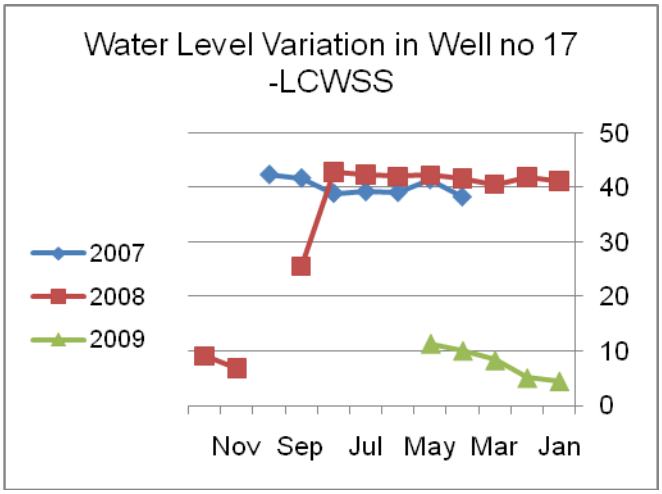
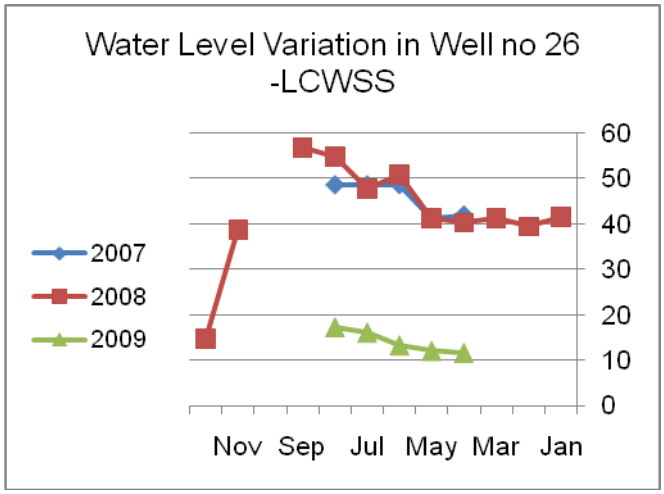


Figure 8



3 REVIEW AND DESIGN OF WATER MONITORING NETWORK

3.1 Introduction

For any water resources management study, all hydro-meteorological data related to the water cycle can be either collected by monitoring or be derived by calculation. In addition to hydro-geological and groundwater data, a surface water and hydro-climatological elements data are also requisite for such study. The aim of using any monitoring network is to collect the following hydro-meteorological information:

- Precipitation: daily, monthly and annual data;
- Climatological data including: maximum and minimum temperature, wind speed and direction, sun shine hours, humidity, soil temperature; and
- Stream flow and spring flow data including runoff and baseflow.

3.2 Existing Network and Data

There is no rainfall station in both wadis, only one weather station is located in the surroundings at Al-Rayan airport. The nearest stations are three located at Wadi Hajr. The one which is out of order now is a weather station located at Sidarah while the other two are rainfall standard gauges located at Mayfa'a Hajr and Al-Heylah. They were installed by Groundwater Soil Conservation Project at 2005. Table 4 shows the location and the organization responsible for maintenance of station in all Hadhramout governorates.

The available data of each station is shown in tables in Annex One. These tables show also that the data collection from the surroundings stations was discontinued from the year 1942 to 2000 at Al-Rayan Station. None of rain gauge stations or the weather station has registered a sufficiently long term data.

From the above, the following features emerge in the existing network system:

- The study area seriously lacks the historic rainfall data; and
- Only one meteorological station maintained by CAMA is having sufficiently long term data.

The ABRI team visit to the site revealed that although the project area has experienced several significant floods in the past but unfortunately no flood measurement has been taken. The reason attributed to the lack of stream flow gauging station. The team also failed to track any records from the two wadi gauging stations which were installed in 1982.

The locations of all previously existing meteorological stations are shown in Figure 9. Figure 10 shows the locations of presently active meteorological stations in and around the project area.

Figure 9: Locations of all Historic Meteorological Stations

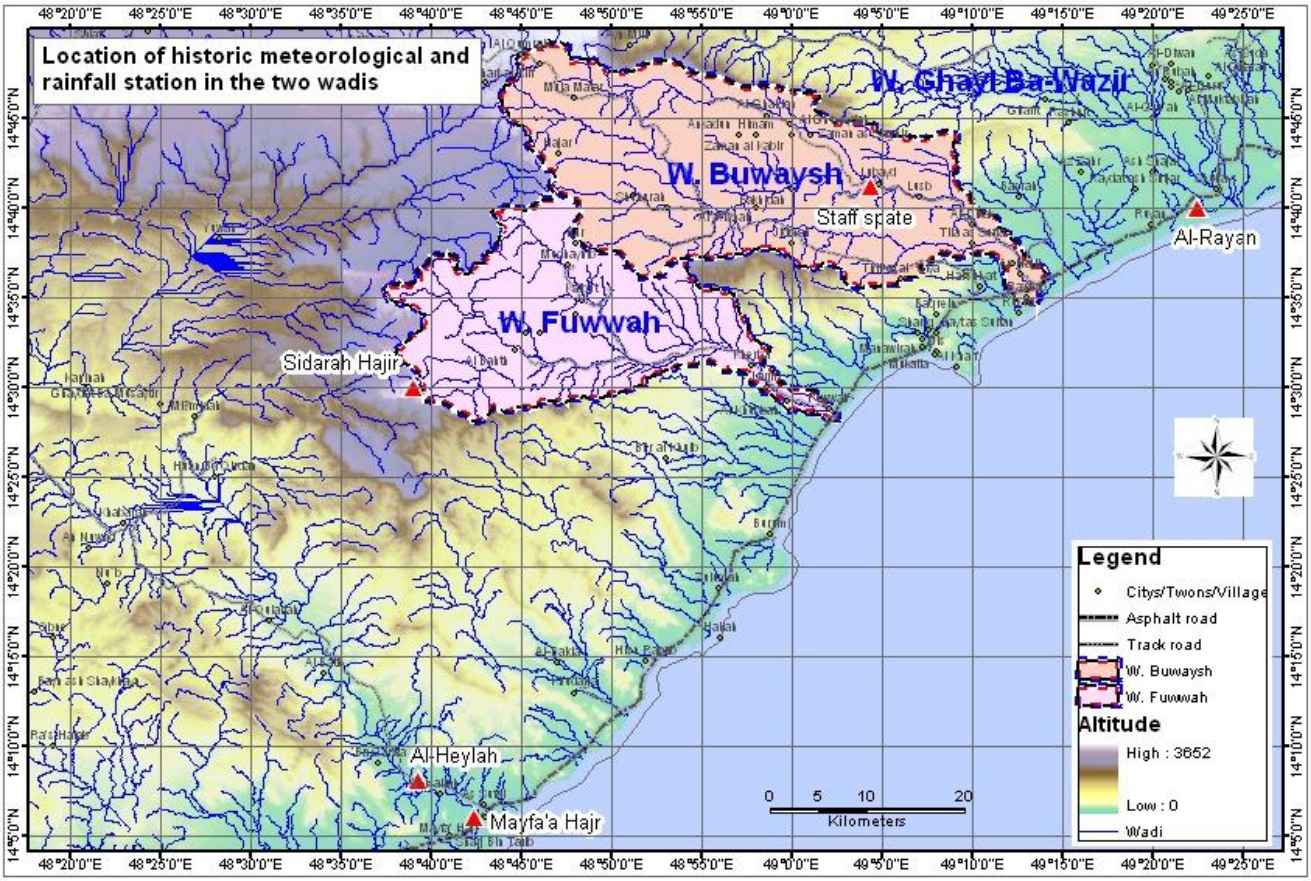


Figure 10: Locations of Active Meteorological Stations In and Around the Two Wadis

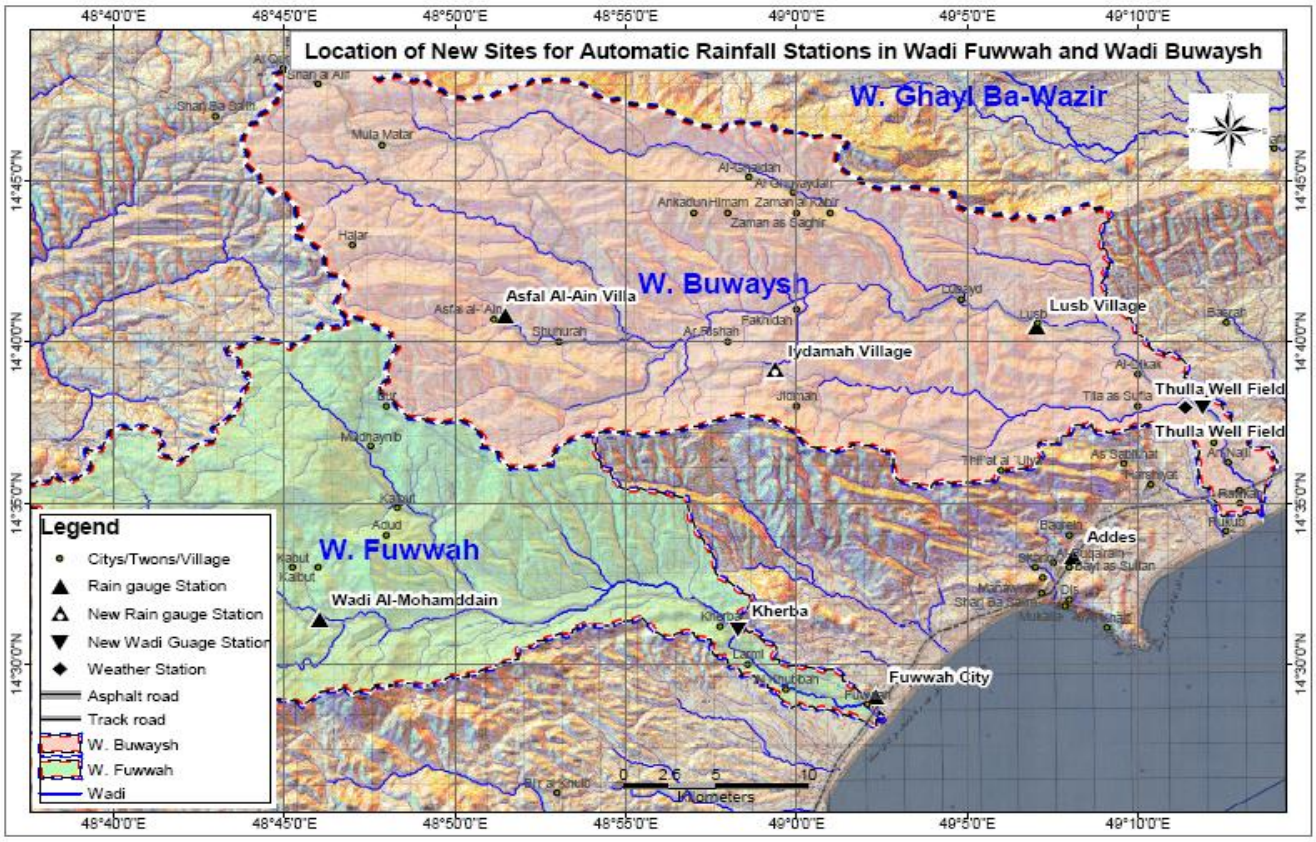


Table 4: Location and Organization Responsible for Maintenance of Station in Hadhramout

Station ID	Station Name	Station Type	District Name	Longitude	Latitude	Elevation	Operational
42	Socotra	Weather	Broom	53.900124	12.6334	47	Yes
59	Seiyun	Weather	Syion	48.799903	15.9668	700	Yes
76	Gharib	Rain	Gail Ban Yeminin	49.016588	15.0168	1400	Yes
129	Sidarah	Weather	Hajir	48.649902	14.5001	460	No
140	Riyan	Weather	Harisah	49.249926	14.5835	25	Yes
188	Gaidun	Rain	Dawa'an	48.316559	15.1001		Yes
189	Khoribeh	Rain	Dawa'an	48.316559	15.1001		Yes
230	Amd	Rain	Amad	47.950124	15.1835	1335	Yes
231	Binyumin	Rain	AlShar	49.34993	15.2001		Yes
233	Aluguhib	Rain	Dawa'an	48.699909	15.2001		Yes
234	Asharif	Rain	Dawa'an	48.53323	15.2001	850	Yes
259	Bamasood	Rain	Rakhyah	47.833444	15.2335		Yes
262	Sobeikh	Rain	Dawa'an	48.383224	15.2501		Yes
264	Bodhan	Rain	Dawa'an	48.299889	15.2501		Yes
299	Alhaleh	Rain	Rakhyah	47.850114	15.3168		Yes
419	Hagrain	Rain	Qalansya	48.316552	15.5008		Yes
471	Sah	Rain	Sah	48.849906	15.5835		Yes
472	Almashed	Rain	Qalansya	48.299882	15.5835		Yes
489	Bahran	Rain	Dawa'an	48.282979	15.7168		Yes
491	Binali	Rain	Shabam	48.633236	15.7501	750	Yes
496	Shibami	Rain	Shabam	48.633238	15.8335		Yes
504	Jueimeh	Rain	Shabam	48.666568	15.9835		Yes
1520	Al-Heylah-A	Rain	Hajir	48.654722	14.1347	49	Yes
1526	Al-Khashah-A	Rain	Dawa'an	48.269722	15.7669	737	Yes
1540	Al-Qatten-A	Rain	Al Qatan	48.418056	15.8205	681	Yes
1610	Mayfa’a-Hajr-A	Rain	Hajir	48.706667	14.1266	28	Yes
1631	Rudhom-A	Rain	Aldola'a	47.740556	14.8447	212	Yes
1637	Sah-A	Rain	Qalansya	48.250556	15.6063	782	Yes

All efforts were made to collect the hydrological and climatological data from all concerned organizations at Al-Mukala or Hadhramout level. It is already reported that only one rain gauge station had sufficiently long term data. Moreover, no wadi gauge data is available in both wadis.

3.3 Design of Operational Network

For areas where rain gauges have not been installed, there is no simple method for determining the required number of gauges. The available option is to use pilot network at certain density.

Since the catching area of a rain gauge is very small compared to the aerial extent of a storm, it is obvious that to get a representative picture of a storm over a catchment the number of rain gauges should be as large as possible, for instance, the catchment area per gauge should be small. On the other hand, economic considerations to a large extent and other considerations, such as topography, and accessibility restrict to some extent the number of gauges to be maintained. The best choice is to use optimum density of gauges from which reasonably accurate information about the storms can be obtained. The recommended densities by World Meteorological Organization (WMO) are shown in Table 5.

Table 5: Recommended World Meteorological Organization (WMO) Densities

Type of Region	Ideal	Acceptable
In flat regions of temperate, Mediterranean and tropical zones	600-900 km^2	900-3000 km^2
In mountainous regions of temperate, Mediterranean and tropical zones	100-250 km^2	250-1000 km^2

The WMO recommendations state that ten percent of rain gauge stations shall be equipped with self-recording gauges to know the intensities of rainfall. Due to non availability of these gauges neither at NWRA branch nor at the two wadis or at Al-Mukalaa we recommended the installment automatic of new rain gauge stations.

The second method is to use a higher number of gauges in the area and to remove those that are not needed at a later stage. This approach can be followed to have a higher accuracy estimate for the mean rainfall. However this is suitable for experimental areas.

If the existing network is used then the adequacy of the available rain gauges cannot be assessed by statistical analysis of record. In the surrounding area of these two wadis five rain gauge stations are existed. The records of those gauges were not continuous.

As per the analysis of record of stations in both wadis, the optimum number of station needed is seven. As per WMO standards, one rain gauge is needed per 100 to 250 square kilometers

in mountainous regions of temperate, Mediterranean, and tropical zones. Considering one rain gauge per 150 square kilometers then the required number of rain gauges becomes seven. Taking into consideration the five rainfall station installed in January 2010, in the two wadis and the rain gauge of the weather station then one more automatic station has to be installed.

Once all the seven rain gauge stations are installed, they can be considered as a pilot network capable of determining, in the coming Years, whether this rain gauge network is saturated or not. A standard procedure can be used to determine that. The new technology of TRMM satellite for rainfall data collection was used since 1998. It was considered as a good source for estimating total spatial rainfall. Meanwhile to use the collected data from these rain gauge stations as a ground stations they have to be calibrated with the TRMM satellite data. Figure 11 shows example of the data collected from TRMM and Figure 12 shows the rainfall during the flood that took place on October 27-28, 2008.

