No.

NATIONAL WATER RESOURCES AUTHORITY (NWRA)
MINISTRY OF WATER AND ENVIRONMENT (MWE)
THE REPUBLIC OF YEMEN

THE STUDY FOR THE WATER RESOURCES MANAGEMENT AND RURAL WATER SUPPLY IMPROVEMENT IN THE REPUBLIC OF YEMEN WATER RESOURCES MANAGEMENT ACTION PLAN FOR SANA'A BASIN

Final Report

SUPPORTING REPORT

November 2007

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

EARTH SYSTEM SCIENCE CO., LTD.
in association with
JAPAN TECHNO CO., LTD.

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TABLE OF CONTENTS (SUPPORTING REPORT)

CHAPTER 4 PRESENT CONDITION OF SOCIO-ECONOMY

CHAPTER 5 PRESENT CONDITION OF WATER USE

CHAPTER 6 CURRENT INSTITUTIONAL AND ADMINISTRATIVE FRAMEWORK

CHAPTER 7 CURRENT ORGANIZATIONAL STRUCTURE

CHAPTER 8 ENVIRONMENTAL AND SOCIAL CONCIDERATIONS

APPENDICES

LIST OF TABLES (SUPPORTING REPORT)

CHAPTER 2 WATER RESOURCES MANAGEMENT PLAN FOR FOR OTHER CRITICAL BASINS

CHAPTER 3 PRESENT STATE OF WATER RESOURCES

CHAPTER 4 PRESENT CONDITION OF SOCIO-ECONOMY

CHAPTER 5 PRESENT CONDITION OF WATER USE

CHAPTER 6 CURRENT INSTITUTIONAL AND ADMINISTRATIVE FRAMEWORK

CHAPTER 8 ENVIRONMENTAL AND SOCIAL CONCIDERATIONS

LIST OF FIGURES (MAIN REPORT)

CHAPTER 3 PRESENT STATE OF WATER RESOURCES

CHAPTER 4 PRESENT CONDITION OF SOCIO-ECONOMY

CHAPTER 5 PRESENT CONDITION OF WATER USE

CHAPTER 8 ENVIRONMENTAL AND SOCIAL CONCIDERATIONS

ABBREVIATIONS

ACU	Agricultural Cooperative Union
CSO	Central Statistical Organization
DPPR	The Third Socio-Economic Development Plan for Poverty Reduction
EC	Electrical Conductivity
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
EPC	Environment Protection Council
ESIP	Environmental and Sustainable Development Investment Program 2003-2008
ETa	Actual Evapotranspiration
GAREW	General Authority for Rural Electricity and Water
GARWSP	General Authority for Rural Water Supply Projects
GDI	General Directorate of Irrigation
GDP	Gross Domestic Product
GVP	Gross Value Product
HDL	Highest Desirable Limit
HGR	Historical Growth Rate
HWC	High Water Council
IRDA	Integrated Rural Development Authority
IWRM	Integrated Water Resource Management
MAF	Ministry of Agriculture and Fisheries
MAI	Ministry of Agriculture and Irrigation
MCM	Million Cubic Meters
MEW	Ministry of Electricity and Water
MPL	Maximum Permissible Limit
MPWH	Ministry of Public Works and Highway
MWE	Ministry of Water and Environment
NEAP	National Environmental Action Plan
NRW	Non-Revenue Water
NWP	National Water Policy
NWRA	National Water Resources Authority
NWRA-SB	National Water Resources Authority -Sana'a Branch
NWS	National Water Strategy
NWSA	National Water and Sanitation Authority
NWSSIP	National Water Sector Strategy and Investment Program
PGR	Programmed Growth Rate
PIUs	Project Implementation Units
PMUs	Project Management Units
PRS	Poverty Reduction Strategy
SAWAS	Sources for Sana'a Water Supply
SBC	Sana'a Basin Commission
SBWMP	Sana'a Basin Water Management Project
SBWRM-PPT	Sana'a Basin Water Resources Management Study
SEA	Strategic Environmental Assessment
SEAR	Sectoral Environmental Assessment Report
SFYP	The Second Five-Year Plan
SWSLC	Sana'a Water Supply and Sanitation Local Corporation
SWSSP	Sana'a Water Supply and Sanitation Project
TDS	Total Dissolved Solid
TWSLC	Ta'iz Water Supply Local Corporation
WEC	Sana'a University Water and Environment Centre

WHO	World Health Organization
WUA	Water User Association
WUF	Water User Federation
WUG	Water User Group
WWTP	Sana’a Wastewater Treatment Plant
YGGMP	Yemeni-German Geological Mapping Project
YSV	Yemen’s Strategic Vision 2025

CHAPTER 1

NATIONAL POLYCY AND SRATEGY FOR WATER

CHAPTER 1 NATIONAL POLICY AND STRATEGY FOR WATER

1.1 NATIONAL WATER STRATEGY

Responding to the serious dimensions of the water crisis, Yemeni government has adopted National Water Strategy (NWS). The objectives of NWS are as follows;

- Protection of water resources from depletion and pollution.
- Optimal utilization of water resources to achieve the highest value for water.
- Provision of water to meet the demands of society for all purposes.

To fulfill the above objectives, NWS follows the following principles; 1) all surface and groundwater resources within the boundaries of the Republic of Yemen are considered natural resources owned as public property, 2) the State shall design the framework of legislation and regulations pertaining to water resources. 3) each citizen has the right of access to water to meet the basic demand of his household, 4) the water sector shall occupy the first rank among economic and social development sectors. Water security is ranked second to national security, 5) existing water rights shall be respected, and 6) NWS defines itself as a basis for other related strategies and policies, National Water Policy (NWP), National Water Sector Strategy and Investment Program (NWSSIP) and Water Law have been established accordance with the ethos of NWS.

1.2 NATIONAL WATER POLICY

To achieve the objectives of National Water Strategy, National Water Policy (NWP) was established. NWP provides that water policies, such as water resources policy, watershed management policy, irrigation policy, domestic water supply policy, and wastewater reuse policy should be formulated and implemented by water sector agencies. NWP prescribes the roles for water sector agencies, such as National Water Resources Authority (NWRA) and Ministry of Agriculture and Irrigation (MAI). This Policy is basis of Water Law.

1.3 WATER LAW

The Water Law is first enabling legislation and institutional back-up for the country's water resource management. After more than 10 years discussion and negotiation among various institutions and authorities, parliament approved the Water Law in 2002. In addition, for further legal and regulatory development a number of other official regulations such as Republican/Cabinet Decree, Prime Minister Resolutions, and Ministry of Water and Environment (MWE)'s Decree have been issued to support and enforce the Water Law of 2002. For example, the Prime Minister Resolution No.227, which issued on 2004 nominates NWRA as the only authority responsible for water well licensing and set down that other institutions should receive a written authorization from NWRA for any licensing and registration activities, or terminate issue of licenses (Article 11a). It is upholding and supporting statements of Article (73) of the Water Law.

However, the Water Law fails to define itself as the sole legal means to manage water resources and water rights rather than other significant laws, such as Islamic Law, Civil Code, and Customary Law in the country, it does not provide legal mechanism to resolve the disputes over resource management and water rights and enforce punishment to the violator according to the LAW.

Therefore, in 2007, the parliament approved the amendment of the Water Law No. (33) of 2002 to attempt to adjust the shortcoming above, however the Water Law still does not have enough effectiveness to regulate water consumptions.

1.4 NATIONAL WATER SECTOR STRATEGY AND INVESTMENT PROGRAM

In accordance with National Water Strategy and National Water Policy, National Water Sector Strategy and Investment Program (NWSSIP) is initiated to prepare a consolidated strategy, action plan and investment program for the whole water sector as a multi-stakeholder process.

If the situation of water scarcity continues as it is without regulation of ground water extraction and use, without reduction of the current unsustainable level of water resources use, and without putting an end to the ongoing resource capture, then this will eventually harm everyone, including farmers, who will be the first victims of water exhaustion. In addition, water regulation is needed to safeguard or the economic and social growth of the cities.