Figure 11: Example for the Data Collected from TRMM Satellite

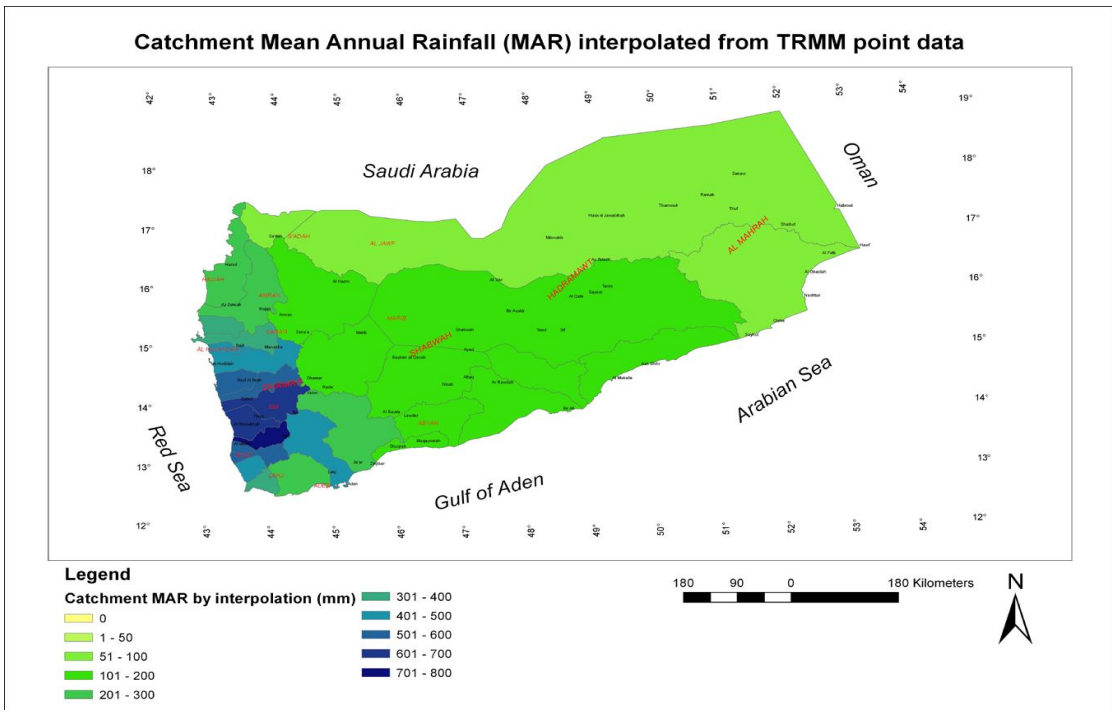
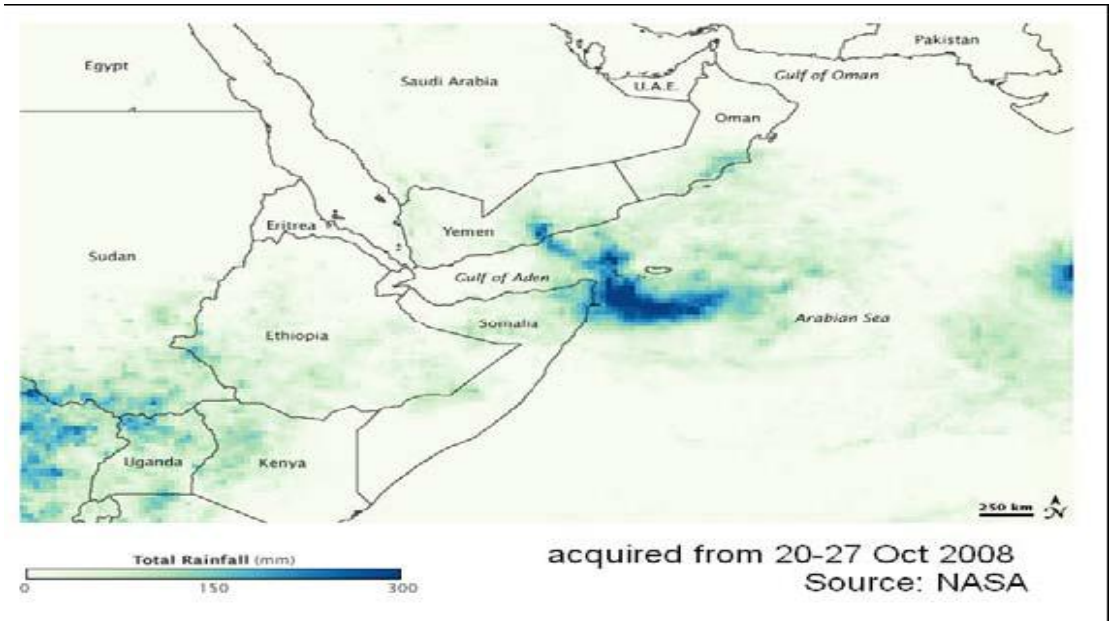


Figure 12: Rainfall During 27-28 October 2008 Flood



3.4 Site Selection

In January 2010, five locations for installing the rain gauge stations were selected. Identifying the location of sixth rain gauge station depends upon the spatial distribution of these existing rain gauge stations and the variability of rainfall over the two wadis. Al-Mukala region generally experiences local heavy showers for a short duration but disturbances resulting from thunderstorm type of precipitation are also occurs within the wadis. Therefore, special care is required in any future development in the networks to avoid any possible faulty assessment of water resources and flood producing potential. Although the rain gauge instruments could be manual, automatic rain gauges are recommended due to the reliability of their data. An automatic station is generally installed at the ground but to avoid tampering, such stations are usually being installed over ceiling of a school or any other governmental buildings.

ABRI technical team has visited the study area to identify new sites for installation of new instruments. The site visit was accompanied by the NWRA Hadhramout branch and LWSSC representatives at Al-Mukala. During the site visit, the team discussed various issues with the local villagers in particular the availability of space for installation, their willingness to cooperate with NWRA Hadhramout branch during monitoring and the protection of the instruments. Accompanied by Hadhramout branch of NWRA and LWSSC at Al-Mukala, another visit was also undertaken by ABRI team in January 2010. The aim was to finalize site selections.

In coordination with Hadhramout branch of NWRA and LWSSC at Al-Mukala officials, a seventh site has been also identified for installation of new equipments. Further discussions were needed with same organization and local people to finalize the location. The locations of the installed and proposed site rain gauge station are given in Table 6.

Table 6: Location of New Sites for Automatic Rainfall Stations in Dhamar Plain

Type of Station	Village	Serve	UTM Easting	UTM Northing	Elevation	Brief Description of site
Rain gauge Station	Wadi Al-Mohamddain	Wadi Fuwwah	48 46 01.1	14 31 23.2	482	On the top of Al-Safl School
Rain gauge Station	Fuwwah City	Wadi Fuwwah	49 2 19.0	14 29 00.5	17	On the top of Fuwwah association
Rain gauge Station	Asfal Al-Ain Village	Wadi Buwaish	48 51 27.4	14 40 48.8	990	On the top of Asfal Al-Ain School
Rain gauge Station	Lusb Village	Wadi Buwaish	49 07 01.3	14 40 30.1	133	On the top of Lusb Health Center
Rain gauge Station	Addes	Wadi Buwaish/ Fuwwah	49 08 5.3	14 33 21.3	40	On the top of LWSSLC
Rain gauge Station	Iydamah Village	Wadi Buwaish/ Fuwwah	48 59 21.7	14 39 06.9	741	The suggested place is on the top of Electricity Buliding
Weather Station	Thulla Well Field	Wadi Buwaish	49 11 22.4	14 37 59	49	At the LWSSC Thulla Well Field
Wadi Guage Station	Thulla Well Field	Wadi Buwaish	49 11 53.6	14 37 55.7	46	Near to LWSSC Thulla Well Field
Wadi Guage Station	Kherba	Wadi Fuwwah	48 58 17.0	14 31 2.0	119	The suggested place is near to canal takeoff
Wadi Guage Station	Lubayed	Wadi Buwaish	49 04 19.8	14 41 09.4	134	Old location and possible place for future

During the eightieths of past century two wadi gauging stations were installed in Wadi Buwaish and Wadi Fuwwah. These two stations do not exist in the field anymore and no trace for their record was found at any organization in Al-Mukala. The remaining part of one these show in Figure 13.

Figure 13: Reaming Part of the Wadi Gauging Stations at Wadi Buwaish

The technical team has also noticed that no working stream flow gauging stations have been installed before in either of the two wadis. Two stream flow gauging stations have been recommended, one in each wadi.

The selection of gauging sites is dictated by the need of water management or by the requirements of the hydrologic network. In fulfilling water management needs, records at the stream gauging site shall be measured periodically and more importantly during the period when water flow takes place within wadi after rain.

Before a stream gauging station is selected, an extensive reconnaissance within the two wadis has been undertaken in order to select suitable sites for the gauging. The geologic, topographic, and other maps of the wadis are also examined during the reconnaissance visits. While selecting a suitable site, the following features of the sites are seen:

- Channel characteristics: A stable banks with steady wadi bed, a considerable distance at upstream and downstream with uniform wadi sections and away from obstructions in the channel such as bridges;
- Opportunity to install an artificial control;
- Little possibility of backwater effect from downstream tributaries or other sources; and
- Accessibility of the site by roads, particularly during flood periods.

Taking the above features in consideration and in consultation with Hadhramout branch of NWRA, the technical team suggested two sites. During January 2010 NWRA Hadhramout

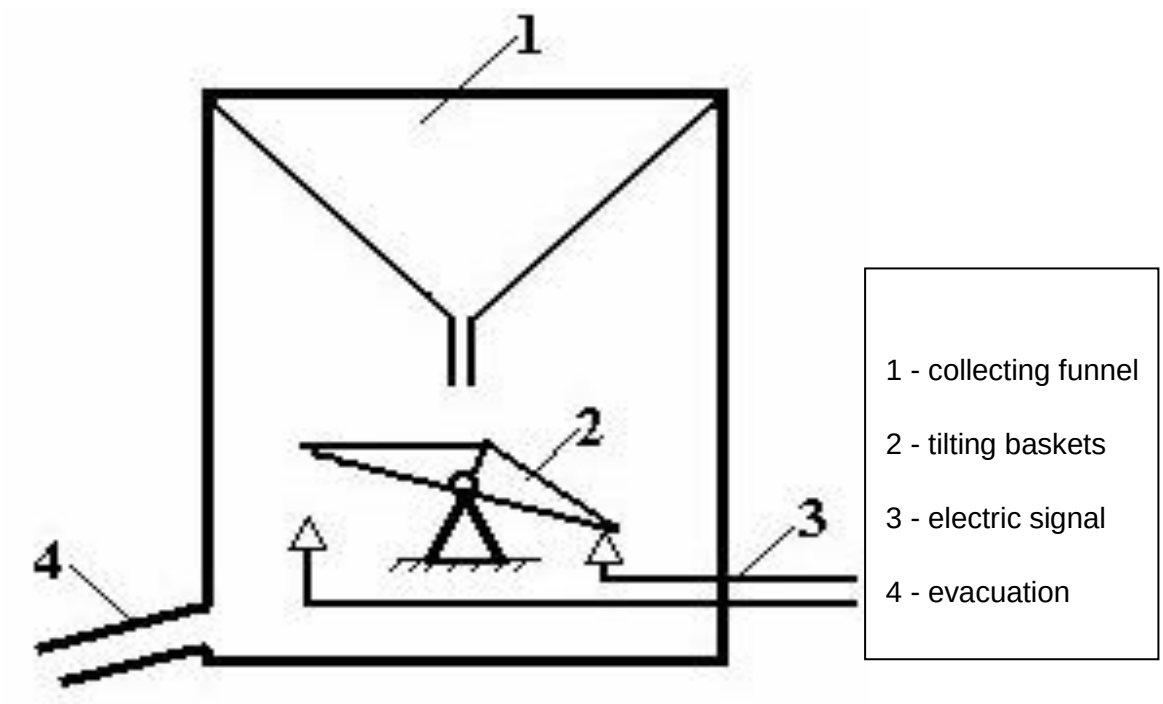
branch has finalized the selection of the Buwaish site and installed a stream flow gauging station. One more station is required to be installed in Wadi Fuwwah.

3.5 Description of Proposed Instruments

Automatic Rain Gauge. The most common method of measuring rainfall automatically is to use a container with a flat bottom and straight sides. While this type of container provides a good idea about the amount of rainfall but it is not as much successful in measuring the precise quantity of the rainfall or in recording very small amounts of precipitation. Figure 14 shows the typical cross section of the tipping bucket of a rain gauge. Because of this more sophisticated instruments, known as tipping buckets are used to more precisely measure area precipitation. The rainfall is collected by a cylinder, eight or twelve inches in diameter, and funneled to one of two small buckets on a fulcrum.

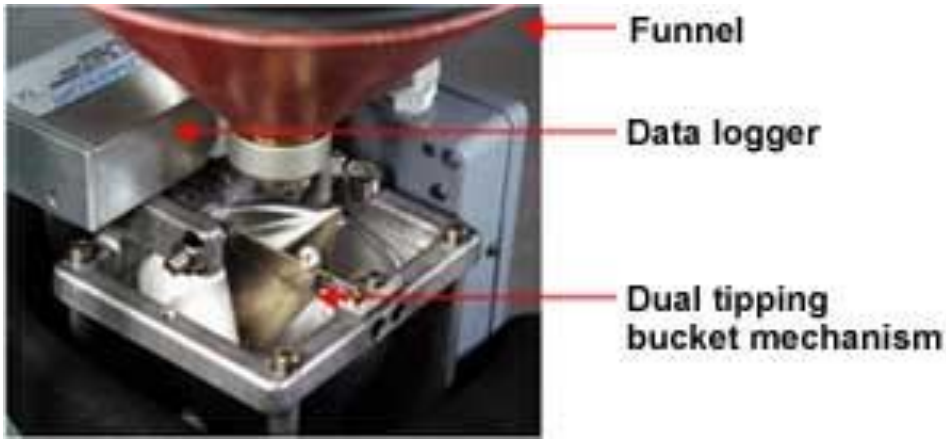
The two buckets are balanced and each holds one one-hundreth of an inch of water. When one bucket fills, it tips down and is emptied while the other bucket fills with rainwater. Each tip of the buckets causes the device to record an increase of one one-hundreth of an inch of rain. This data is then collected by the observer after site visits in order to be transferred to files or to computers.

Figure 14: Cross Sectional View of the Tipping Bucket of a Typical Rain Gauge



Factors such as wind, buildings and trees can modify the amount of precipitation that reaches a rain gauge. Because of this gauges are typically placed on top of buildings and other elevated structures. Figure 15 shows the rain gauge from inside.

Figure 15: Cutaway View of Rain Gauge and Data Logger



This Data Pod type tipping bucket rain gauges are automatic and recording the data by cable to a data logger. The tipping bucket rain gauge sensor has an eight inch orifice top screen in the funnel opening; built-in level and a cable with a sufficient length connecting the rain gauge to the data logger. For best results of measurement, it should be mounted at or near ground level, allowing enough room underneath for the measured water to drain. This sensor normally is mounted onto a concrete pad, which helps to prevent vegetation from growing in or around the sensor parts. It also provides a solid surface, which helps in leveling the sensor. The most recommended has specifications as shown in Table 7.

Table 7: Specifications

Rain Gauge	Rain Gauge with impulse output, pick-up for data pod-system, tipping bucket with level, and leveling screw
Memory	At least 10,000 data points
Analog Input	At least two channels; zero to five volts
Operating	Download data to PC laptop throw USB cable or bluetooth
Power supply:	One 9V alkaline or lithium battery or equivalent
Enclosure	Steel or fiberglass
Accessories	USB communication cable to PC laptop, operating software with graph, operational manual, connecting software to be working with XP, Vista or Windows 7
Environmental	-20 to +70; zero to 100 percent RH

Stream Flow Gauging Station. Specifications of the recommended stream flow gauging station are shown in Table 8.

Table 8: Stream Flow Gauging Station

Type	Wade flow and temperature data sensor logger
Material	Rated case which houses the logger, built-in lithium batteries, sensor connection to PC laptop throw USB port
Size	Minimum (22 mm x 154 mm)
Memory	Minimum 512 KB internal memory even with recordings every minute up to 60,000 readings of pressure, water level and temperature, displayed as temperature compensated level
Power	Minimum 8V lithium ion battery in life ten years
Environment	-35 to +60 °C; zero to 100 percent RH
Communication	USB connection to PC compatible with Windows OS
Pressure Sensor	Recording interval with minimum/maximum average water level, temperature, and pressure
Resolution	0.002 to 0.0006 percent FS
Range	Minimum zero to 15 meters
Vested Cable	Up to 50 meters
Material	Stainless steel housing with screened nose cone; polyethylene jacketed, shielded cable with vent tube.
Warranty	Minimum one year

Table 9: Meteorological Station

Humidity and Temperature Sensor	Combined humidity and temperature sensor for measuring air humidity and temperature
	Digital sensor for measuring air humidity, measuring range: 0-100 percent RH, resolution: 0.5 percent RH, accuracy: ± 1 percent at 20 to 80 percent, long-term stability
	Sensor for measuring air dry temperature, measuring range: -20 °C to +60 °C, resolution: 0,1 °C, accuracy: ± 0.1 °C
Wind Velocity	Sensor for measuring wind speed,
	Measuring range 0-70 m/s, max. load 100 m/s, accuracy ±0.2 m/s
Wind Direction	Sensor for measuring wind direction,
	Measuring range 0 - 360°, max. load 100 m/s, housing material aluminum, initial deflection <0.2 m/s
Solar Radiation	Sensor for measuring solar and global radiation,
	Radiation measuring range: 0.3 - 3.0 µm, linearity <±1%, stability <± 3% per year, settling time 95 percent <20 sec, cosinus formula zenith angle 0 - 60 <± 1% and zenith angle 60 - 80 <± 3%, output :2 - 3 mV
Precipitation	Rain gauge with impulse output, pick-up for data logger-system, unilateral ball-beared tipping bucket with level and leveling screw,
	Resolution minimum 0.01 mm precipitation, aerodynamic design
Data Logger	Data logger for storage values on internal memory with a minimum of twelve analog inputs four digital I/O ports, as well as additional arithmetical channels. Analog inputs with two, three, or four line connections. Wide selection of measuring ranges.
Configuration System	User-achievable menu-guided configuration under Windows 95/98/NT/2000/XP/Vista and Windows 7.
Data storage	Internal memory 4MB up to 8MB
Resolution	0.003...0.03 percent, range dependant
Accuracy	0.01...0.3 percent; range dependant
Construction	Aluminum/ABS housing for installation on standard rail or equivalent
Power supply	Using chargeable battery 12 V with solar panel
Input	Max. 18 V DC resp. max. 2 kHz;
Output	Open collector, max. 18 V DC resp. max. 100 mA
Retrieval Data	Laptop with Intel® Core TM 2 Duo Processor

Figure 16: Wind Velocity

Figure 17: Meteorological Station

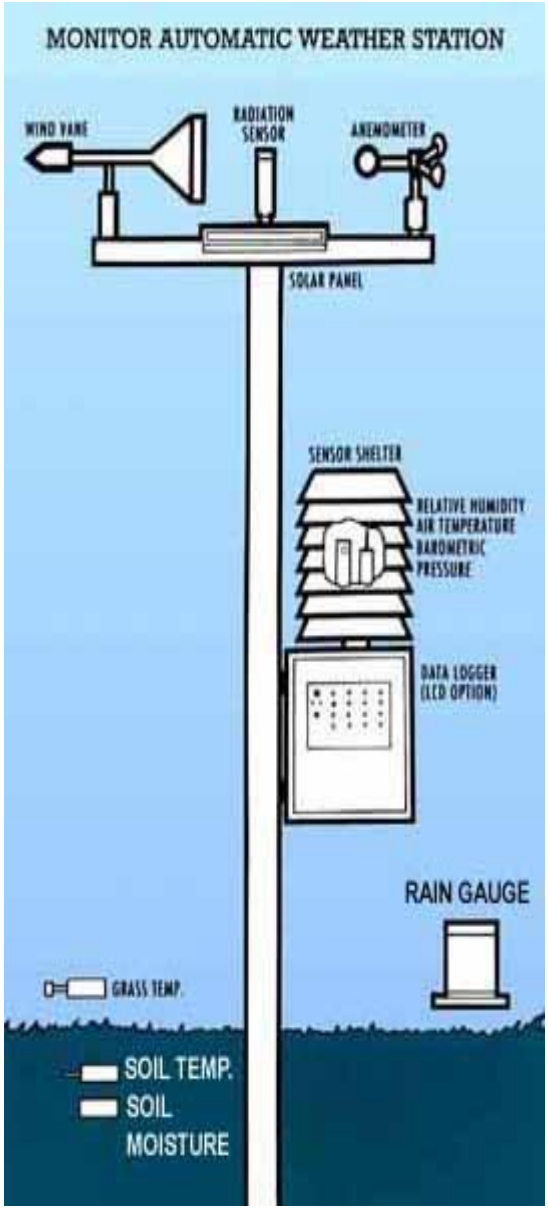


Figure 18: Air Pump

Figure 19: Sensor Used for Wadi Flow Measurements

4 WELL AND SPRING INVENTORY AT WADI BUWAISH AND WADI FUWWAH

4.1 Objectives

To obtain authenticated and updated information on groundwater occurrence, quality and utilization, a comprehensive well inventory was undertaken as a part of the scope of the study by well equipped team. Along with the well inventory, spring inventory is also carried out which is intended to obtain information about location of springs along with quality and quantity of water available from them. The scope of well inventory study embraces the followings:

- Review of previous well inventories;
- Carry out well inventory according to the NWRA format and guideline;
- Obtain a ground water level measurements from the surveyed wells, whenever possible, as well as measurements of the conductivity, pH and temperature;
- Store data in NWRA data base system;
- Process collected data;
- Interpret the results of inventory on maps and graphs; and
- Describe and evaluate the results.

Within the period 1978-1980**,** a French consulting engineer**,** SOGEREAH**,** has undertaken a water resources study for the areas of Fuwwah, Mukalla, and Khird. The aim was to estimate the water resources available in these areas and also to identify locations for new wells to satisfy the growing water demands of the adjacent towns and villages.

The study was very thorough covering many water resources aspects such as hydrology, geology and stratigraphy, water bearing properties of the formation, characterization of the alluvial reservoirs as structure of the catchments area, surface water, groundwater circulation, water quality, present use of the water, water balance etc. It also showed that Wadi Buwaish's well field is consist of 13 wells all situated on the right bank of the wadi near its confluence with Wadi Thiah. The extracted quantity of water used for domestic supply for Mukalla was 48 liters per second and for agricultural use were 50 liters per second. The town water requirements were estimated to be around 140 liters per second to 167 liters per second in 1990 and 203 to 245 liters per second in the year 2000. In general the water quality in the area was good except for the coastal areas were the water is saline containing more than three grams of salt per liter.

Between 1982 and 1984 SOGREAR undertook the second study for the same wadis entitled, “Study of Artificial Recharge of the Aquifers Underlying the Wadis Buwaish, Khirba, and Huwayrah." The study has concentrated on the geological and hydro-geological studies, with the simulation of operation of the Wadi Buwaish aquifer by means of a mathematical model.

The well and spring inventory survey was conducted according to NWRA guidelines. Well and spring inventory questionnaire was obtained from NWRA which incorporates

comprehensive information on wells and springs.

The well and spring inventory has been undertaken under the supervision of NWRA's representatives who made frequent trips to the area of the project. The well and spring inventory of Buwaish is being carried out by a team of three persons. Day to day work of the team has been supervised by Senior Engineers of Consultancy. The team has been equipped with a four wheel drive vehicle along with necessary equipments including water quality measuring kit for measuring the EC, pH, and temperatures in addition to GPS unit for geographical positioning of wells and springs plus additional equipment for measuring well depth, well discharge and water levels.

Upon arrival at the water point, all well/spring owners and farmers were briefed on the objectives of the study. This action helped insuring their cooperation with the team. The team coordinator allocated a serial identification number to the well/spring and identifies geographical coordinates of the water point using a GPS. At the same time the team coordinator interviewed the well/spring owners to obtain basic information on the wells. The team took measurements for water level in the wells, their discharge, electrical conductivity, pH, and temperature. In cases where the well owner was not available during the visit, some of the basic information was obtained from the neighbors.

At the office, the team reviewed the data sheets and marked the inventoried points on the Google Earth and finally all data is being entered into database using computerized format similar and approved to NWRA’s database,

In total three field visits to the wadi were undertaken. As the details of the first one is mentioned above, the purpose of second visit was to cover few small areas which could not be covered during the first one. The third visit was undertaken to study the consequences of 2008's big flood. Many wells were buried causing instability of the water level of other wells. This incident threatened the consistently of the collected well inventory data. Hence, the third visit was carried out to see if some of the buried well has become operating again and also to enhance the collected data with more measurements.

4.2 Data Analysis of Well Inventory Survey

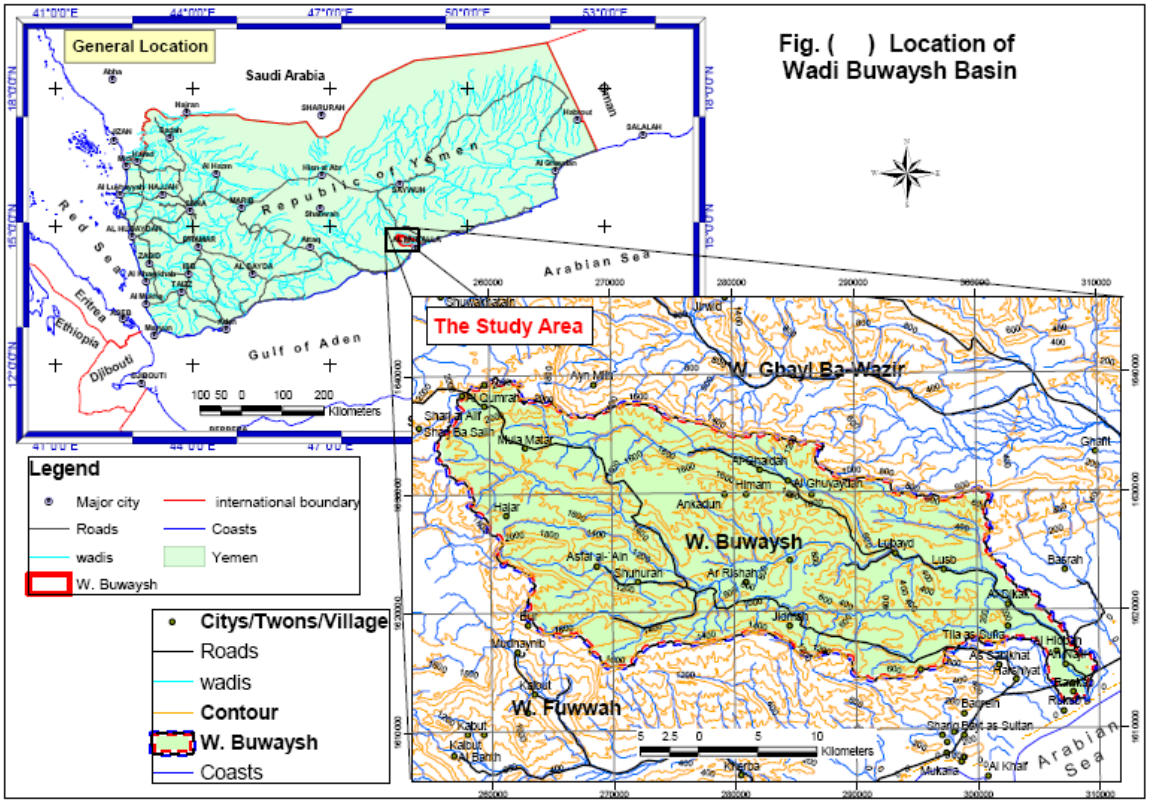
All data gathered from well inventory survey was entered into the data base system using the Microsoft Access Data Base program adopted by NWRA. The data thus entered in data base system, was used for tabulation and analyses. The main findings based on the survey in Wadi Buwaish are discussed in subsequent paragraphs and finally the soft copy of the database file was handed over to the NWRA representative.

4.3 Area Characteristics

Location. The location of the catchments areas of Wadis Buwaish in the Republic of Yemen is shown in Figure 20. They are boarded by longitudes 266000 in the west and 310000 in the east and latitudes 1610000 in the south and 1640000 in the north. The total catchment area is around 650 square kilometers begins at the edge of the plateau of Jol at an altitude of 1,700 meters. This area also catches the water of two other main wadis, Himam in the north and Shururah in the south. They run from west to east with their tributaries draining a total surface area of about 450 square kilometers. The confluences of these two wadis at Lubayd, Thulla is suited in the south downstream section of Wadi Buwaish.The rainfall decreases as

we move from the mountainous area towards coastal desert of Mukalla and ranges between 50 millimeters to 100 millimeters.

Figure 20: Location of Wadi Buwaish Basin



Climate. The annual rainfall is generally ranges between 50 to 100 millimeters with 80 percent normally take place in the period January through June. There are two distinct rainy seasons, the first starts at mid March and continues until the beginning of July while the second is during August.

The potential evapotranspiration (PET) for an average year varies depending on the altitude and wind exposure. The PET ranges between 3.5 to 4.0 millimeters per day during cold period and at around 9.5 to eleven millimeters per day in July and August. The yearly total average amount of evapotraspiration is about 2,700 millimeters per day.

The mean monthly maximum temperature varies within a range of 27.5 to 30 degrees Celsius during winter months and 40 to 41 degrees Celsius during summer. The mean monthly minimum temperature varies between eleven degrees Celsius during winter months and 25 degrees Celsius during the summer months. The mean daily relative humidity in the region varies according to the seasons. The mean daily relative humidity varies within 20 to 30 percent during the cold and dry period and decrease down to 20 percent during summer season.

The average number of sunshine hours is lowest from July to August was eight to 9.5 hours per day and highest during the other months 9.5 to 11.8 hours per day.

4.4 Well and Spring Inventory Data

Well and spring inventory data collection started in March 2009 and was completed in April 2009. Although data of 113 wells and 24 springs were gathered, however, not all wells and springs full information could be retrieved, due to:

- The majority of farmers refused or hesitated to cooperate with the technical team. The reason was attributed to the deterioration of the farms by latest flood and consequently they conditioned their cooperation by getting compensation from government;
- Owners of wells were not available;
- For no apparent reason, some farmers just refused to run their pumps to allow the team to take discharge measurement;
- Some farmers showed some skepticism about the questionnaire and thus refused to cooperate; and
- Few spring sites were difficult to reach.

The well and spring locations were identified by GPS readings. Their identification numbers were based on Mukalla topographical map D-39-14 which was published by the Military Survey Authority (MSA). The team has added sequences numbers to the map number to identify the location of each well and spring.

4.5 Well and Spring Inventory Data Statistics

A total a number of 113 wells and 24 springs were visited. It is estimated that these figures represent more than 97 percent the actual number of wells and springs in the Buwaish area at the time of the inventory. The new wells have increased rapidly at mid of eighties and the beginning of nineties. Figure 21 shows the increase of total number of wells in time. The number of wells per square kilometer is presented in Figure 22.

Figure 21: Increased Total Number of Wells 1975-2009

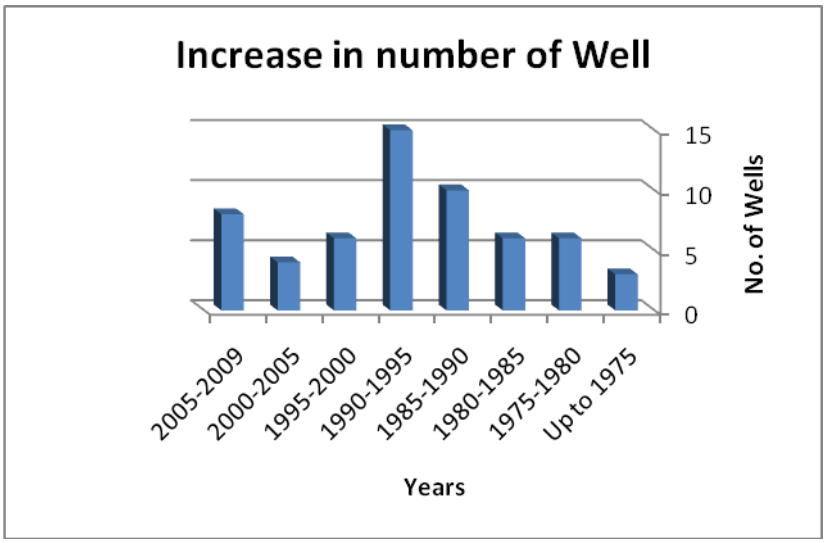
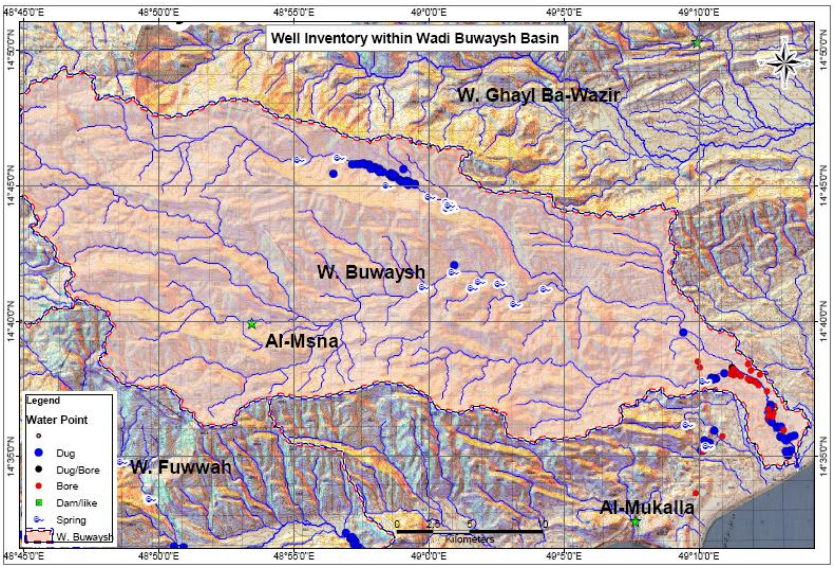
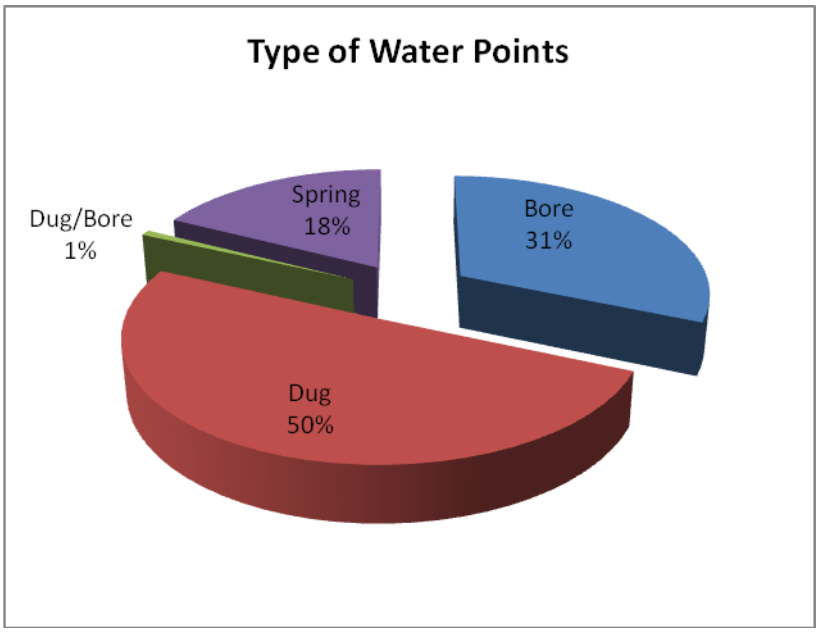


Figure 22: Well and Spring Locations



Well Type. The wells in the Wadi Buwaish area are either hand dug well with large diameters ranging from one to more than four meters or bore wells with small diameter ranging between eight and 15 inches. All wells have been classified according to their types and the figures shows that out of the total number 50 percent were dug wells, 31 percent boreholes, one percent dug/boreholes and 18 percent was spring. Sixty percent of boreholes are owned by local water supply and sanitation authority and only seven wells were operational. See Figure 23.