Thus, NWSSIP proposes a set of institutional, financial and other measures, which aim at addressing discrepancies in the five sub-sectors (water resources, urban WSS, rural WSS, irrigation and environmental aspects of water) in order to protect the interests of all stakeholders in the resources.

NWSSIP sets four objectives for sector management.

- To ensure coordination among all partners working in urban and rural water supply and sanitation sub-sectors to ascertain that policies in each two sub-sectors are unified and that investments are equitably allocated among governorates according to unified rules and that no projects are duplicated
- To ascertain integration of water policies and national policies of sustainable growth and poverty reduction
- To ensure that sector financing effectively supports sector goals
- To monitor and evaluate performance

To achieve these objectives, NWSSIP proposes three policies.

- Giving immediate priority to defining and implementing the strategy, investment program and action plan
- To organize the institutional and administrative setup of sector institutions and to ensure that they are properly functioning and managed
- To ensure that cross-cutting issues are being dealt with in an integrated manner (funding, community contribution, tariffs, training, etc)

Regarding to water resources management, NWSSIP set following five objectives.

- To ensure greater degree of sustainability

- Giving priority to domestic needs of rural and urban populations
- Improved water allocation, while mindful of equity, social norms, meeting the domestic needs and maximizing economic benefits
- Creating a realistic and holistic water vision among the general population
- Contributing to poverty alleviation by promoting efficient water use and equity in water allocation.

1.5 DEVELOPMENT PLAN FOR POVERTY REDUCTION

The third Socio-Economic Development Plan for Poverty Reduction (DPPR, 2006-2010) is the second in a series of national plans designed to fulfill Yemen's Strategic Vision 2025 (YSV), which aims to raise the country's international ranking from a 'least developed country' to one of 'medium human development'. The Second Five-Year Plan (SFYP) served as the launch pad for realizing this national vision. It also provided a general framework for the national Poverty Reduction Strategy (PRS) for 2003-2005, as poverty reduction became the central theme for cooperation and partnership with the international community. The SFYP and the PRS included a group of goals and objectives to achieve economic growth, alleviate poverty, and create more job opportunities through diversification and strategic investments in promising sectors while ensuring political and social stability. What follows is a summary of results achieved under SFYP.

Yemen's severely scarce water resources are in increasing domestic, agricultural and industrial demand and suffers from poor management and use practices. Depletion of water resources has become a major constraint to growth and development and a serious threat to the stability and sustainability of Yemeni society. The DPPR's vision is to achieve integrated management of resources, improve the legislative environment, and safeguard access to water as a right. In the present circumstances, agriculture accounts for 91% of total water consumption, while domestic consumers account for 7%, with another 2% used for industry. The DPPR's vision aims to increase the domestic and industrial shares of total water use to 15% and 4% respectively and, to reduce the depletion ratio to 25%, while increasing water resources by 5% a year. The DPPR's vision is to provide safe water and appropriate sanitation services for all regions, and thus to improve the health and environmental human development needs of the country. Yemeni government aims to increase coverage of safe water supplies to about 71% of the urban and 47% of the rural populations. Similarly, sanitation services will be extended to 52% of the urban and 37% of rural residents by the year 2010. Furthermore, water loss in the networks will be cut down to 15%, and waste water treatment will be raised from 50,000m^3 in 2005 to 100,000m^3 by 2010.

CHAPTER 2

WATER RESOURCES MANAGEMENT PLAN FOR OTHER CRITICAL BASINS

CHAPTER 2 WATER RESOURCES MANAGEMENT PLAN FOR OTHER CRITICAL BASINS

2.1 GENERAL

The Republic of Yemen is divided into 14 Water Basins and Zones. Actually, water resources management plan for two of them, namely Ta'iz Region and Sa'dah Basin have the management plan formulated and implemented. Formulation of management plan ongoing is for Sana'a Basin (this study), for Hadhramawt Basin and for Tuban-Abyan Basin. Management plan for Amran Basin, Rada-Dhamar Basin and Tihama Basin is planned to be formulated.

Five of the basins mentioned above were designated to be "Water Protection Zone" by the Cabinet Decree No. (344) in the year of 2002 and they are considered as critical basin on the point of view of water resources. These basins are Ta'iz Region, Sa'dah Basin, Hadhramawt Basin, Tuban-Abyan and Sana'a Basin.

Water resources management plan for others basins are listed in *Table 2.1* below.

Table 2.1 Water Resources Management Plan for Other Basin

Name of the Basin /Region	Title (year formulated)	Status
Ta'iz	Water Resources Management Action Plan for the Ta'iz Region (2000)	Implementation started in 2004
Sa'dah	Water Resources Management Plan for Sa'dah Basin (2005)	Implementation started in 2007
Sana'a	Water Resources Action Plan for Sana'a Basin (2007)	Formulated in this study
Hadhramawt	Title undecided (expected to be formulated in 2007)	Formulation is ongoing
Tuban - Abyan	Title undecided (expected to be formulated in 2007)	Formulation is ongoing
Amran	Title undecided (expected to be formulated in 2009)	Design study for the formulation is ongoing
Rada-Dhamar	Title undecided	Planned to be formulated
Tihama	Title undecided	Planned to be formulated

Water resources management plan for Ta'iz Region and Sa'dah Basin are described below.

2.2 WATER RESOURCES MANAGEMENT ACTION PLAN FOR THE TAI'Z REGION

2.2.1 BACKGROUND

Ta'iz Region, with catchments area of 650 km^2, is located in the upper part of the Wadi Raysan, which is one of the major wadis draining the highland and midland regions of the Red Sea Basin. Ta'iz City, distant 268 km south of Sana'a Capital City, is located inside the catchments area.

According to the results of 2004 census, the population of Ta'iz Region was around 650,000 inhabitants and the population of Ta'iz City was accounted at 317,000 inhabitants with a high growth rate of 7.9%. Nearly half of the population of the Region lives in the rural area and they are heavily dependent on agriculture relied on spate irrigation and rainwater harvesting methods. Ta'iz Governorate is one of the hubs of industrial activity in Yemen and a large number of industrial plants are located in and around Ta'iz City.

In the year of 1996, the total quantity of water consumed in Ta'iz Region was estimated at 43 MCM where groundwater consumption accounts for 95% (41 MCM). Groundwater consumption for agriculture use showed the highest ratio of consumption which was accounted for 27 MCM (67%). The higher quantity of water consumed by the sector was caused by the increasing in the number of wells accompanied by expansion of cultivated area. Other factor to be considered is the low irrigation efficiency of irrigation methods adopted by the farmers, causing over exploitation of groundwater. Urban water supply consumed around 7 MCM and industries around 4 MCM.

Water resources of Ta'iz Region are heavily dependent on rainfall and the mean annual precipitation is around 568 mm. The groundwater recharge was estimated at around 15 MCM, what means that the groundwater consumption is near to three times higher than the recharge and decreasing of groundwater level and depletion of water in some wells were observed.

In the following sectors, a brief explanation of the Water Resources Management Action Plan for the Ta'iz Region is described.

2.2.2 CONTENTS OF THE ACTION PLAN

The "Water Resources Management Action Plan for the Ta'iz Region" prepared between the years of 1996 and 2000 was issued in 2000 and approved by parliament in 2004.

(1) Water Resources Management Strategy

The water resources management strategy for the Ta'iz Region consists of five main components with sixteen subcomponents as shown in *Table 2.2*.

Table 2.2 Components of the Strategy

Components	Aproaches
General management enabling activities	Infromation system
	Awareness raising programs
	Communication and co-ordinations
Establishing regulatory framework for allocation of water	Regulatory framework for groundwater conservation
	Regulatory framework for rural-urban water transfers
Enhancing public water supply infrastructure and services	Program for improving Ta'iz urban water supply program
	Rural water supply program
Combating damage from water by means of wastewater control and flood control	Expansion of urban sewerage system
	Urban domestic wastewater treatment
	Industrial wastewater treatment
	Re-use of the treated wastewater
	Flood control and protection works
Sector targeted demand management	Recycle or re-use of treated wastewater
	Other urban demand management measures
	Improving the efficiency of agriculture water use
	Creating non-agricultural employment opportuities

Main important prerequisites for a successful implementation of the water resources management strategy are:

- *Consensus, ownership and commitment*
- *Maintaining a balanced and integrated view*
- *Flexibility*
- *Planning and providing operational inputs*

(2) Packages of Actions to be Implemented

Actions to be implemented by the Action Plan and their activities are listed below.