Figure 23: Types and Percentage of Water Points



Depth. Two types of wells can be distinguished according to well depth. Firstly, a dug wells with an average depth between five to 35 meters (See Figure 24) and secondly a bore wells with an average depth 35 to 800 meters (See Figure 25). The deepest wells occurring in Wadi Buwaish are for those drilled for Mokalla water supply where depths reach 340 meters and 800 meters.

Figure 24: Depth Distribution for Dug Wells

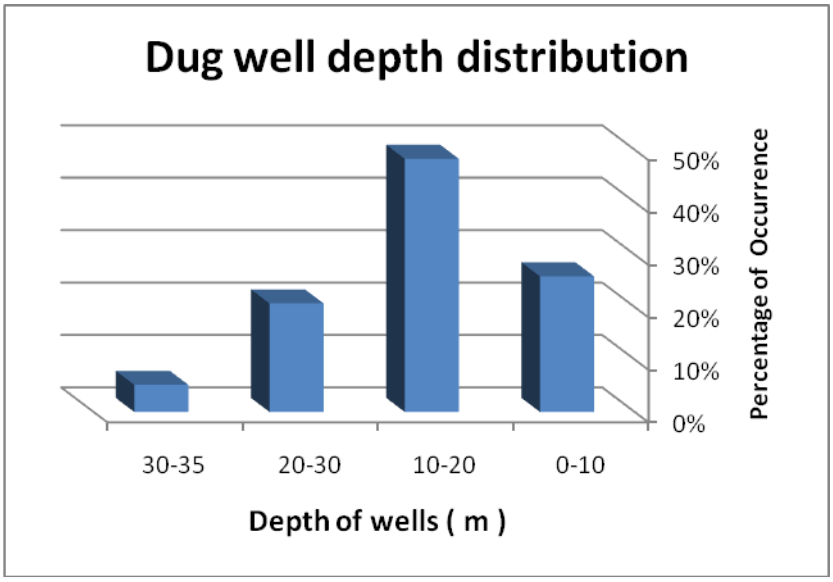
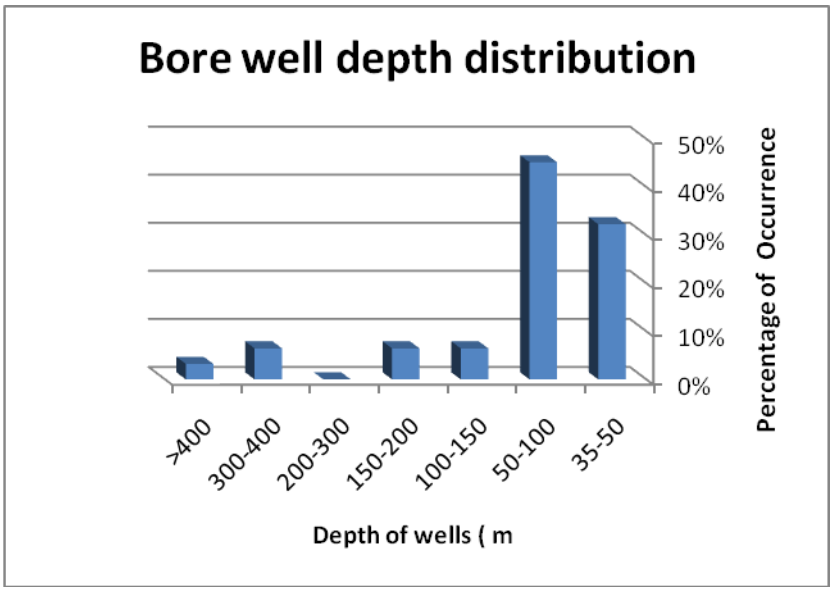
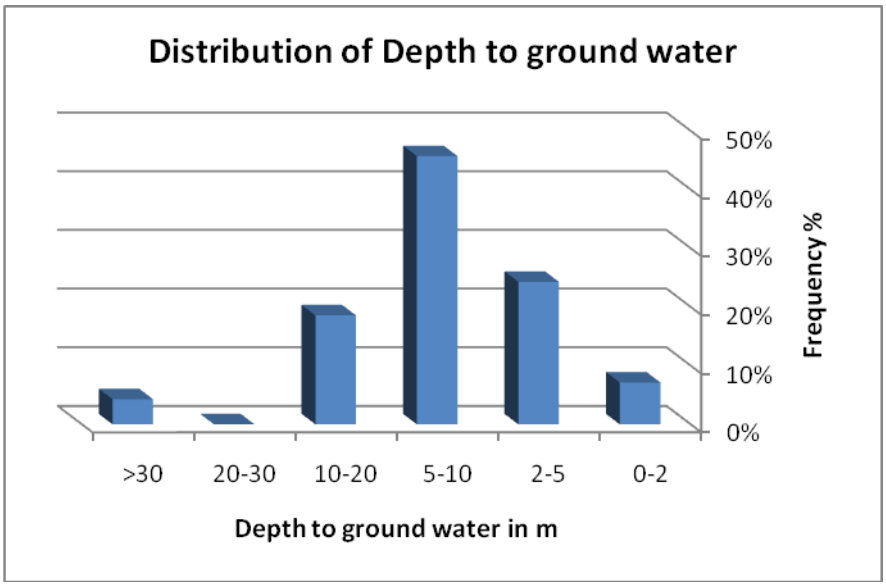


Figure 25: Depth Distribution for Bore Wells



The total number of wells in which the ground water levels could be retrieved was representing about 70 percent of all wells. Figure 26 shows the distribution of the ground water. Shallow ground water within two to ten millimeters occurs in most cases while maximum depth found in the area was 64 meters and the minimum was half a meter.

Figure 26: Distribution of Depth to Groundwater



Lithological Description. Wadi Buwaish ground water has been found in coarse recent alluvial- proluvial deposits which are very permeable and about 30 meters thick. The sandy, gypseous marl with underlying limestone bed forms an extension of this aquifer.

Electrical Conductivity. The electrical conductivity gives a general picture of the variation of salinity of the groundwater in and around the area. The electrical conductivity in Buwaish has been measured in 65 percent of the total wells in the area. Their values ranged from 1,131 to 9,680 microseconds per centimeter. In other wells the recorded electrical conductivity has exceeded 10,000 microseconds per centimeter while values of 18,850 microseconds per centimeter were found more downstream near the coastal areas. Most of the high electrical conductivity wells used for cement blocks industry. The average of all measured values is 2,988 microseconds per centimeter while the values of electrical conductivity of the springs were found to be within the range 125 to 2,680 microseconds per centimeter, the average was 1,310 microseconds per centimeter. Figure 26 shows wells and springs EC frequency distribution and Figure 28 shows the EC contour line.

Figure 27: Wells and Springs EC Frequency Distribution

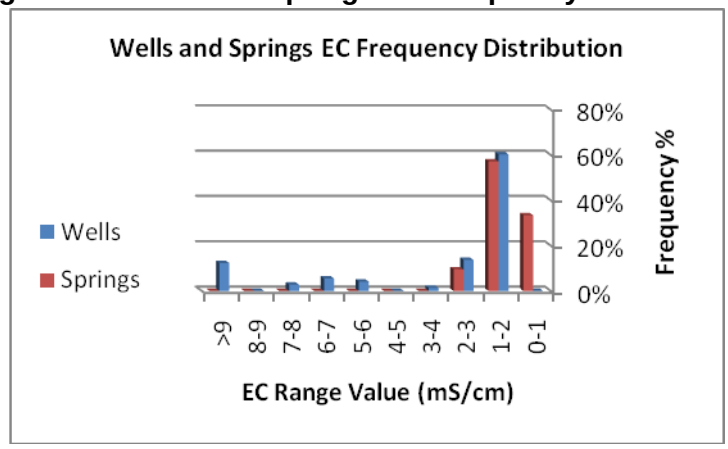
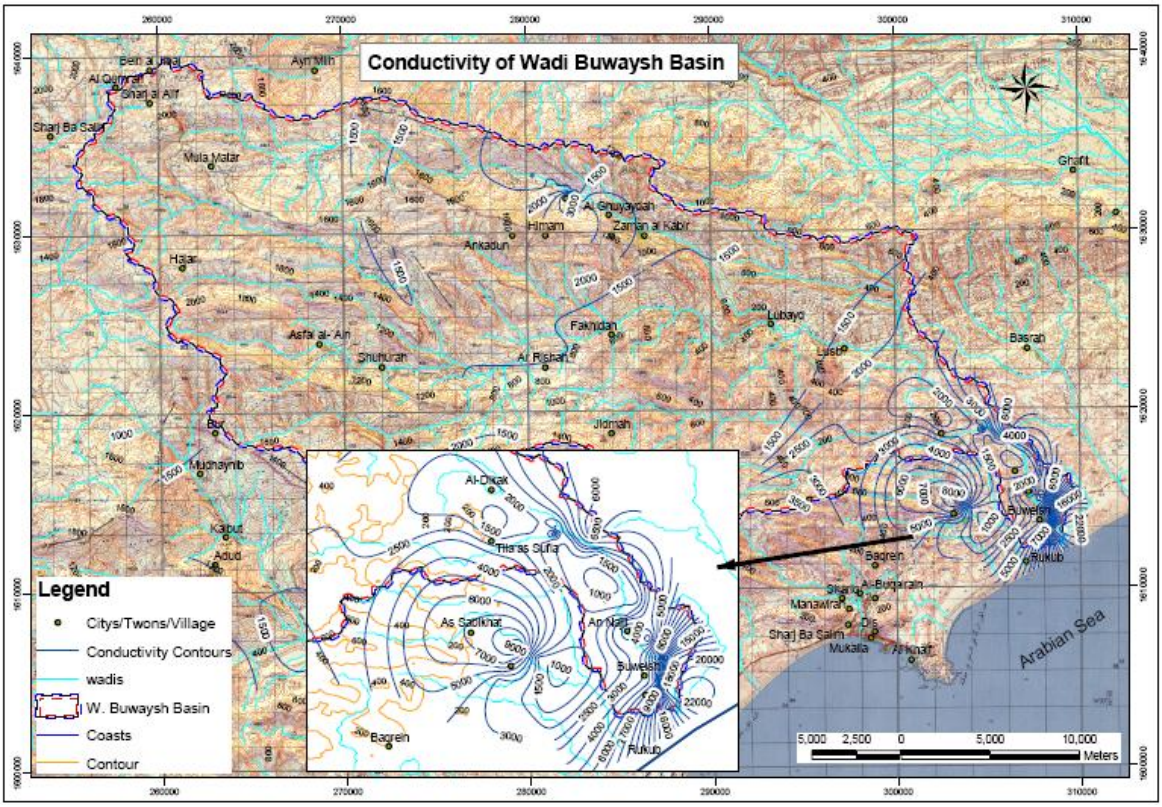


Figure 28: Map of Conductivity of Wadi Buwaish



pH of Groundwater. Based on the hydrogen ion concentration measurements, the pH values of wells and springs were generally natural and basic except for some cases where the recorded values of the have been lower. Figure 29 shows well and spring pH frequency distribution

Figure 29: Well and Spring pH Frequency Distribution

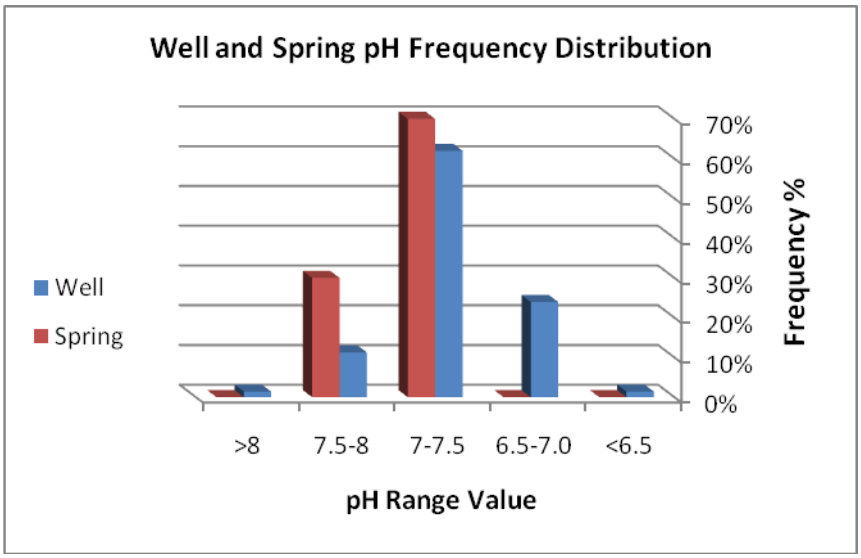
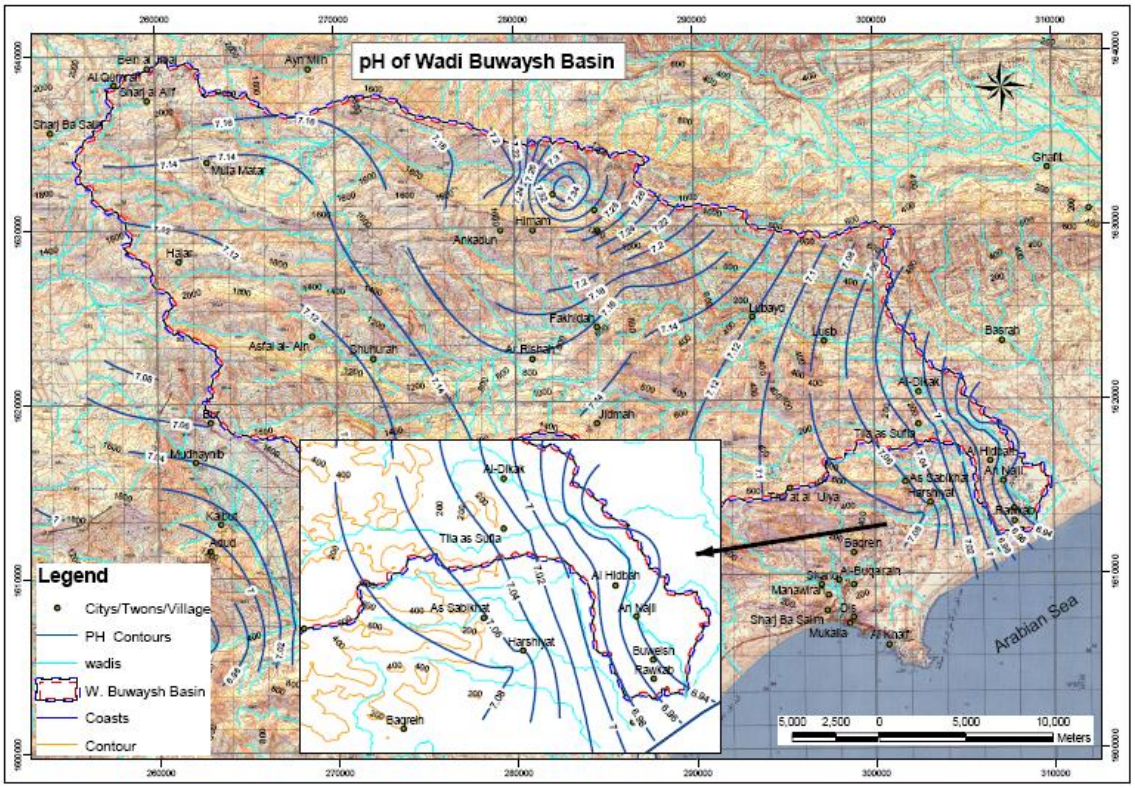


Figure 30: pH Counter Lines



Groundwater Temperature. Groundwater temperature is generally influenced by four factors, namely they are: the mean annual air temperature, well depth, volcanic activity, and recharge intensity. Data gathered through the inventory showed that the water temperature in the study area ranged from 23 to 38 degrees Celsius. Figure 31 shows the distribution of groundwater temperature and Figure 32 shows the contour lines.