1) Development and Operation of Information System

Activities

- Monitoring networks of rainfall, runoff, groundwater level and water quality
- Monitoring systems for periodic assessment of diversion/abstraction of water, water use, waste and wastewater production, wastewater treatment, benefits from water, etc.
- Databases containing the collected monitoring and related administrative data
- Chemical laboratory for analysis of water samples
- Periodic updates of the diagnosis on water-related problems

2) Raising General Awareness on Water Problems and Solutions

Activities

All kinds of awareness raising activities have to be programmed: designing and disseminating posters and brochures; workshops; informative meetings in the field; messages at schools and mosques; radio and TV-messages; etc

3) Communication and Co-ordination

Activities

Monitoring on what is being done regarding the action plan; disseminating this information among relevant stakeholders; organizing meetings to discuss operational aspects of the action plan.

4) Establishing Regulatory Frameworks for Conserving Groundwater for Sustainable Use

Activities

- Defining zone(s) where the regulatory framework should be developed (conservation zones)
- Developing a communication structure between NWRA and the water stakeholders of the zone
- Establishing a local groundwater user association or any other organization with sufficient local support (or mandate) to organize local groundwater conservation
- Discussing principles on which groundwater rights should be based
- Defining and registering groundwater rights and the period of time of their validity
- Setting a target for maximum annual groundwater abstraction in the zone, and any other targets
- Discussing and agreeing on self-imposed restriction on groundwater abstraction (quantities abstracted, well spacing, pumping regime, etc) and on other activities (e.g. land use) needed to reach the targets

- Monitoring compliance
- Punishing violators

5) Establishing Regulatory Framework for Rural-Urban Transfer of Water

Activities

- Defining zone(s) where the regulatory framework should be developed (with priority)
- Developing a communication structure between NWRA and the water stakeholders of the zone
- Establishing a local water user association or any other organization with sufficient local support (or mandate) to negotiate water transfers from the zone to Ta'iz city
- Discussing principles on which groundwater rights should be based
- Defining and registering groundwater rights and the period of time of their validity
- Discussing and agreeing on conditions for transferring water to NWSA (quantities, price, term of payment, individual or community transfers, etc)
- Negotiation of deals between rural zones and NWSA
- Defining rules of arbitration in case of no compliance of any partner

6) Improving Ta'iz Urban Water Supply

Activities

- Rehabilitation of the urban public water distribution network in Ta'iz
- Institutional reform of NWSA's Ta'iz branch in order to increase efficiency and to enable complete cost recovery
- Eliminating illegal connections and revising the tariff structure as important demand management measures
- Exploratory studies to identify possible additional sources of water
- Initiating the development of rural-urban water transfer frameworks
- Exploratory drilling, in particular in zones where permeable Tawilah Sandstone are found at reasonable depths
- Feasibility studies for additional source development for urban water
- Negotiating deals between NWSA and local communities on rural-urban water transfers
- Design and implementation of works for capturing additional sources of water for urban water supply
- Feasibility studies (covering engineering, and financial aspects) for treating brackish water for augmenting urban water supply

7) Rural Domestic Water Supply

Activities

- Area-wide inventory and evaluation of rural water supply conditions
- Preparing annual plans for new schemes
- Preparatory field work at sites selected for new schemes
- Implementation of new schemes (usually by drilling completion, with pump and civil works)

8) Upgrading Urban Sewerage

Activities

In broad lines the work will consist of planning and design, procurement / tendering and other logistic activities, technical construction of the sewerage system, and administrative measures.

As the activity is a component of the Ta'iz Water Supply and Sanitation Project

9) Urban Domestic Wastewater Treatment

Activities

- Determining of type and concentration of pollutants in the untreated wastewater
- Setting water quality targets or standards for treated wastewater
- Identifying the optimal technical treatment system
- Designing and costing of a treatment system
- Defining a cost recovery system for urban water treatment
- Building the treatment plant(s) and related works
- Putting the treatment plant(s) in operation

10) Industrial Wastewater Treatment

Activities

- Determining of type and concentration of pollutants in the untreated wastewater
- Setting water quality targets or standards for treated wastewater
- Setting recycling targets for various types of industries
- Identifying the optimal technical treatment system
- Designing and costing of a treatment system
- Defining a cost recovery system for industrial water treatment
- Building the treatment plant(s) and related works
- Putting the treatment plant(s) in operation

11) Flood Hazard Reduction

Activities

- Forestation programs in the upper catchments of wadis where flood damage hazards are considerable
- Rehabilitation and proper maintenance of terraces in the upper catchments of wadis where flood damage hazards are considerable
- Providing for temporary storage of peak flow volumes at locations where they can do little harm
- Construction of defense walls or other defense structures in wadi beds
- Incorporating flooding risks as a criterion for land-use planning

12) Wastewater Recycling or Re-Use

Activities

- Identifying suitable combinations of wastewater producers and treated water users (e.g. several industries may recycle their own treated wastewater; treated urban domestic wastewater may be suitable for irrigation of certain crops).
- Organizing and evaluating pilot projects for wastewater recycling and wastewater re-use
- In case of favorable results: promoting wastewater recycling and wastewater re-use on a large scale and providing incentives to encourage this

13) Other Urban Demand Management Measures

Activities

- A strongly progressive water tariff
- Elimination of all illegal connections and of all privileged families that are currently

exempted from paying the water bills
- Public education on proper water economizing practices at the scale of single households

14) Improving the Efficiency of Agricultural Water Use

Activities

- Lining of canals and ditches
- Land leveling
- Replacing flooding irrigation by furrow, sprinkler or drip irrigation methods
- Changing to crops with relatively low unit water use
- Encouraging a shift away from irrigated cereals; increasing the yields of rainfed cereals
- Changing to crops with relatively high economic returns per unit of water used

15) Creating Non-Agricultural Employment Opportunities

Activities

- Improving and diversifying education at the rural level
- Identifying promising options for diversification of economic activities in the area (industries, manufacturing, services, etc)
- Government supported

The implementation activities of action plan related to NWRA-Ta'iz Branch started in May, 2006. Unfortunately, it has stopped since September, 2006 as result of ceasing the financial support. The implemented activities during the above mentioned period are as follows:

- Wells inventory and economic survey.
- Establishing of meteorological network.
- Monitoring of groundwater levels and meteorological network.
- Preparing the social mobilization team to establish associations of water users in some areas.
- Four workshops were done about public awareness for schools and mosques to explain the water problem dimensions.

2.3 WATER RESOURCES MANAGEMENT PLAN FOR SA'DAH BASIN

2.3.1 BACKGROUND

Sa'dah Basin lies at the north part of Yemen and it is represented by Sa'dah catchment area; extends approximately more than 900 km² which includes Sa'dah plain (213 km²). Sa'dah City is located in the middle of Sa'dah plain at about 255 km north of Sana'a Capital City.

In 1970, there were 800 wells in Sa'dah plain and most of the water extracted from the wells was used for irrigation. However, the number of wells increased by a rate of 10 to 15 wells/year until 1976 due to an introduction of drilling technologies, such as rigs and pumps. The number of wells came up to 2,000 in 1983 and 4,700 in 2002. The average depth of wells is 250m in Sa'dah plain and 400m outside of Sa'dah plain.

The average annual rainfall on the plain is about 128 mm/year. The total quantity of extracted groundwater is about 112 MCM/year, while the recharge is about 6 MCM/year. 84 MCM (75%) of the extracted groundwater volume is used for irrigated agriculture and urban and rural domestic groundwater use is estimated at 2 MCM (1.5%). About 26 MCM (23.5%) relate to unspecified and other uses.

Over exploitation of groundwater for irrigation, unregulated construction of new wells and the high rate increase of urban population (growth rate of 3.8%) are the factors to increase the groundwater consumption and it is clear, as mentioned above, that the groundwater extraction is around 20 times higher than the groundwater recharge. Consequently, the depletion of groundwater is observed through the decreasing of water level which is 3 to 6 m/year.