Figure 31: Groundwater Temperature

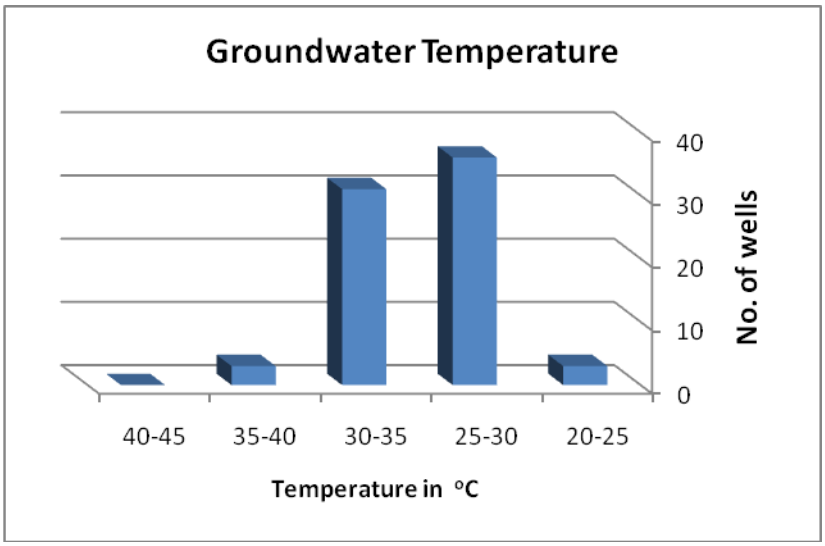
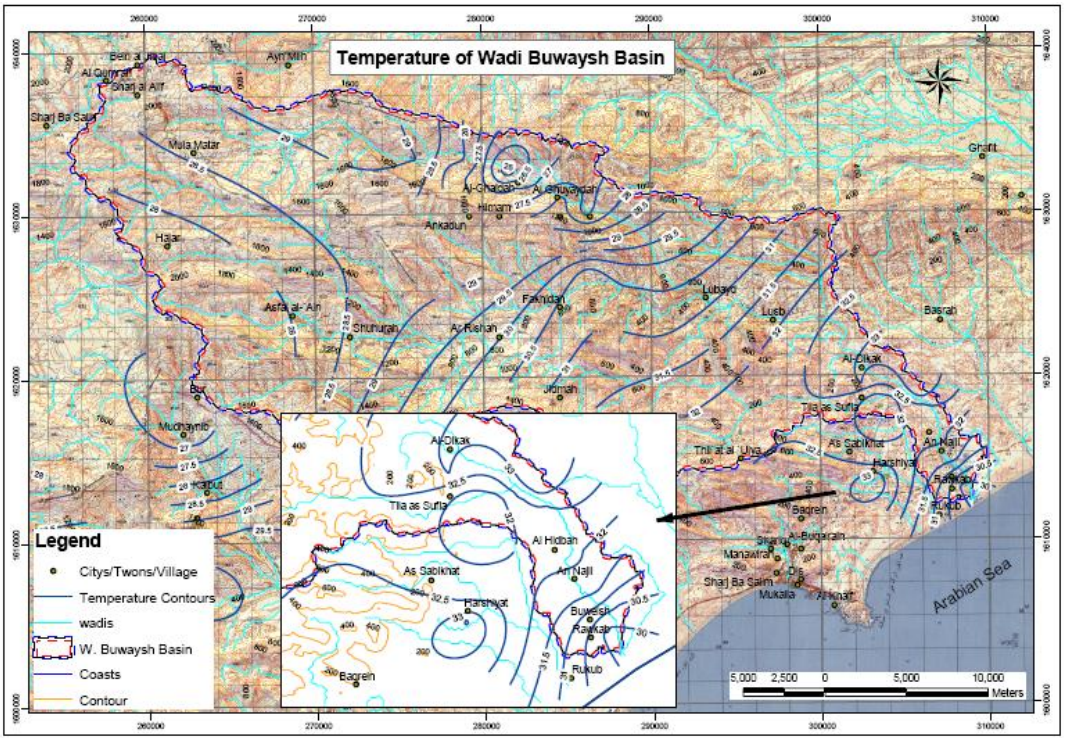


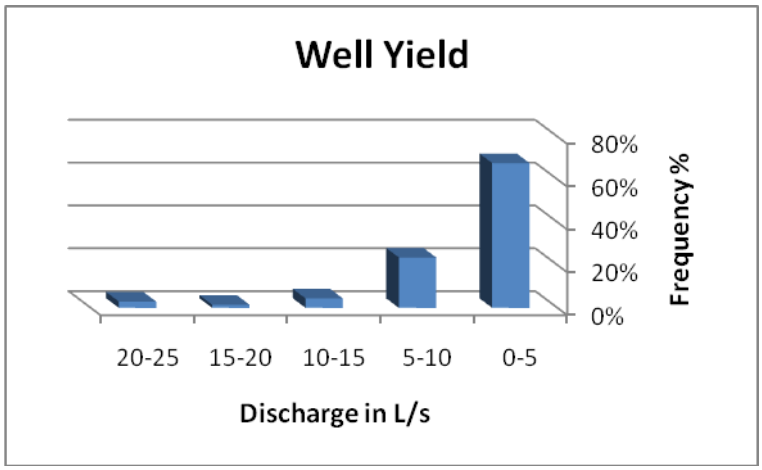
Figure 32: Groundwater Temperature



Well Yield and Groundwater Abstraction. Yield data are available for 60 percent of the pumped wells. The measured yields range between three and 24.5 per second. For the dug wells the range was between three and 17 per second while the yield of the bore was between four and 24.5 per second. That of the springs was between one and 2l per second.

Ground water abstraction rates depend on the yield of each well and its pumping duration. The period of operations of the wells is divided into two parts depending on the nature of the season and whether it is dry or wet. In dry season the average seasonal working hours per well is 3,600 hours while in wet season the average seasonal working hours per well is around 735 hours.

Figure 33: Well Yield



The total annual abstraction of ground water for agricultural use is 6.11 million cubic meters. The wells are used by the local corporation for water supply and sanitation in Hadhramout, Mukalla Governorate and the total reported abstraction is seven wells situated in Wadi Thulla. The total annual abstraction of ground water for domestic use is 2.31 million cubic meters.

Water Use Pattern. Of 137 water points inventoried in Buwaish, 89 were found operational. Agriculture is the main consumer of water where 82 of the operational water point are used for irrigation. Only eleven percent of the wells are exclusively used for municipal purpose and about six percent of the wells are being used for small Industrial while the rest one to 1.5 percent is utilized for special uses such as drinking water for domestic animals, supply of water to mosques, and tankers.

Agricultural Practices and Cropping Pattern. Economical aspects of agricultural activity are directly related to water availability. With context of a short wet season accompanied by low rainfall and long dry season, agricultural activities fall into one main category; irrigation production system. Groundwater irrigation and uncontrolled spate irrigation are mainly concentrated in low to medium altitude areas of the study area while springs are concentrated in its upper altitude. A summary of the cropping pattern and irrigation frequencies of the main crop in the area is given below:

Irrigation Practice. The pumped water is conveyed through earthen channels to the fields. Only few farmers used lined channels. Surface irrigation methods are generally used as the main irrigation systems; strip border, furrow and basin. The border method is usually used for tobacco, maiz and alfalfa while furrow is used for vegetables, and basin for fruit crops like mango, lemon, and bedan. Time intervals between the irrigation applications ranged between three to 15 days depending on the crop type. The highest frequency of irrigation applications is banana. Tobacco dominates the upper part of wadi.

Industrial Use. The study area has a very limited industry. The main industrial plant is that of cement blocks which is located near the sea. The plant has its own well with high salinity water.

Domestic Use. The total annual abstraction of ground water for domestic use is 2.31 million cubic meters. This represents eleven percent of the total water use in the area. A total of seven wells are used by the local corporation for water supply and sanitation in Hadhramout to supply the town of Mukalla.

Chemical Analysis. To get an idea about the occurring geochemical composition of the water in the Wadi Bouwish, nine groundwater samples were taken from Mukalla water supply wells. The samples were collected by the local corporation for water supply and sanitation in the Hadramout in 2008 and were analyzed at the laboratories of the same corporation. The analysis which was thorough aimed at measuring the physical properties and the chemical constituents of water. The conducted tests were: temperature, color, turbidity, pH, conductivity, total dissolved solid, pH alkalinity as calcium carbonate, total alkalinity as calcium carbonate, total hardness as calcium carbonate, calcium hardness as calcium carbonate, magnesium hardness calcium carbonate, carbonate hardness as calcium carbonate, non-carbonate hardness as calcium carbonate, chloride, sulfate, sodium, nitrous oxide, fluoride, iron, manganese, calcium, magnesium, potassium and bicarbonate .

Groundwater Quality. The drinking water quality standards developed by NWRA provided two thresholds – highest desirable limit (HDL) and maximum permissible limit (MPL). Table 10 below shows distribution samples.

Table 10: Suitability of Water for Drinking Purposes

Element	HDL (mg/l)	Number of samples above HDL	MPL (mg/l)	Number of samples over MPL
Calcium	75	7	200	1
Magnesium	30	8	150	0
Sodium	200	-	400	-
Potassium	8	-	12	-
Bicarbonate	150	8	500	0
Chloride	200	8	600	0
Sulfate	200	3	400	5
Nitrate	10	8	50	0
Iron	0.3	8	1	0
TDS	650	8	1500	0

In 90 percent of the samples, concentration of one of the main ions – magnesium, calcium, sodium, bicarbonate, sulfate – exceeded the HDL. The nitrate levels in samples points to a serious health hazards due to contamination. In each sample, nitrate level was above HDL, and five out of the eight samples had sulfate levels above 400 milligrams per liter.

Suitability of Groundwater for Irrigation. When irrigation water evaporates, dissolved substances remaining in soil affect both plant growth and soil structure. Plant growth may be retarded due to modification of osmotic process as salts restrict water uptake. Soils may also become harder and their permeability may deteriorate as sodium replaces calcium and magnesium on clays and colloids. The structure and drainage properties of soils are affected as sodium absorption ratio (SAR) exceeds ten. The table below provides the hazard level of SAR values of irrigation water.

The chemical quality of groundwater of Wadi Buwaish is generally good and is suitable, with few exceptions, for domestic supply, livestock and irrigation. Analyses of the water samples taken from eight wells of local corporations for water and sanitation showed predominantly a calcium- or magnesium carbonate composition with the electrical conductivity values ranging

from 1,090 and 1,829 microseconds per centimeter and low concentrations of the major ions being below the WHO guidelines for drinking water quality. Water had a sulfate relatively high the WHO guideline indicating a presence of gypsum in the water-bearing sediments. The water in the wadi is general highly hard, usually from 430 to 780 milligrams per liter of the total hardness as calcium carbonate.

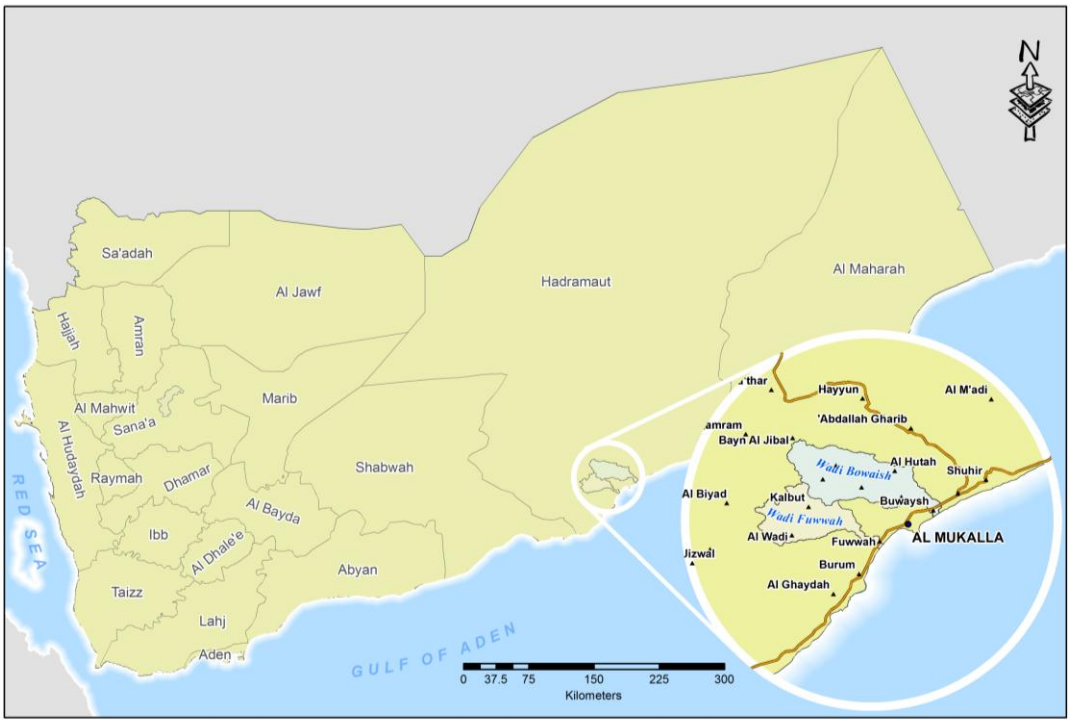
The total dissolved solids (TDS) concentrations were found to range between 698 and 1,214 milligrams per liter. The ion of hydrogen carbonate was higher than WHO guideline and below Yemen guideline for domestic and flour content were found to range 0.52 and 1.41 milligrams per liter. Overall quality of the water was considered good for both domestic and agricultural use.

5 GROUNDWATER MODELING AT WADI BUWAISH AND WADI FUWWAH

5.1 Introduction

The two wadis, Buwaish and Fuwwah, begin on the high limestone plateau of the Jol at an altitude of 1,800 meters. It runs from northwest to southeast and flows into the sea. Wadi Fuwwah is located twelve kilometers west of Mukalla while Wadi Buwaish is at 18 kilometers to the east in Figure 34. The study areas are the recent alluvial formation that present in the downstream at Wadi Buwaish and Wadi Fuwwah in Al-Mukalla, Hadharamout governorate.

Figure 34: Map Showing the Locations of the Wadis



Location Map of the Study Area

Modeling is an attempt to replicate the behaviors of natural groundwater or hydrologic system by defining the essential features of the system in some controlled physical or mathematical manner. It plays an extremely important role in the management of hydrologic and groundwater system.

The reliability of any groundwater model depends on a proper simulation of the groundwater situation in the basin. This depends on proper calibration, for which the availability of the data on the geometry and hydraulic characteristics of the aquifer and data on water levels and

the water balance are indispensable. During the calibration phases additional information might be needed or obtained. In the following section we describe:

- The conceptual model;
- The choice of finite difference method and application of Visual Modflow;
- The boundary conditions;
- The geometry, the hydraulic characteristics of the aquifer and water table and water balance data applied as input of the model; and
- The details model inputs and results.

The groundwater movement and model development is broadly defined by the following equation. The partial-differential equation of ground-water flow is given as under:

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(kyy\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(kzz\frac{\partial h}{\partial z}\right)+W=+S_s\frac{\partial h}{\partial t}$$

k_{xx} , k_{yy} , and k_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T); h is the potentiometer head (L)W is a volumetric flux per unit volume representing sources and/or sinks of water, with W is less than zero for flow out of the groundwater system, and W is greater than zero for flow in (T-1); SS is the specific storage of the porous material (L-1); and t is time (T).

Even though, the groundwater equations have been developed considering homogeneous aquifers, in general, they do not occur in real life situations. The conductivity values vary considerably in all directions as well as the Storability values also vary considerably. In normal modeling designs, k_{xx} and k_{yy} values are taken as same unless otherwise specifically obtained and observed in pumping test data and the vertical permeability data is considered about ten times less than the horizontal permeability and calibrated subsequently to check these values. Even Visual Modflow itself calculates the vertical conductivity giving ten times less conductivity to the base aquifer and calculates upward.

The finite difference transformation of equation above is considered for in Visual Modflow for studying the groundwater movement in the area.

The basic idea of the finite difference method is that the model area is subdivided into a number of subareas or polygons. The simplest type of polygon networks is made by two families of straight parallel lines, to the x and y direction, respectively, which together form a mesh of rectangles. The basic theory of the finite difference method is simple and it is usually requires little computer memory and computation time. The finite difference method is reliable, simple to program and widely used. USGS has developed three-dimensional finite-

difference groundwater flow model- (MODFLOW) in FORTRAN and widely followed. Many academic institutions and private companies have developed various front end modules to make the application of program easy and quickly adopted. “VISUAL MODFLOW” is one such software which is easy to understand and operate. It is widely used along with MODFLOW of USGS.

5.2 Surface and Groundwater

Wadi Fuwwah begins at the high limestone plateau of the Jol at an altitude of 1,800 meters. It runs from northwest to southeast and flows into the sea. It is about 50 kilometers long. In Wadi Fuwwah the maximum rainfall of Fuwwah-Mukalla-Ash Shihr region is 350 millimeters per year occurs on the high limestone plateau of Jol. Precipitation is concentrated over the upper western and north-western parts of the Wadi Khirba-Fuwwah catchments area. This precipitation provides the wadi with about five floods per year, of which three are large with a discharge more than 50 cubic meters per second.

These floods are brief. Their duration is estimated at three to six hours. A large volume of water is lost to the sea. The basin's average annual inflow is 220 liters per second. Part of the water infiltrates into the alluvial deposits of the central plain at Khirba and in the coastal plain. It is estimated that 110 liters per second are lost to the sea during heavy floods.

Flood water infiltrating upstream of Khirba, accumulates in the alluvial deposits of the central plain. Upstream of the plain the alluvium is totally dry, water being found at a depth of 20 meters within the Eocene gypsum and marl. Downstream water comes progressively nearer the surface and is found within the alluvial deposits and at Khirba. It actually appears in the wadi bed where it is used to irrigate palm groves.

In the gorge, due to the non-existence of alluvium, all the groundwater appears at the surface where there is a permanent flow. An extensive canal system diverts this water to palm groves in the upper part of the coastal plain where it is used for irrigation purposes. In November 1979 the permanent flow discharge was 70 liters per second. In the coastal plain the water once again infiltrates into the alluvial aquifer.

In the high limestone plateau area, the annual rainfall in Wadi Buwaish reaches 300 to 350 millimeters. The runoff from floods over the catchments area of th Qadis Rima and Shururah provides a total annual volume of 4.9 cubic millimeters that is an average continuous discharge of 155 liters per second.

The wadis experience an average ten floods per year of which four flow more than 50 cubic meters per second. These floods have a brief duration period. The flood water is not totally infiltrated in the alluvium and about 95 liters per second is lost to the sea.

Water from the Cretaceous sandstone aquifer supplies springs which are tapped in the Shururah oasis on the Wadi Shururah and in the Al Ghuyayah Zamam, Saghir, and Zamam Al Kabir oases on the Wadi Himam.

All the groundwater accumulated in the upper part of the catchment area flows at the surface over the Al Hutah sill where the discharge is 85 liters per second.

Water balance for the Wadi Khirba-Fuwwah can be summarized as follows:

Groundwater recharge to the Alluvium Aquifer	=	60 l/s
Agricultural Domestic and industrial uses	=	180.7 l/s
Deficits	=	120 l/s

Water balance for the Wadi Buwaish can be summarized as follows:

Groundwater recharge to the Alluvium Aquifer	=	92 l/s
Agricultural Domestic and industrial uses	=	346.0 l/s
Deficits	=	254 l/s

5.3 Model Set Up

The modeled areas are the recent alluvial formation that present at the downstream of Wadi Buwaish and Wadi Fuwwah in Al-Mukalla, Hatharamout governorate as shown in Figure 34. This formation is considered as the main aquifer in that area and represents the wadi bed. Its thickness in Buwaish is about 100 meters. while in Fuwwah is about 50 to 75 meters. Bu the year 1960 the groundwater levels used to be at the surface as springs and streams in the wadi. The first drinking water project for Al-Mokalla city had been implemented in 1965 by the British and some wells were drilled in the area and started to pump water to the Al-Mukalla city with the capacity of 40 liters per second. The pumping rate has been increased up to 100 liters per second in the 1980s.

The numerical groundwater flow models were developed using Processing Modflow Pro and ArcGIS as the pre- and post-processors. Processing Modflow is a modified version of United States Geological Survey (USGS) code Modflow. It is a modular, three-dimensional groundwater flow model that uses a block-centered, finite difference technique to simulate both the horizontal and vertical flow of groundwater in a multi-layered system, for steady-state and transient conditions. The model allows abstraction, recharge and interaction between surface and groundwater to be simulated. Processing Modflow Pro also allows transport of contamination to be modeled.

Two groundwater flow models have been developed for Wadi Fuwwah well field at Khirbah, and for Wadi Buwaish well field at Buwaish. The groundwater flow models produced for this project have been calibrated in steady-state conditions by matching the static water table with the modeled water level. These models have been calibrated in transient flow by matching the measured drawdown with the modeled drawdown.

The required data that were collected from the Al-Mukalla water boards and from well inventory are presented in Table 11.

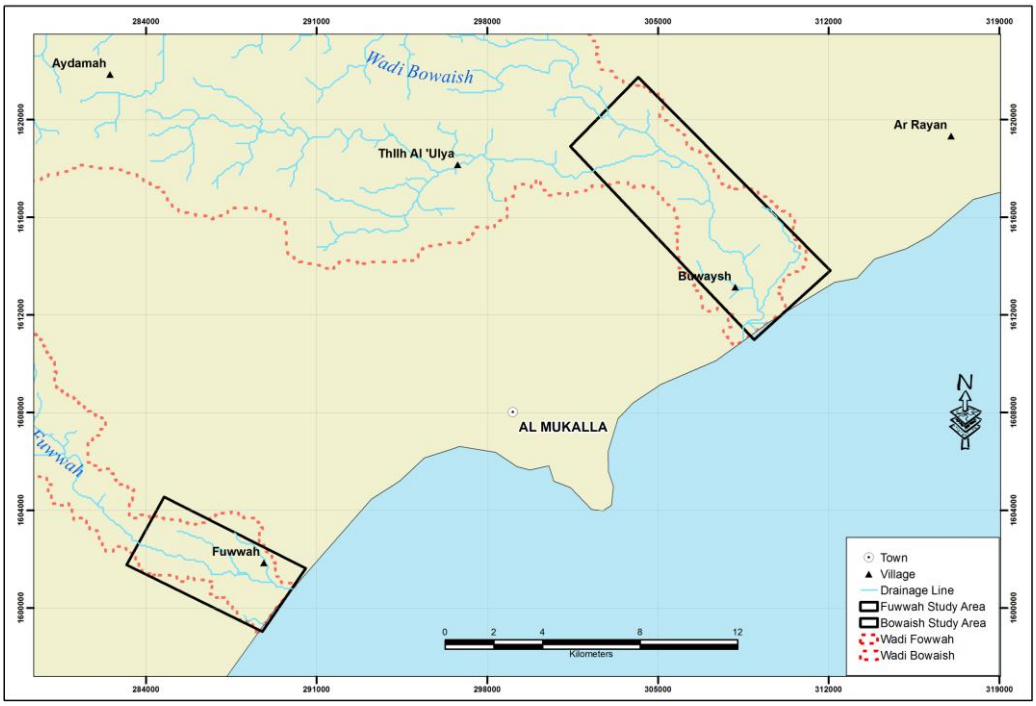
Table 11: Well and Aquifer Data of the Modeled Areas

Model area	Number of Wells	Type of Aquifer	Transmissibility
Fuwwah	58	Alluvium	~ 2.3 *10-^4 m^2/s
Buwaish	63	Alluvium	~ 3 *10-^2 m^2/s

The two models represent one layer within the modeled area. This is a two-dimensional groundwater flow model simulating the horizontal flow within Alluvial formation that presents in the D/S stream in Wadis Fuwwah and Buwaish east Al-Mukalla as shown in Figure 35. This formation has been considered as the main aquifer in the modeled areas which represented with the wadi bed. The top of the layer is the ground surface of the modeled area. The thickness of the layer is about zero in the north to around 75 meters in Fuwwah while in Buwaish it represented by wadi bed which reach up to 100 meters. The groundwater surface used to be at the surface in 1965 for Buwaish and 1978 in Fuwwah as springs for both wadis. Both sides of wadi catchments were taken as dry in the modeled areas.

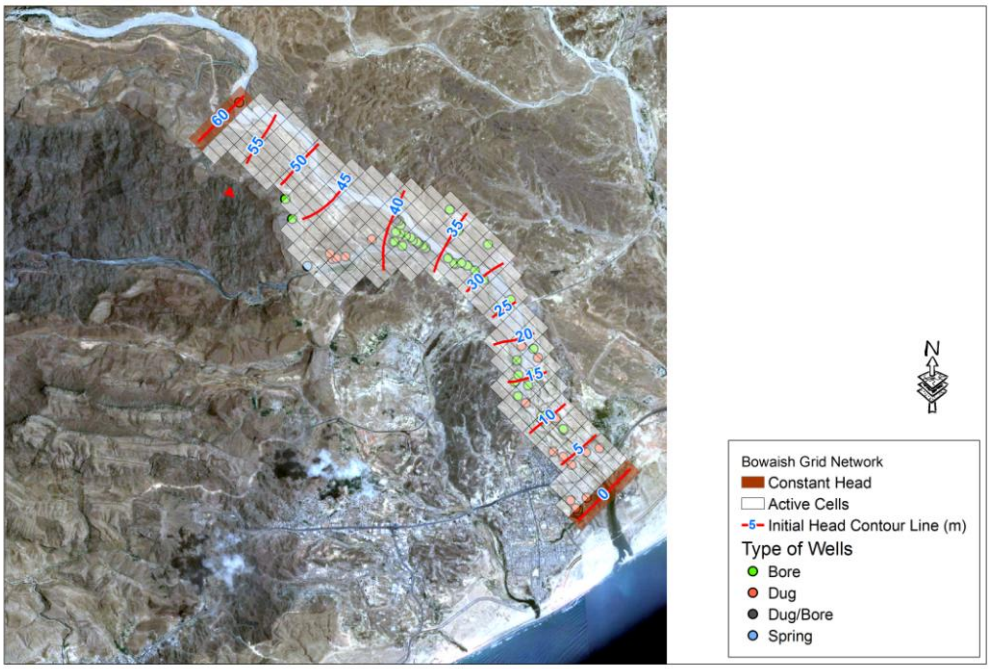
The first drinking water project for Mukalla city has been done in 1965 by the British and some wells were drilled in the area to pump water to Al-Mukallah city. The pumping rate has been increased to 100 liters per second in the 1980s.

Figure 35: Map Showing the Locations of the Modeled Areas



Study Areas Map

Figure 36: Steady State Initial Head with Wells for Wadi Buwaish



Wadi Bowaish Initial Head for Steady State Simulation

Figure 37: Steady State Initial Head with Wells for Wadi Fuwwah

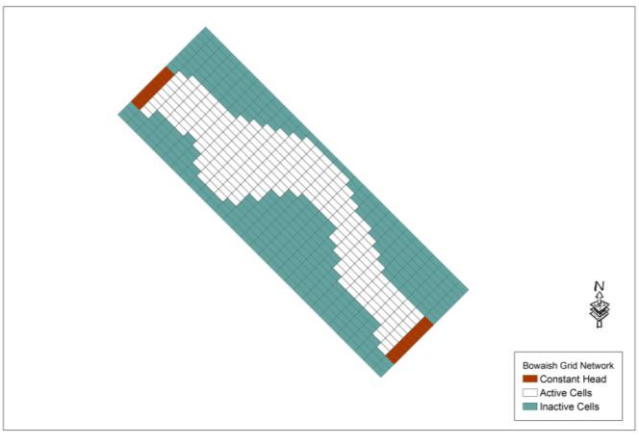
Wadi Fuwwah Initial Head for Steady State Simulation

The model grid for the both wadis and the grid spacing vary for each model area and are shown in Table 12 and Figures 38.

Table 12: Model Grid for the Modeled Areas

Model	Number of rows	Number of columns	Cell area (m²)	Total area (km²)
Wadi Fuwwah	6	11	200x400(80000)	5.52
Wadi Buwaish	20	30	200x400(80000)	48

Figure 38: Wadi Buwaish Model Grid



Bowaish Grid Network Map in Steady State Simulation

The hydraulic parameters of the alluvial aquifer are based on the pumping test analysis and outputs of the groundwater model. Initial hydraulic parameters were entered into the model and have then been modified during the calibration of the steady-state and transient conditions. These parameters are presented in Table 13.

Table 13: The Hydraulic Parameters of the Alluvial Aquifer

Wadi	Hydrogeological unit	Hydraulic conductivity (m/day)	Effective porosity	Specific yield
Fuwwah	Alluvial	1 - 0.5	17	18.1
Bouwish	Alluvial	2.5- 0.8	12	23.4

The rainfall over the modeled areas is significantly low; most of it evaporates and the rest runs off to the sea. In addition, there are minor agricultural activities in these wadis. The recharge to the wadi deposit from the wadi inflow in Wadis Fuwwah and Buwaish are estimated to be 60 millimeters and 92 millimeters respectively. The recharge from rainfall on the modeled area assumed to be ten millimeters per year.

The abstractions of each wadi have been recorded and added to the models in cubic meters per day, the records of annual abstraction as indicated in the well inventory carried out for Wadi Fuwwah and Wadi Buwaish in 2009 are 15,616 cubic meters per day and 29,917 cubic meters per day, respectively.

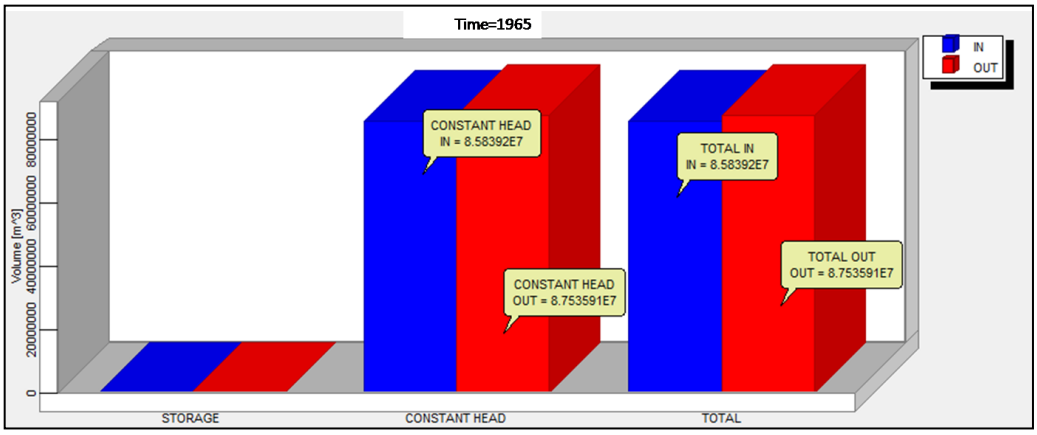
5.4 Groundwater Flow Models

The steady-state simulation was run for the two models of Wadi Buwaish and Wadi Fuwwah before the abstraction started and the groundwater used to be at the ground surface as springs.

The Wadi Buwaish first wells were drilled by British in 1966 and started operating in 1967. The year 1965 was chosen to run the steady-state model using the same initial hydraulic conductivity of eight meters per day. The results of the steady state simulation are as follows:

- The initial head of water elevation is shown in the Figure 37, which represents the groundwater to be at the surface as streams and springs;
- The total inflow from the selected constants heads in the northern part of downstream area almost equal the outflow from the southern part to the sea as shown in Figure 39 and Table 13; and
- Water levels of steady state were used to run the transient simulation.

Figure 39: Total Inflow from the Selected Constants Heads in Wadi Buwaish



The wells in Wadi Fuwwah were drilled in 1977 and started operating in 1978. The year 1978 was chosen to run the steady-state model, which represent the groundwater to be in the surface as streams and springs.

The results of the steady state simulation are as follows:

- The initial head of water elevation is shown in the Figure 39 where the groundwater levels used at the surface; and

- The total inflow from the selected constants heads in the northern part of downstream area is almost equal to the outflow to the sea as shown in the Figure 40 and Table 14.

Figure 40: Total Inflow from the Selected Heads in Wadi Fuwwah

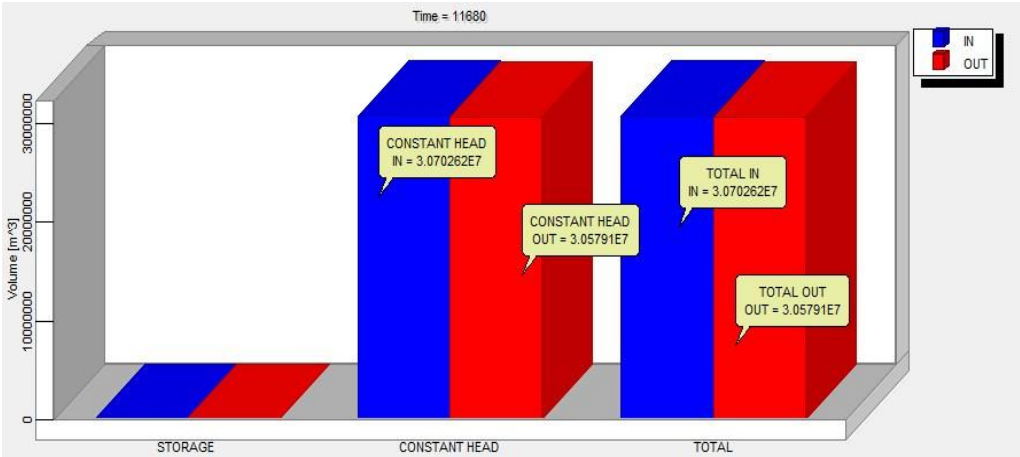


Table 14: Steady-State Water Balance

Model	In-flow Mm^3/year	Out-flow Mm^3/year	Discrepancy (%)
Wadi Buwaish	~ 8. 6	~ 8.7	-1.96
Wadi Fuwwah	~ 3.1	~ 3.1	0.4

In the transient state simulation, the initial heads used are taken from steady state simulation. Also, the constant heads in the Northern part of study area have been replaced by General Head boundary because this kind of boundaries will be affected by the activity that happens in the modeled area. The area starts to be affected by the 37 selected pumping wells. Among these seven wells have been selected as observation wells for calibration. Also the recharge value has been calculated for the study areas ten percent of the main inflow plus ten percent of total rainfall infiltrated in to the alluvial aquifer in both wadis.