2.3.2 WATER RESOURCES MANAGEMENT ACTION PLAN

(1) Plan Objectives and Planning Methodology

Approaches to be followed:

- Preparation of a hydrometric networks report summarizing current and future monitoring requirements
- Assessment of available water sources and preparation of water resources inventory
- Calculation of water demand forecasts
- Development and implementation of water resources and balancing tools
- Formulation of development scenarios
- Formulation of detailed resources and management strategies
- Formulation of mid-term investment plan for the water sector

These approaches proposed are based on the specific conditions set by principles of Integrated Water Resources Management (IWRM) and experience of the consultants.

(2) Plan Implementation

Plan implementation has three starting points:

1. Measures directly undertaken by NWRA
2. Measures undertaken by other stakeholders of the water sector
3. Planning and execution of investment projects

(3) Interventions at National Level

- Collection and Review of the Existing Data
- Assessment of Available Water Resources
- Calculation of Demand Forecast
- Investment Planning in the Water Sector
- Demand Management
- Formulation of Water Resources and Demand Management Strategies
- Formulation of Development Scenarios
- Formulation of Mid-Term Investment Plan for the Water Sector
- National Well Inventory

(4) Interventions at Sa’dah Basin Level

- Support to NWRA Sa’dah Branch Office
- Cooperation with World Bank Groundwater and Soil Conservation Project (WB GSCP)
- Developing Public Awareness Strategies
- Use of Non-Conventional Water Resources
- Community Partnership and Self-Regulation
- Training Program
- Institutional Set-Up and Expertise Required for WRMP Implementation

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CHAPTER 3

PRESENT STATE OF WATER RESOURCES

CHAPTER 3 PRESENT STATE OF WATER RESOURCES

3.1 GENERAL

This chapter describes the natural condition, namely geological, hydrological and hydrogeological setting, and water resources occurrence in the Sana'a Basin based on the previous study reports.

The main comprehensive water resources studies have been conducted to secure the resources for water supply to Sana'a city since 1970s, as tabulated below.

Table 3.1 Previous Studies in the Sana'a Basin

Study	Term	Organization	Consultant	Summary
Water Supply for Sana'a and Hodeida. Sana'a Basin Groundwater Studies	1970-1973	NWSA	Italconsult	The first study for Sana'a water supply system. The study area was a part of Sana'a basin, around Sana'a city. 15wells were drilled in the northwest of the City, where Tawilah Sandstone is distributed.（Western Well Field）.
Water Supply for Sana'a Phase 2	1980, 1983	NWSA	Howard Humphreys & Sons	Addition to the above 15 wells, 15 wells were drilled in the Western Well Field and other 15 wells were drilled in the Eastern Well Field in order to meet the increasing water demand of Sana'a City.
Sana'a Basin Water Resources Scheme	1986	MAF	Mosgiprovodkhoz	The first study of the whole Sana'a basin. MAF conducted to meet the increasing agricultural use of groundwater in 80s. Wadi Kharid Dam was proposed for the future water supply.
Assistance to the High Water Council in the Preparation of a Water Master Plan	1988-1992	HWC	Individual Experts	The water resources study on the whole of Yemen.　Geological and Hydrogeological characteristics were described in the northern part and the southern part of Yemen.
Sources for Sana'a Water Supply (SAWAS)	1987-1996	NWSA	TNO Institute of Applied Geoscience	The study on the condition and future plan of water supply. The rehabilitation of water supply system and non-conventional water sources including desalination of Red Sea Water were proposed and evaluated. Test wells were drilled to investigate the deeper sandstone and resulted negative. Water resources condition in Sana'a basin was summarized on the whole.
Sana'a Basin Water Resources Management Study (SBWRM-PPT)	2001-2003	NWRA	Sana'a University, WEC	The water points (well, spring, dam, etc) inventory survey and analysis in Sana'a Basin.
Sana'a Basin Water Management Project (SBWMP)	2003-	NWRA	Hydrosult, Others	Ongoing project for water resources management, including groundwater studies, irrigation improvement, capacity building and public awareness campaign.

3.2 TOPOGRAPHY AND GEOLOGY

3.2.1 TOPOGRAPHY

Yemen can be divided into 5 main topographical regions, which are the coastal plains, the western highlands, the central midland, the eastern plateau and the desert of Rub Al Khali and Ramlat Sabatayn. The Sana'a Basin is located in the eastern end of the western highland with the highest peak of the Jabal An Nabi Shu'ayb with the altitude of 3,666 m. The total area of the Basin is about 3,240 km^2, which is the figure calculated by the Satellite Imagery Analysis (GAF, 2007)[1] recently.

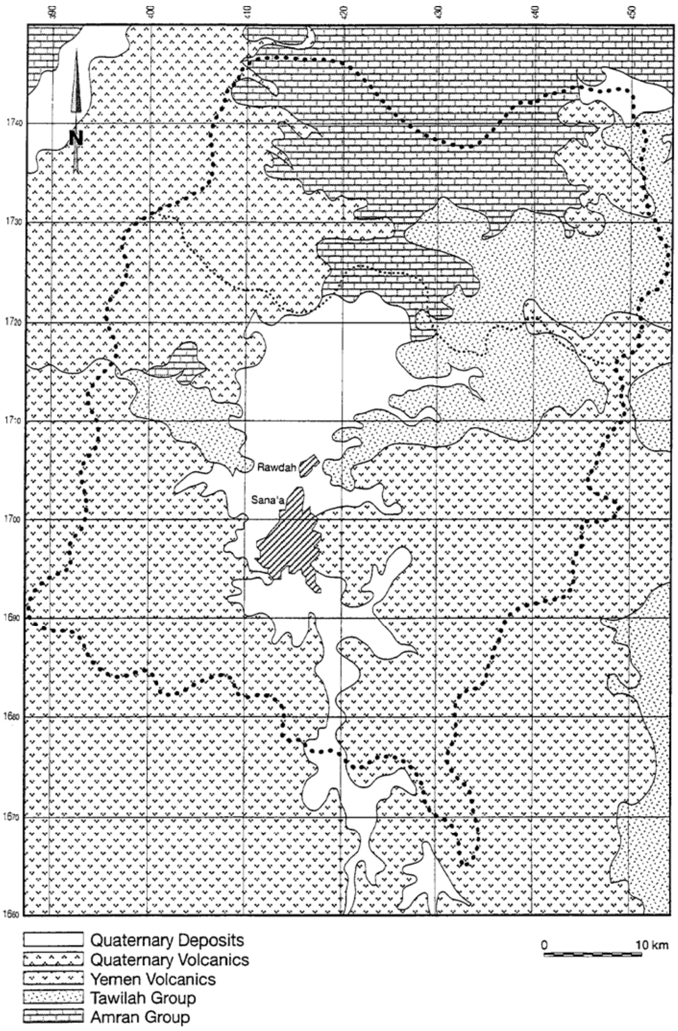
The Basin mainly consists of the central plain area with the altitude of 2,100-2,400 m surrounded by the western and eastern mountainous area.

3.2.2 GEOLOGY

Basement complex of Yemen consists of granite, gneiss, schist and other formations of the Precambrian, and is overlain by various younger rocks, or marine and continental sediments and volcanic rocks. In the Sana'a Basin, the distributed geologic units are categorized into five, namely Amran Group, Tawilah Group, Tertiary Volcanics, Quaternary Volcanic and Quaternary Deposits. The lithological summary of these five groups is described in the table below.

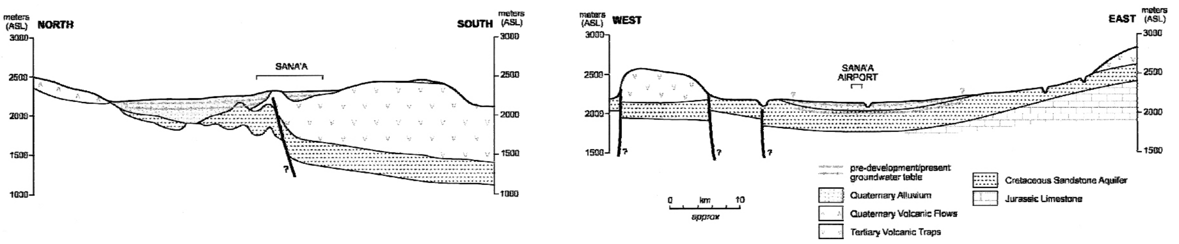
Table 3.2 Geology in the Sana'a Basin

Formation	Thickness	Lithology	Hydrogeological Description
Quaternary deposits	- 350m	Active alluvium, sand and gravel Gravel sheets, gravel plains and alluvial fans generally in areas of low relief with a stony surface Loess and ancient dunes: areas of wind-blown soils and sands (generally fertile land)	Unconfined aquifers are common, but semi-confined aquifers occur in places. Originally highly productive, but recently falling water tables are found throughout the alluvial aquifer. Water level fluctuations show a rapid response to rainfall.
Quaternary volcanics	- 400m	Trachytic flows and domes Basaltic lavas and scoria	Petrographically similar to Tertiary volcanics, but relatively unweathered and less permeable. Local and limited groundwater potential.
Tertiary volcanics (Yemen Volcanics)	2000m<	Gabbro Ignimbrite and ash-flow deposit Rhyolite and dacite Trachyte Basalt	Fracturing is widespread. Groundwater occurs in bedded ashes and tuffs, fractured lava flows, boundary zones between flows and major fault zones. Rhyolitic aquifers seem to provide higher yield. Overlie Tawilah group
Cretaceous Sandstone (Tawilah Group)	150 – 400m	Sandstones with minor calcareous horizons.	White, yellow or reddish fine to coarse grained sandstone. Generally productive aquifer, but highly anisotropic.
Jurassic Limestone (Amran Group)	100 – 400m	Bituminous limestone, dolomitic marl and sand	Fracture zones and bedding plane discontinuities, poorly productive aquifer



Source; SAWAS Technical Report No.9 (1995)

Figure 3.1 Geology in the Sana'a Basin



Source; Stephen Foster (2003), Yemen: Rationalizing groundwater resource Utilization in the Sana'a Basin, World Bank

Figure 3.2 Schematic Geological Cross Section in the Sana'a Basin

3.3 METEOROLOGY AND HYDROLOGY

3.3.1 GENERAL CLIMATE

Yemen is located within the tropical and subtropical climate zones. Although Yemen has no major seasonal difference, we can broadly divide it into summer from April to October with high temperatures and a milder winter season from October to April. There are 2 rainy periods, one from March to May, and the other from July to September. In the highlands and mountain regions, where the Sana'a Basin is located, the weather is moderate in summer, but in winter, it is cold during the night and early morning and moderate during the day.

3.3.2 MONITORING NETWORK

Monitoring of the hydrological and hydrogeological condition is one of the most important factors to do an appropriate management of water resources in the area. The monitoring information shall be essential for long-term operational strategy of water resources.

At present, the hydrological monitoring network in the Sana'a Basin consists of two meteorological stations, nine rainfall gauge stations, 33 water level monitoring wells, and no stations for wadi runoff. The locations of the meteor/rainfall stations are shown in *Figure 3.3* and listed in *Table 3.3*.

Monitoring Network in Sana'a Basin

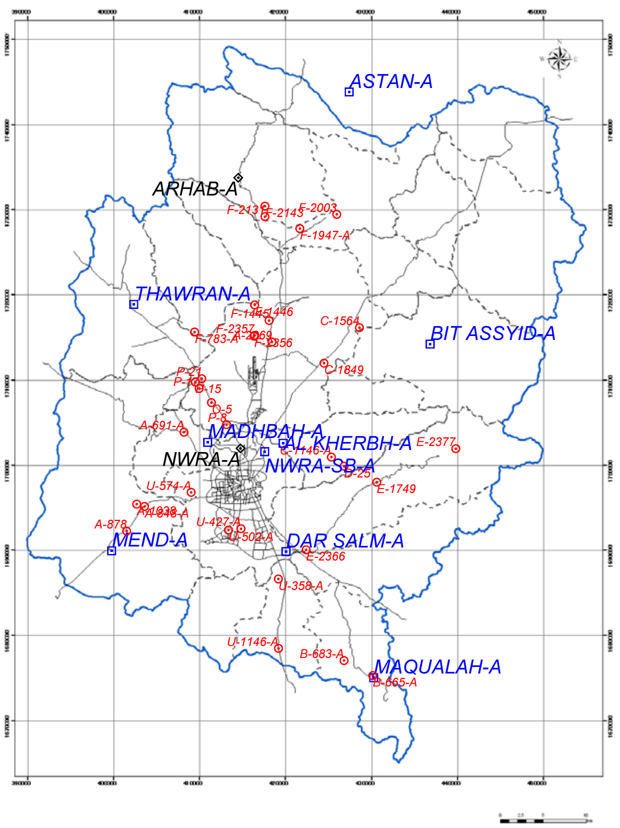


Figure 3.3 Meteor/Rainfall Monitoring Station in the Sana'a Basin

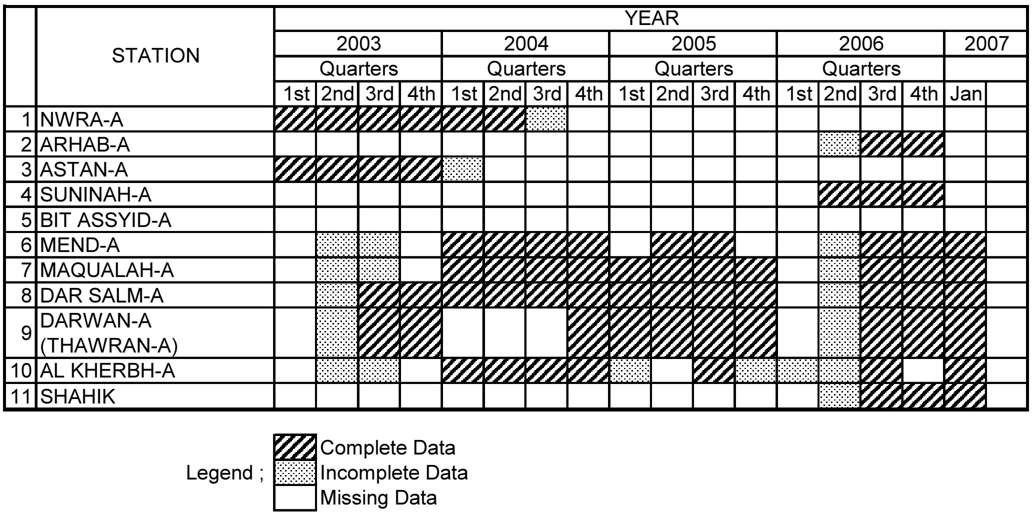
Table 3.3 Meteor/Rainfall Monitoring Station in the Sana'a Basin

No	StationName	StationType	UTM_N	UTM_E	Status	Installed
1	NWRA-A	Meteorological	1701935	414581	repairing	20-Apr-89
2	ARHAB-A	Meteorological	1733500	414310	operating	20-Dec-05
3	ASTAN-A	Rainfall	1743500	427250	operating?	09-Jul-91
4	SUNINAH-A	Rainfall	1695550	405422	operating	02-Apr-06
5	BIT ASSYID-A	Rainfall	1714095	436689	operating?	31-Aug-03
6	MEND-A	Rainfall	1690005	399550	operating	14-May-03
7	MAQUALAH-A	Rainfall	1675200	430100	operating	12-May-03

8	DAR SALM-A	Rainfall	1689906	419887	Operating	12-May-03
9	DARWAN-A (THAWRAN-A)	Rainfall	1718733	402126	Operating	14-May-03
10	AL KHERBH-A	Rainfall	1702540	419550	Operating	15-May-03
11	SHAHIK	Rainfall	1701830	439650	Operating	20-Jul-06

The two meteorological stations have been equipped with automatic recorders for relative humidity, temperature, wind speed, wind direction, rainfall, solar radiation and barometric pressure. Rainfall stations have been also equipped automatic data loggers. The water levels of 33 monitoring wells, however, have been measured manually with electrical tapes every month. Presently, surface water runoff has not been measured. SBWMP Technical Note (Norman and Mulat 2007)[2] has recommended installing three flow gauges in their experimental watersheds, Wadi Sirr and Wadi Barian. Additionally, seven sites of existing dams have been listed for installing staff gauges and water level recorders in order to determine the amount of water coming and stored in these reservoirs.