Both Pumping rates and recharge value are added to the transient model. The abstraction of the Wadi Buwaish well field has been added to the transient model for two simulated pumping period as follows:

- 1965 to 1984 with the rate of five million cubic meters per year; and
- 1984 to 2010 with the rate of 15 million cubic meters per year.

The results of the first and second periods 1984 and 2010 of calibration of observed and calculated heads, for Wadi Buwaish are shown in the Figure 41 while the calibration of observed and calculated head of Fuwwah area are shown in Figure 42.

In Figures 41 to 46, time is represented from zero days (1965) to 6,570 days (1984) and 16,425 days (2010). Figure 43 shows the calculated and observed head values for the years 1984 and 2010, while Figure 44 shows the calculated and observed drawdown values for the years 1984 and 2010. Figures 45 and 46 show the water balance as inflow-outflow values for both areas.

Figure 41: Calculated vs. Observed Head (1984)

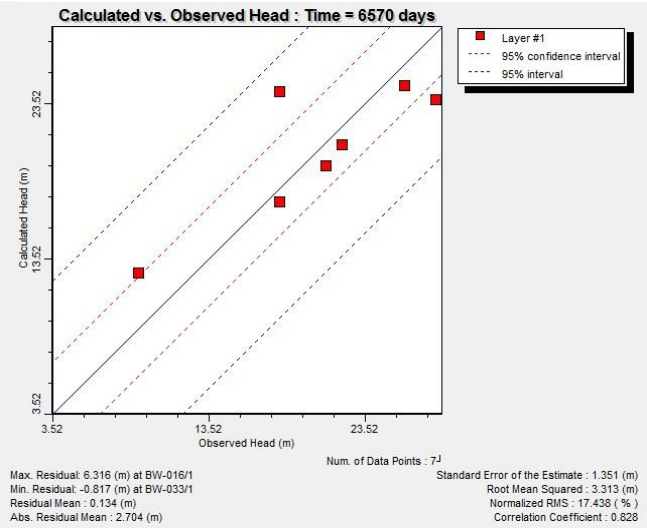


Figure 42: Calculated vs. Observed Head (2010)

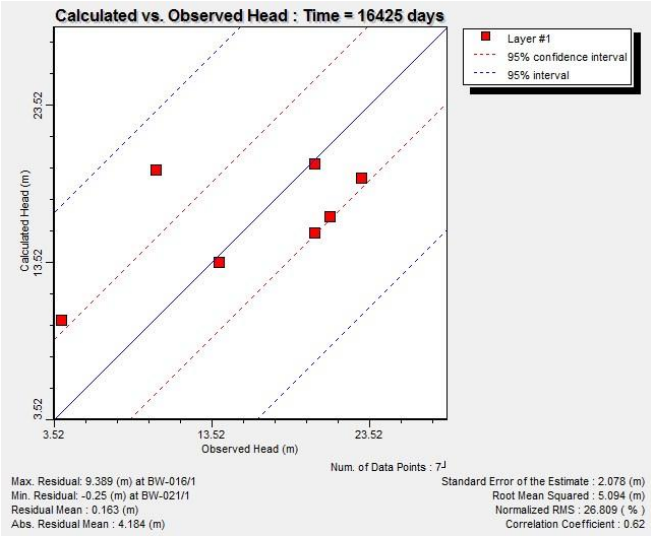


Figure 43: Head vs. Time (1984 – 2010)

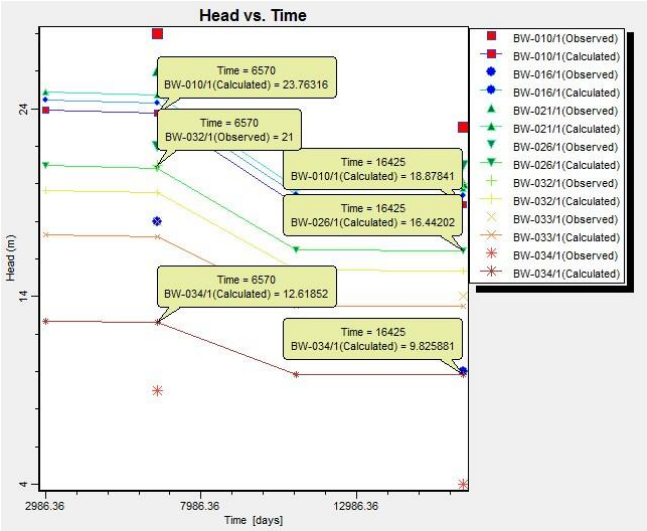


Figure 44: Drawdown vs. Time (1984 – 2010)

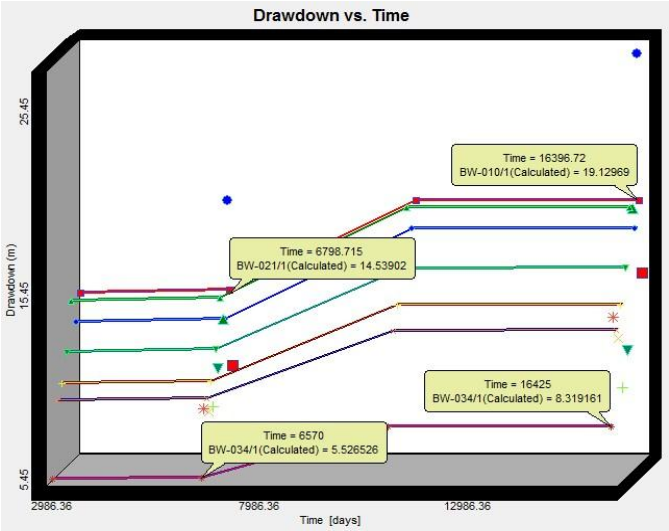


Figure 45: Inflow and Outflow for the Period 1984

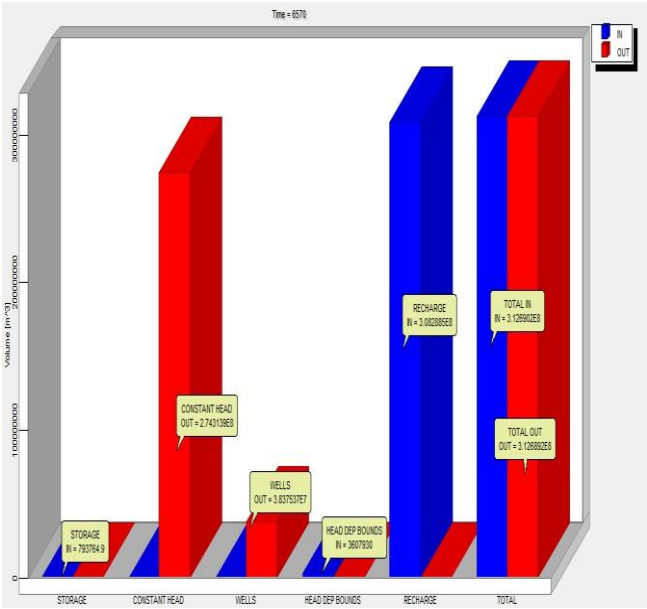
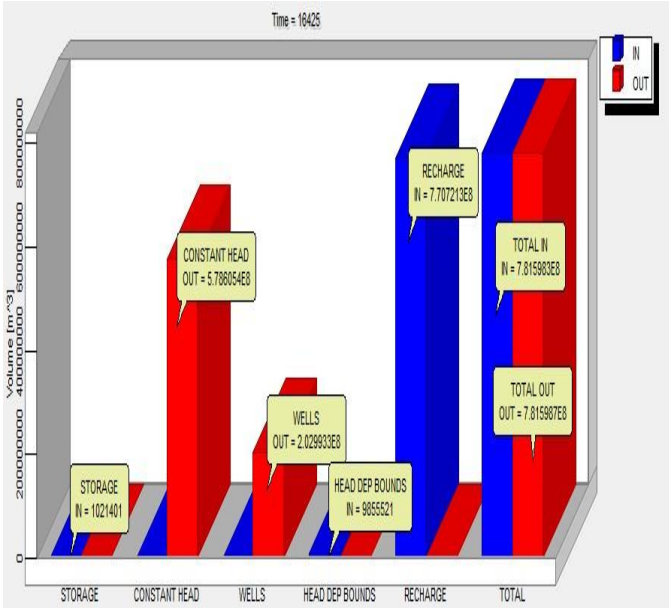


Figure 46: Inflow and Outflow for the Period 2010



The abstraction of the Wadi Fuwwah well field from 15 pumping wells has been added to the transient model. Eleven of these used as observation wells for only one simulated pumping period 1978 to 2010, due to lack of data for the period in between. The results of calculated and observed heads, drawdown and water balance for Wadi Fuwwah are shown in the Figures 47 to 52. In these figures the time is represented from zero days (1978) to 11,680 days (2010). Figure 47 shows the calculated and observed head values for the years 1978 and 2010, while Figure 48 shows the calculated and observed drawdown values for the years 1978 and 2010.

The sea water intrusion has been observed in the area in 2010 due to highly pumping rate of 2,445 cubic meters per day, while the maximum drawdown has been observed in the center of the area where the abstraction wells are located as show in the Figure 49 and 50, respectively. As shown in Figures 51 and 52 the water balance is covered by the inflow from the constant head located in saline water, which causes seawater intrusion and polluted the aquifer.

Figure 47: Calculated vs. Observation (2010)

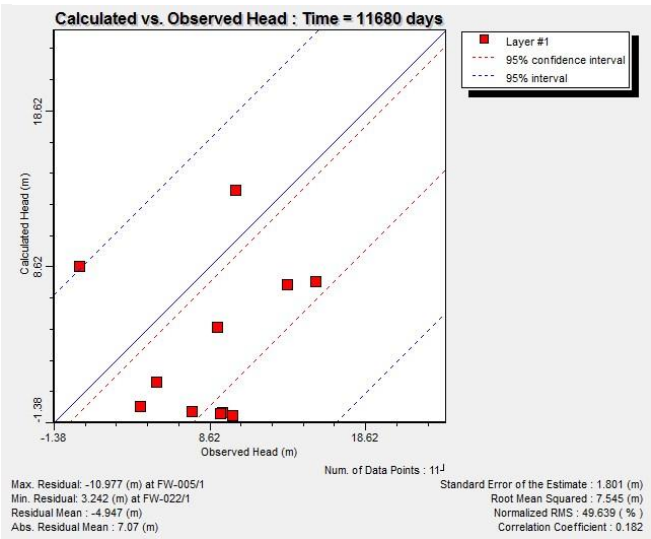


Figure 48: Head vs. Time (1978 – 2010)

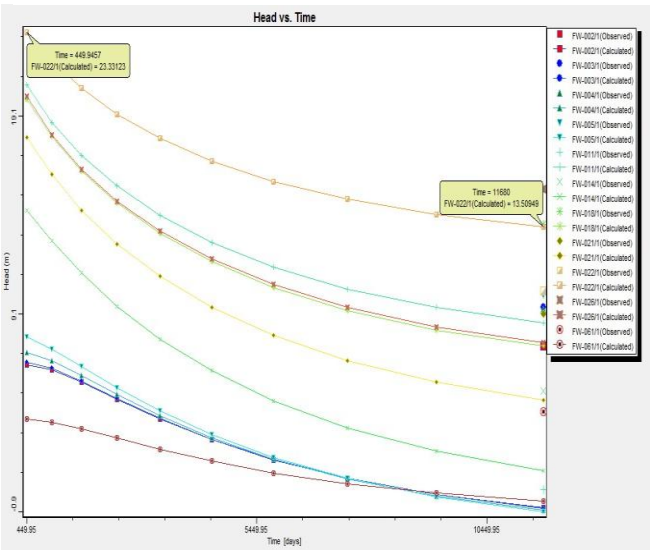


Figure 49: Drawdown vs. Time (1978 – 2010)

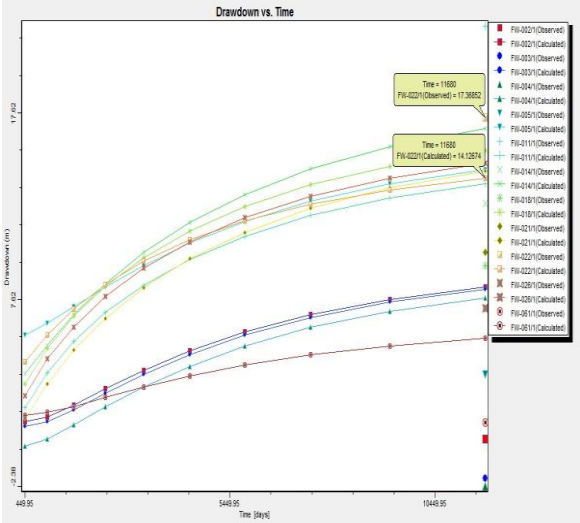


Figure 50: Head Contour Lines (2010)

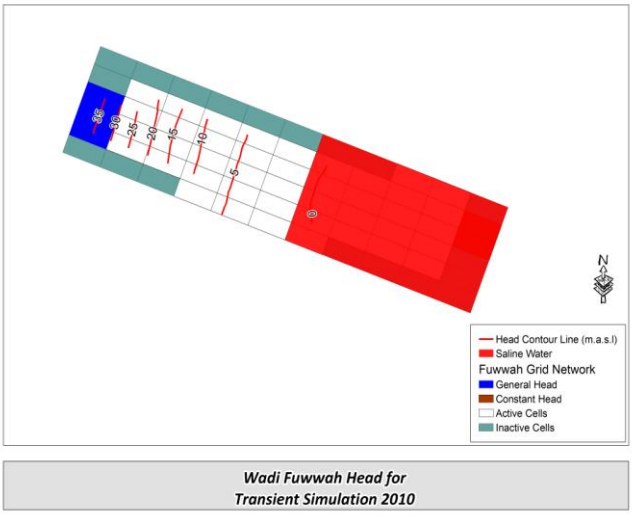


Figure 51: Drawdown Zones (2010)

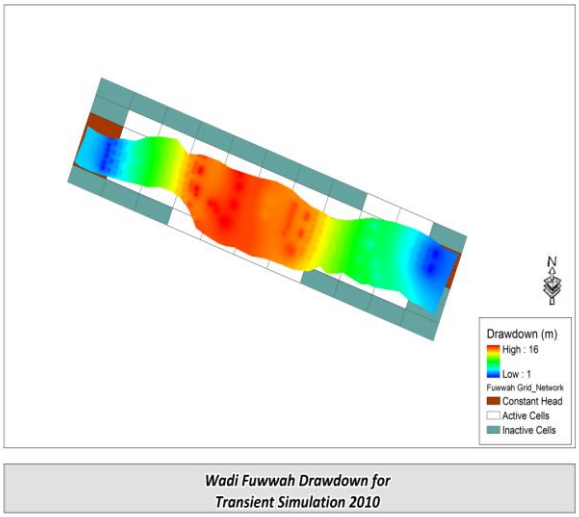
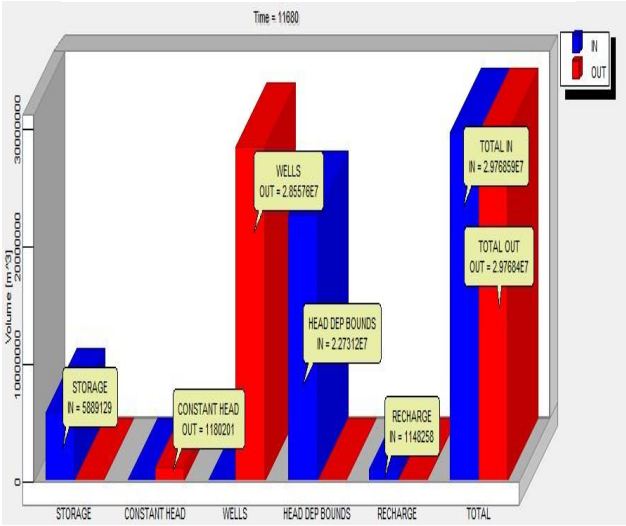


Figure 52: Inflow and Outflow (2010)



5.5 Scenarios

Scenarios have been simulated only for modeled area of Wadi Buwaish, while could not have been applied for Wadi Fuwwah due to the 2010 simulation results which indicated that the sea water encroachment the aquifer.

For the study area of downstream of Wadi Buwaish, the first scenario was for the next 20 years. It was undertaken according to the demand abstractions under normal condition. The second scenario is for the next 20 years according to the demand abstractions under extreme condition.

The simulated actual and future abstractions for both Wadi Buwaish and Wadi Fuwwah are shown in Figures 53 through 58.