Table 3.4 Collected Rainfall Data



Some of rainfall data are missing as shown in *Table 3.4.* Unfortunately, in addition, the reliability of the collected data is partly doubtful[3]. Technical Report (NWRA-SB, 2006)[3] noted the following causes of the lack of the data, that is, a deficiency of financial resources to have field visits on time, lack of awareness of local people who abused and damaged the gauges, and some technical problems.

3.3.3 TEMPERATURE

Figure 3.4 and *Table 3.5* show the average monthly temperature recorded at the station of NWRA-A. The obtained records used to draw the figure are very limited. The figure, however, seems to show a general tendency in the Sana'a Basin.

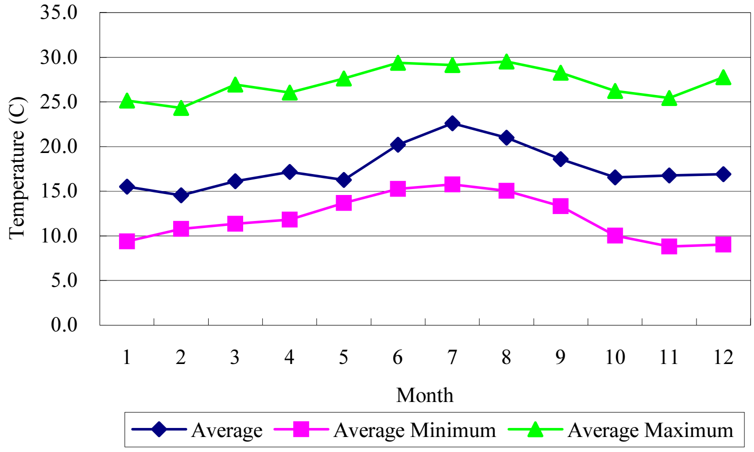


Figure 3.4 Monthly Temperature (NWRA-A, 1989-1997)

The hottest season is from June to August, and the coldest season is around January and February. The average monthly temperature ranges between about 15 and 25 C.

The station, NWRA-A, is located in the north edge of the urban area of Sana'a with the altitude of about 2,250 m. In the northwestern area, where the altitude is lower than Sana'a, the temperature may vary widely.

Table 3.5 Monthly Temperature (NWRA-A)

YEAR		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Average	Maximum	Minimum
1989	Average						22.1	23.5						22.8	23.5	22.1
	Minimum						14.9	15.9						15.4	15.9	14.9
	Maximum						28.5	28.6						28.6	28.6	28.5
1990	Average	15.5	16.8	18.6	18.9				23.2	21.4	19.4			19.1	23.2	15.5
	Minimum	8.6	11.7	11.5	12.2				16.7	13.9	11.3			12.3	16.7	8.6
	Maximum	23.8	23.8	27.1	26.2				29.9	28.3	25.8			26.4	29.9	23.8
1992	Average														0.0	0.0
	Minimum										6.6	6.6	6.0		6.6	6.0
	Maximum														0.0	0.0
1993	Average	15.3	15.6		17.2	20.5	23.1	22.8	22.5					19.6	23.1	15.3
	Minimum	8.0	10.4		11.9	14.2	15.8	16.5	15.6					13.2	16.5	8.0
	Maximum	23.5	22.7		24.7	27.4	29.9	30.2	30.1					26.9	30.2	22.7
1996	Average							21.7	22.5	21.8	18.0	15.1		19.8	22.5	15.1
	Minimum							16.2	15.7	14.3	9.6	6.9		12.6	16.2	6.9
	Maximum							29.0	30.1	28.3	25.8	23.6		27.4	30.1	23.6
1997	Average	15.7	11.2	13.6	15.4	12.1	15.4	22.4	15.7	12.5	12.3	18.5	16.9	15.1	22.4	11.2
	Minimum	11.6	10.3	11.2	11.4	13.2	15.1	14.4	12.2	11.7	12.6	12.8	12.0	12.4	15.1	10.3
	Maximum	28.1	26.5	26.8	27.3	27.9	29.7	28.7	28.0	28.2	27.1	27.3	27.8	27.8	29.7	26.5
Average	Average	15.5	14.6	16.1	17.1	16.3	20.2	22.6	21.0	18.6	16.6	16.8	16.9	17.7	22.6	14.6
	Minimum	9.4	10.8	11.4	11.8	13.7	15.3	15.8	15.0	13.3	10.0	8.8	9.0	12.0	15.8	8.8
	Maximum	25.1	24.3	27.0	26.0	27.6	29.4	29.1	29.5	28.3	26.2	25.4	27.8	27.1	29.5	24.3

3.3.4 PRECIPITATION

Figure 3.5 and *Table 3.6* show the monthly rainfall recorded at NWRA-A from 1989 to 2004. According to the table, the annual rainfall ranges from around 110 mm to 300 mm or more. The maximum annual rainfall was recorded at 341 mm in 1998. The figure indicates that rainy or wet seasons are generally from March to May and July to September, although there were some exceptional years. It is rather difficult to say about a long-term tendency.

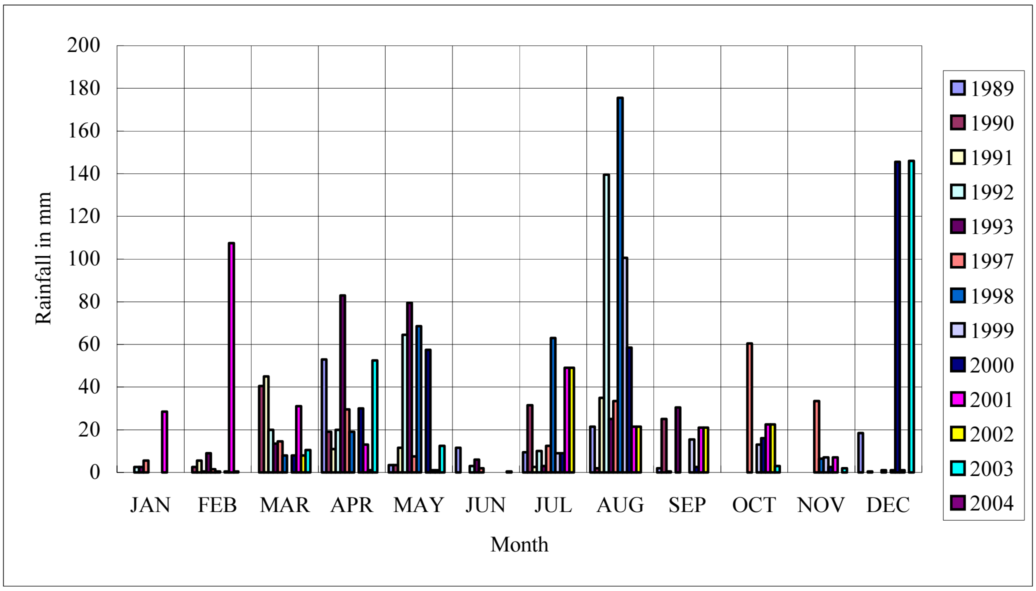
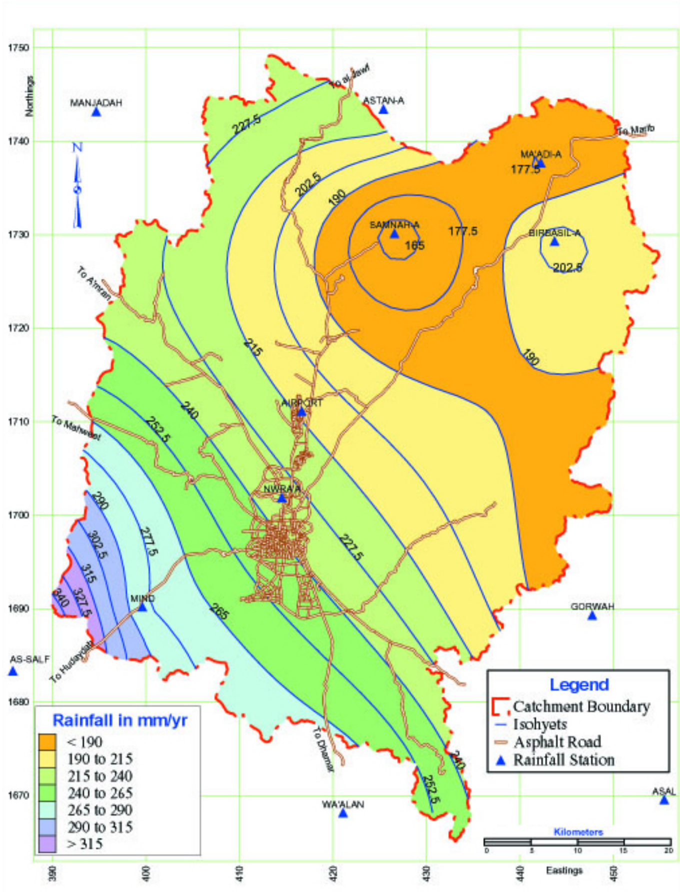


Figure 3.5 Monthly Rainfall (NWRA-A) 1989-2004

Table 3.6 Monthly Rainfall (NWRA-A)

	MONTH												
YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
1989				53	3.5	11.5	9.5	21.5	2	0	0	18.5	119.5
1990	0	2.5	40.5	19	3.5	0	31.5	2	25	0	0	0	124
1991	0	5.5	45	11	11.5	0	2.5	35	0.5	0	0	0.5	111.5
1992	2.5	0.5	20	20	64.5	3	10	139.5					260
1993	2.5	9	13.5	83	79.5	6	3	25	30.5				252
1997	5.5	1.5	14.5	29.5	7.5	2	12.5	33.5	0	60.5	33.5	1	201.5
1998	0	0.5	8	19	68.5	0	63	175.5	0	0	6.5		341
1999							9	100.5	15.5	13	7	1	146
2000		0.5	8	30	57.5		9	58.5	2.5	16	2.5	145.5	330
2001	28.5	107.5	31	13	1	0	49	21.5	21	22.5	7	1	303
2002	0	0.5	8	1	1	0	49	21.5	21	22.5	0	0	124.5
2003	0	0	10.5	52.5	12.5	0.5	0	0	0	3	2	146	227
2004	0	13.5	9	23	37	1	6.5	8.5					98.5
Average	3.9	12.9	18.9	29.5	29.0	2.2	19.6	49.4	10.7	13.8	5.9	34.8	230.5
Maximum	28.5	107.5	45.0	83.0	79.5	11.5	63.0	175.5	30.5	60.5	33.5	146.0	
Minimum	0.0	0.0	8.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Figure 3.6 shows the distribution of rainfall in the Sana'a basin provided by NWRA.



Source; NWRA Sana'a Branch (2006): Monitoring Activities in Sana'a Basin. Technical Report (2003-2005)

Figure 3.6 Isohyet Map of the Sana'a Basin

The northeastern area in the Basin has less than about 200 mm/year rainfall and the central plain area has from 200 to 250 mm. In the southwestern mountainous area, the annual rainfall reaches more than 300 mm.

It may be possible that the figure indicates the eastern mountainous area may actually have more rainfall. The further continuous observation is necessary to obtain more details precisely. And also it may be desirable to install another rain gauge station in this area[2].

3.3.5 EVAPOTRANSPIRATION

1:250,000 Hydrogeological map (Robertson 1990)[4] describes that potential evaporation estimated by the Penman method averages about 2,000mm annually. SAWAS (1995)[5] calculated that the potential evapotranspiration was an annual total of 2,475 mm based on a meteorological statistics. And it reported that calculated monthly potential evapotranspiration showed a seasonal variation, with a maximum in June (average 9.4 mm /day) and a minimum in February (4.8 mm/day). In any case, the figures are substantially higher than annual rainfall.

GAF (2007) estimated actual evapotranspiration based on the satellite imagery analysis in SBWMP. According to the report, the total of 113.1 MCM water were transpired in the Sana'a Basin during the period from 1 July 2004 to 30 June 2005. The figure was obtained on the basis of the irrigated area and the crop pattern analyzed in the study.

3.3.6 SURFACE WATER

(1) General Feature

The Sana'a Basin is the upper part of the catchment of the Wadi Kharid streaming to the northeast of the Basin, which is one of the two main sub-catchments of the Wadi Jawf. The Wadi Jawf is also one of the primary watersheds streaming into the Ar Rub Al Khali, or the desert of Empty Quarter, in the east of Yemen.

There is no perennial flow in the Basin except a part of Wadi Kharid that has a base flow fed by springs whose discharge was reported to be about 0.2 m^3/sec (Mosgiprovodkhoz, 1986)[6]. And another exception is the flow discharged from a treatment plant for Sana'a. The outflow of the treatment plant was 22,700 m^3/day, or 260 l/sec, on the average of 2002.

The Sana'a Basin can be divided into 22 sub-basins as shown in *Figure 3.7* and *Table 3.7*. The figure shows also the flow direction of these sub-river systems. The mountainous area to the west, south and east of the Sana'a plain drained into the plain, that is, the catchments of the Wadi Al Mawrid and the Wadi Bani Huwat, and the flow direction goes northward. The surface flow, however, in the wadis flowing out of the mountainous area normally disappear in the Quaternary sediments of the plain.

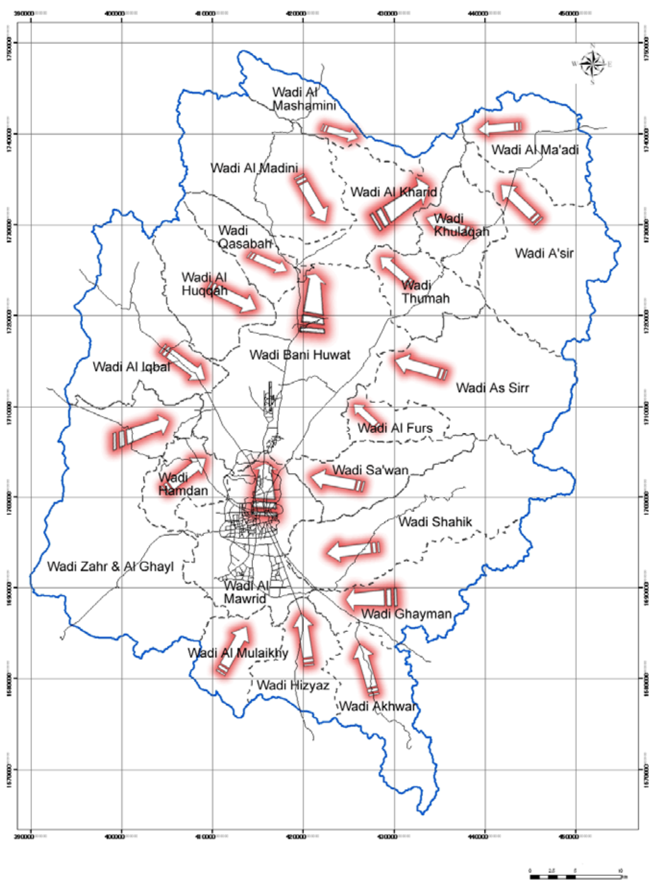


Figure 3.7 Sub-Basins in the Sana'a Basin

Table 3.7 Sub-Basins in the Sana'a Basin

	Sub-Basin	Catchment (km^2)
1	Wadi Al Mashamini	77.8
2	Wadi Al Madini	213.3
3	Wadi Al Kharid	138.2
4	Wadi Al Ma'adi	111.3
5	Wadi A'sir	208.8
6	Wadi Khulaqah	75.7
7	Wadi Qasabah	64.5
8	Wadi Al Huqqah	120.3
9	Wadi Bani Huwat	327.0
10	Wadi Thumah	77.0
11	Wadi As Sirr	218.6
12	Wadi Al Furs	45.8
13	Wadi Al Iqbal	202.9
14	Wadi Zahr & Al Ghayl	360.8
15	Wadi Hamdan	63.5
16	Wadi Al Mawrid	179.2
17	Wadi Sa'wan	95.9
18	Wadi Shahik	238.7
19	Wadi Ghayman	143.3
20	Wadi Al Mulaikhy	69.7
21	Wadi Hizyaz	81.9
22	Wadi Akhwar	125.6
	Total	3,239.8

(2) Runoff

At present, wadi runoff is not monitored at all as described already.