The calculated and observed heads are shown in Figures 53 and 54. It can be noticed, for instance, that well observation number BW-010, where head has been reduced from 30.67

meters in year 1983 to -15.7 meters in year 2030. The observed drawdown are shown in Figure 55 and 56 where it can be noticed that well number BW-010, where drawdown has been reduced from 30.67 meters in year 1983 to -22.5 meters in 2030.

The water balance scenarios of the year 2030 are presented in Figure 57 and 58. The first scenario shows about 70 cubic millimeters for the whole period enters from the constant head boundary as sea water, while the second scenario has been stopped at 2022 because the pumping wells get dry.

Figure 53: Simulated Head vs. Time (Scenario One), Wadi Buwaish

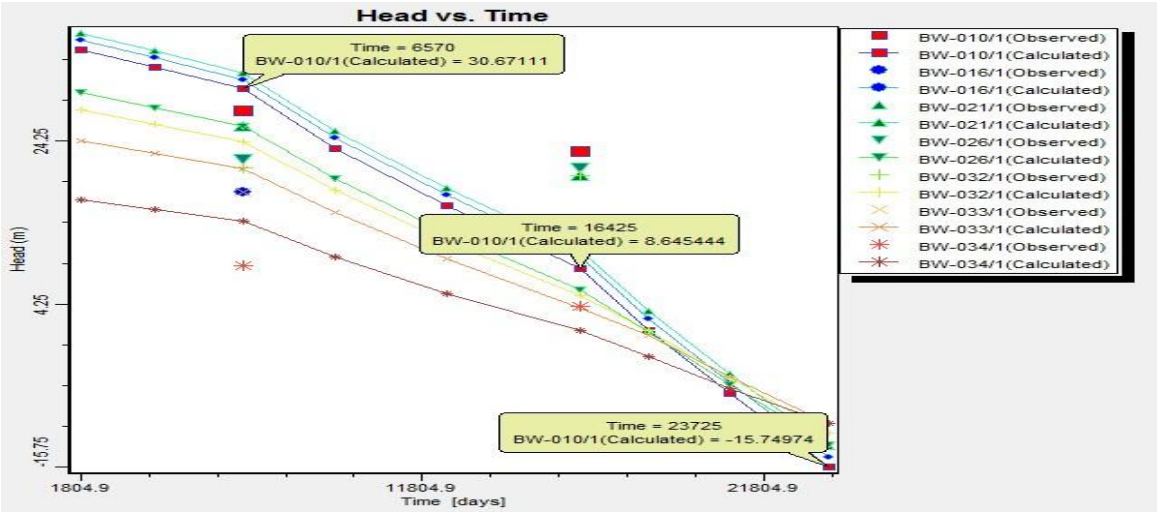


Figure 54: Simulated Head vs. Time (Scenario Two), Wadi Buwaish

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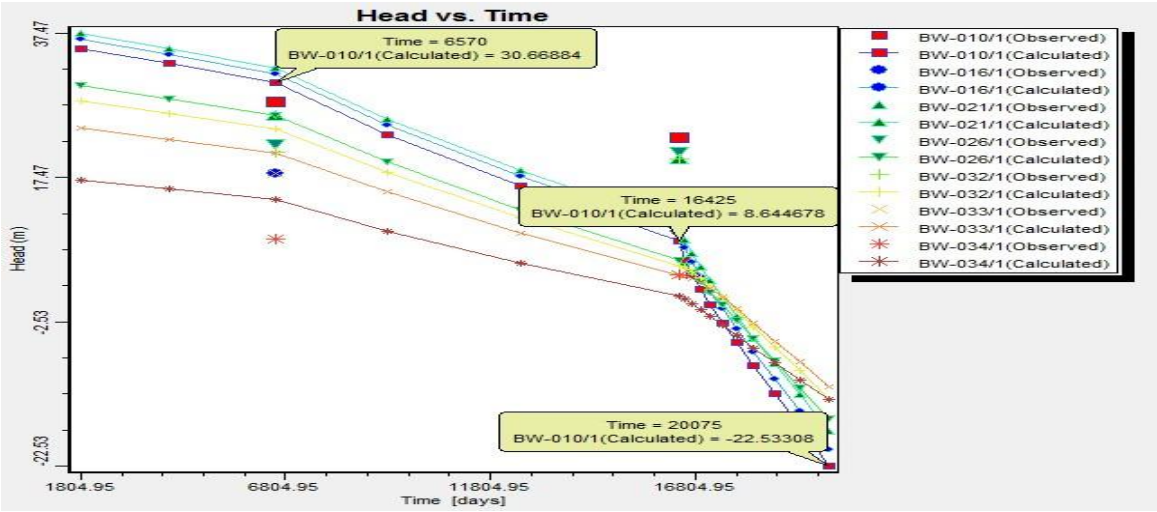


Figure 55: Drawdown vs. Time (Scenario One), Wadi Buwaish

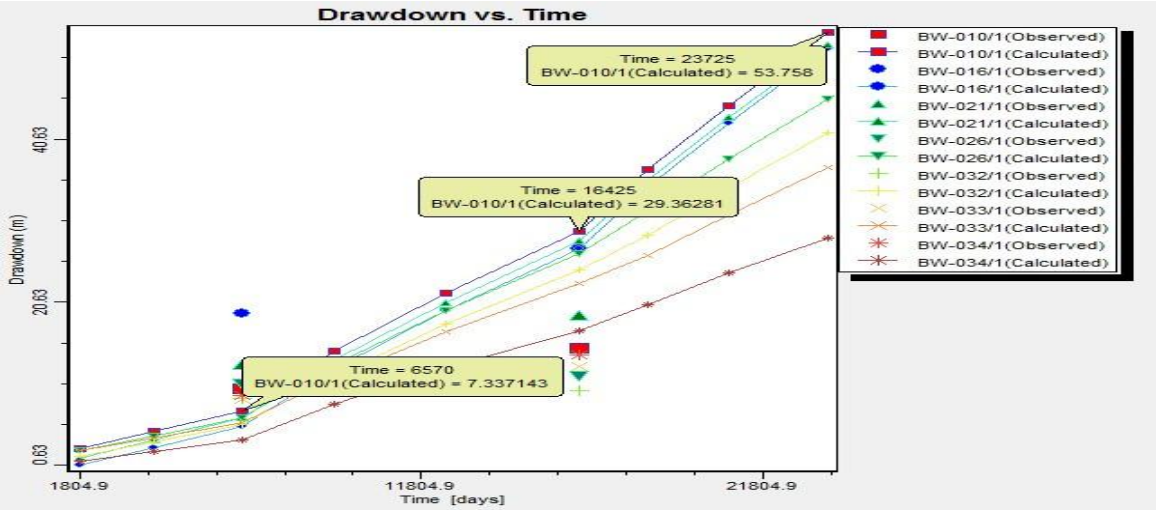


Figure 56: Drawdown vs. Time (Scenario Two), Wadi Buwaish

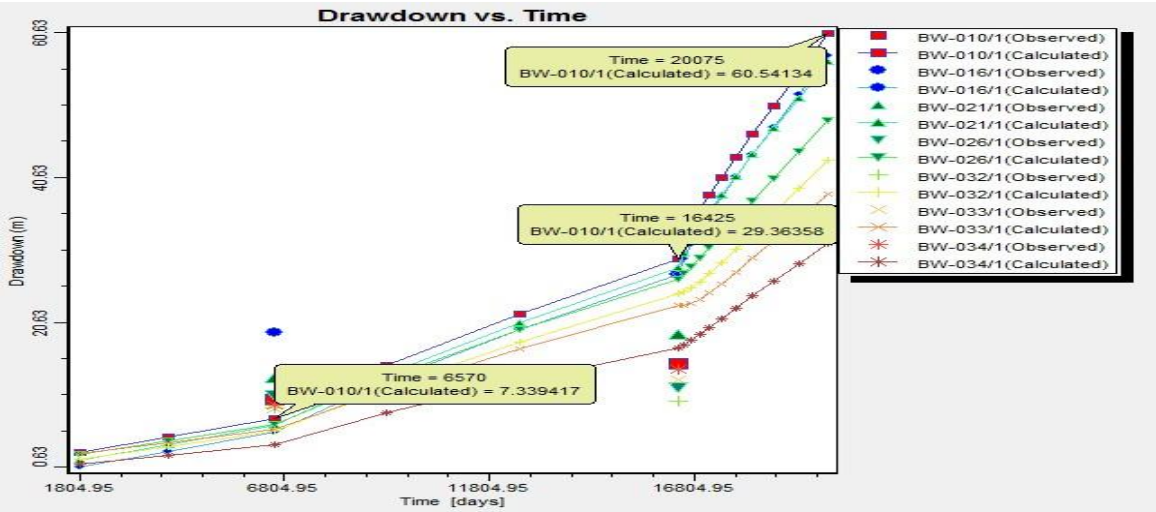


Figure 57: Simulated Water Balance (Scenario One), Wadi Buwaish

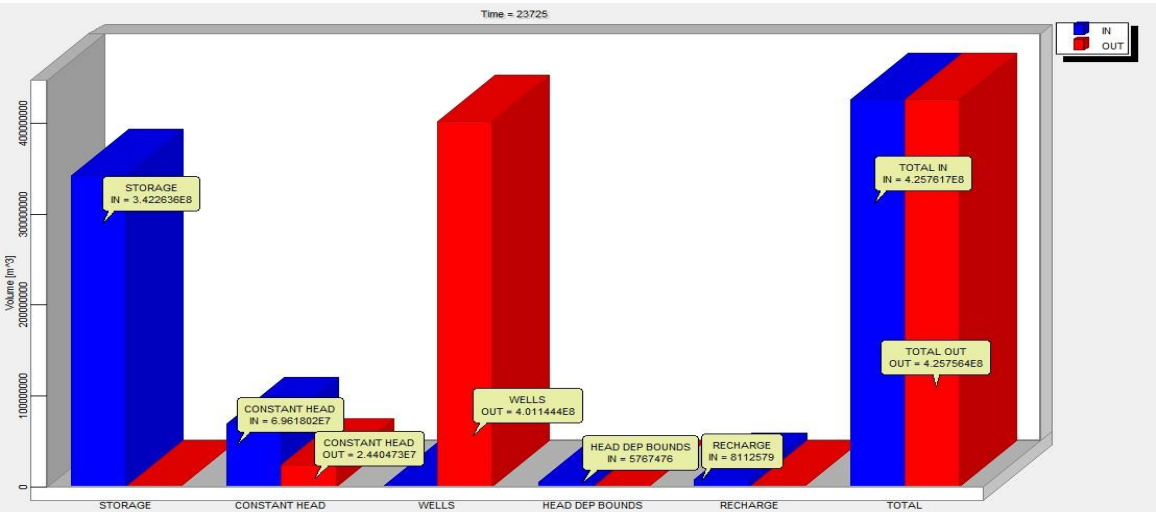
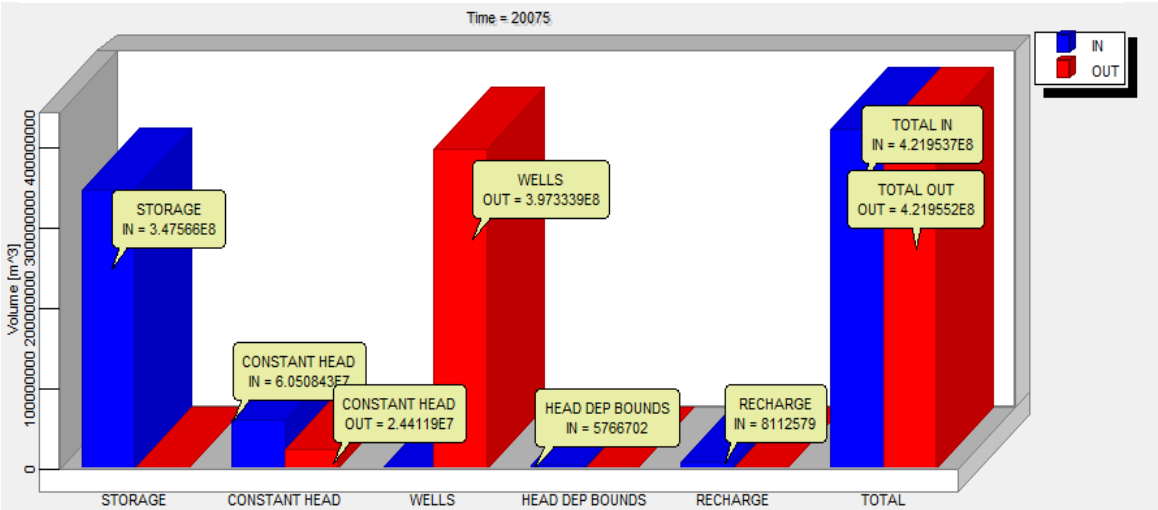


Figure 58: Simulated Water Balance (Scenario Two), Wadi Buwaish



5.6 Conclusions and Recommendations

Both Buwaish and Fuwwah aquifers are extremely important for Al Mukala city. They are the main water suppliers for major requirements such as domestic and irrigation in that area. Those aquifers are unconfined and consist of Quaternary alluvial. The surface and subsurface hydrogeological data are very rare and sparse. Steady and transient state models are simulated for the area to be used as reference now and in the future. The data collected are used to simulate and construct a steady and transient state three dimensional finite difference groundwater flow model.

Different simulations were run involving changing the some variable values until the best match of the inflow outflow and water level values in the study area was obtained. The steady state condition was used to determine the values of inflow, outflow, and initial heads in that time. The transient state model was run by using general head boundaries in the inflow part north of study areas. Many pumping wells distributed out of study areas. In Wadi Buwaish the pumping periods used in the model are grouped into two periods were 5,841 cubic meters per day from 1965 to 1983 and 16,704 cubic meters per day from 1983 to the present.

Table 15 indicates that the values of drawdown in observation wells from 1983 to 2010 and both scenarios.

Table 15: Wadi Buwaish Drawdown Values

ID	1983		2010		Scenario (1)		Scenario (2)	
	OBSERVED	CALCULATED	OBSERVED	CALCULATED	OBSERVED	CALCULATED	OBSERVED	CALCULATED
BW-010	10.01	7.34	15.01	28.93	none	53.76	none	60.54
BW-016	19.21	5.42	27.21	26.79	none	51.71	none	57.48
BW-021	12.99	6.43	18.99	27.69	none	52.17	none	56.67
BW-026	10.58	6.49	11.58	26.20	none	45.61	none	48.53
BW-032	8.80	5.61	9.80	24.16	none	41.40	none	43.03
BW-033	8.74	5.89	12.74	22.57	none	37.17	none	38.28
BW-034	9.15	3.72	14.15	16.82	none	28.51	none	31.48

Volumetric budget for entire model for different simulations (Buwaish and Fuwwah) is shown in the Tables 16 and 17. The most important values that we should concentrate on are those of constant head in the inflow part as well as those of pumping from wells. In scenarios one and two for Wadi Buwaish about 69.6 and 60.1 million cubic meter of saline water enter from the sea as sea water intrusion while in Wadi Fuwwah it is about 2.12 million cubic meters. However, the pumping rates from wells in Wadi Buwaish for the same scenarios are very high while the value in the table below is cumulative value for the whole period. The value of pumping rate of Wadi Fuwwah area is about 2,445 cubic meters per day.

Therefore, it is very important to keep the pumping rate in the safe side not exceed 16,500 cubic meters per day in Buwaish and 1,500 cubic meters per day in Wadi Fuwwah to control the sea water intrusion.

Table 16: Volumetric Budget for Entire Model for Different Simulations (Buwaish)

	Steady State 1965 (Mm^3)	1965-1983 (Mm^3)	1983-2010 (Mm^3)	Scenario (1) (Mm^3)	Scenario (2) (Mm^3)
Inflow					
Constant Head	85.8			69.6	60.1
General Head		3.6	9.8	5.8	5.8
Recharge		308	770.7	8.1	8.1
Total	85.8	312	781	425.8	422
Outflow					
Constant Head	87.5	274	578.6	24.4	24.4
General Head					
Wells		38	203	401.1	397.3
Total	87.5	312	781.1	425.8	422

Table 17: Volumetric Budget for Entire Model for Different Simulations

Inflow		
Constant Head	30.7	1.14
General Head		**22.1**
Storage		**7.5**
Total	**30.7**	**30.8**
Outflow		
Constant Head	**30.7**	**2.12**
Wells		**28.6**
Storage		
Total	**30.7**	**30.8**

We recommend the following measures be taken to control seawater intrusion and to keep the aquifer in these areas sustainable and incessant:

- Well field should be not less than four kilometers from sea;
- Distance between wells should not be less than 250 meters;
- Modification of pumping pattern by changing the locations of pumping wells;
- Entire pumping rate should not exceed 16,500 cubic meters per day in Wadi Buwaish and 1,500 cubic meters per day in Wadi Fuwwah;
- Never drill bore wells in areas where water table is less than ten meters above sea level except shallow dug wells with very law pumping rate;
- Observation wells should be drilled in the southern part of the area where the water head elevation is less than seven meters above sea level;
- Entire drawdown in the southern areas should not reach four meters above sea level in Wadi Buwaish and two meters in Wadi Fuwwah. Both areas should be protected from any activities cause pollution such as sewage or fertilizers; and
- Increase the groundwater recharge by constructing diversion barriers or any water harvesting method in the downstream and never build dams in the upper stream areas.