Two types of method have been used to estimate the runoff volume of wadis in the previous studies. One is the method using a runoff coefficient, or the ratio of runoff depth to precipitation depth, obtained by hydrological observation of main wadis in Yemen. Report WRAY-35 (1995)[7] suggested the average runoff coefficient of 0.055 for wadis in Yemen based on the observed flow volumes from primary watersheds. SAWAS Technical Report No.9 (1995) also calculated a runoff coefficient of 0.049, if only direct runoff was taken into account, and 0.061, if it was referred to total runoff. The volume of runoff in the Sana'a basin is estimated at about 40.9MCM/year with the supposition of the 230 mm of annual rainfall, the 3,240km^2 of the area of the Sana'a Basin and 0.055 of the runoff coefficient.

Another method to calculate runoff volume is the estimation using the SCS method that is the empirical model prepared by the U.S. Soil Conservation Service. TS-HWC Vol. III (1992)[8] constructed a rainfall-runoff model using the SCS method and obtained the figures shown in *Table 3.8*, which indicated the mean total and base flow per day was 74,000 and 67,000 m^3 respectively in the Sana'a Basin. It means the total outflow of the Sana'a Basin is 27 MCM/year.

Table 3.8 Mean Flow of Sana'a Basin

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean	Annual Total
Total flow	26	29	75	208	110	63	68	129	69	45	41	24	74	26,980
Flood flow	0	0	0	50	4	0	0	29	0	0	0	0	7	2,525
Base flow	26	29	75	158	106	63	68	100	69	45	41	24	67	24,455

Source: TS-HWC Vol. 3 Surface Water Resources, 1992 Unit: thousand m^3/day

The reports of the feasibility study of 13 dam rehabilitations or constructions submitted by Hydrosult Inc.(2002)[9] also adopted the SCS method to estimate runoff volume in the wadi where a proposed dam site was located. The obtained runoff coefficient ranges from 0.049 to 0.17.

SBWMP (Noaman and Mulat, (2007)) carried out rainfall-runoff analysis for 22 sub-basins in the Sana'a Basin using SCS-CN method. The obtained runoff coefficient ranges from 0.22 to 0.122. The results have been used for the water balance analysis for each sub-basin, which is explained in the section of 3.6.

In addition to the above, General Directorate of Irrigation (GDI) provided a report of Engineering Data Sheet, or dam database. The data sheet is the summarized report of a survey of 44 existing dams in 2001. It describes the hydrological condition around each dam site including estimated runoff coefficient, which ranges from 0.03 to 0.4, although it is not clear how to be estimated the figures. The estimated mean annual flow of 44 dam sites totaled about 22.3 MCM.

(3) Usage of Surface Water

In the Sana'a basin, two surveys of the existing surface water points have been conducted since 2000, that is, the existing dam survey by GDI in 2001 described in the previous section, and the water point inventory survey by SBWRM in 2002. In the former survey, the information of 44 dams was summarized as the data sheets of dams and the latter survey listed 24 dams/pools and 125 springs in the Sana'a basin. These 24 dams/pools include obviously some small-scale cisterns. In addition to the above, a map of the Location of Dams in Sana'a Basin was recently issued by the project of Geo-Environmental Map of Sana'a, YGGMP (2004)[10], the explanatory note of which has not been provided yet. 56 dams including under or stopped construction ones are plotted on the map.

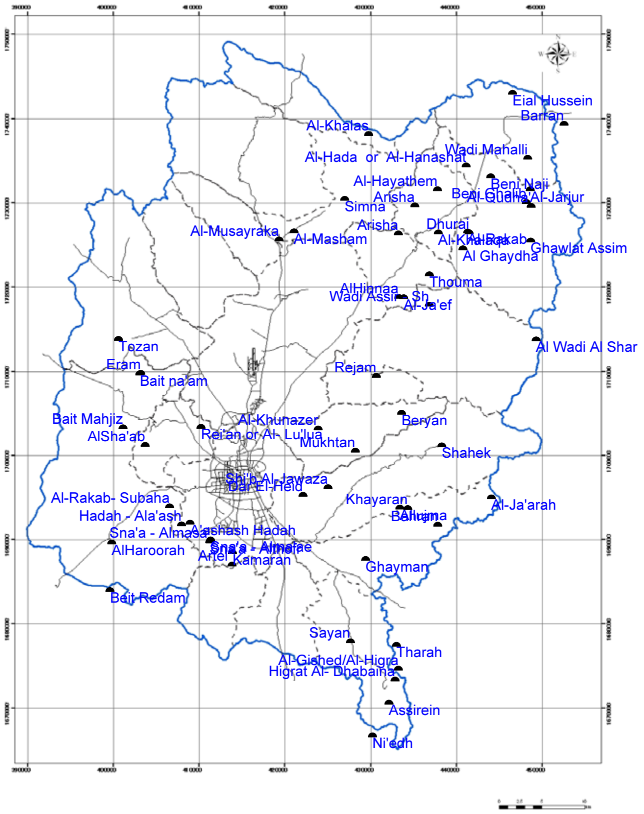


Figure 3.8 Locations of Dams in the Sana'a Basin

Table 3.9 Dams in the Sana'a Basin

No.	Name of Dam	GDI Dam No	Basin	UTM N	UTM E	Recharge	Irrigation	Drinking	Condtion	SBWMP rehabilitation	Catchment (km^2)	Annual Rainfall (mm)	Runoff Coefficient	Yiels (l/s)	Annual Flow 10^3m^3	source
1	Al-Khalas	8	1	1737900	429850	●	●		bad		64.87	42.3	0.15		412	Data sheet by GDI and Inventroy survey by SBWMP
2	Al-Masham	11	3	1726450	421125	●	●		good	○	2276.44	172	0.067		70.5	
3	Al-Musayraka	12	3	1725500	419375	●			good		2270.32	172	0.067		9500	
4	Simna	40	3	1730275	427050	●	●		bad		2407.93	172	0.067		1433.5	
5	Barran	20	4	1739100	452700	●			not operated		2.7	150	0.3		122	
6	Eial Hussein	27	4	1742750	446675	●			bad	○	1.36	187.7	0.15		38	
7	Wadi Mahalli	44	4	1735100	448450	●			bad	○	13.68	150	0.2		410	
8	Al Ghaydha	1	5	1724450	440875	●			good		1.875	191.4	0.2		72	
9	Al-Hada or Al-Hanashat	3	5	1734200	441250	●			not operated		187.67	210	0.087		3006.7	
10	Al-Jarjur	6	5	1731400	448750	●			good		8.575	191.4	0.15		246	
11	Al-Qudha'	13	5	1729450	448850	●	●		good		1.1	191.4	0.15		32	
12	Al-Rakab	14	5	1726425	441425	●			bad		1.925	191.4	0.2		74	
13	Beni Ghalib	22	5	1729900	448300	●			bad		0.225	191.4	0.15		6.46	
14	Beni Naji	23	5	1732925	444125	●			bad	○	6.63	210	0.087		121	
15	Dhurai	26	5	1726325	441600	●			good		2.1	191.4	0.2		80	
16	Ghawlat Assim	29	5	1725370	448800	●			good		2.5875	191.4	0.2		99	
17	Al-Hayathem	4	6	1731400	437900	●			……	○	32.195	191.4	0.15		924	
18	Al-Khalaqa	7	6	1726325	438000	●			not operated		5.525	200	0.35		387	
19	Arisha	17	6	1729500	435250	●			bad	○	6.45	140.9	0.2		182	
20	Al-Ja'ef	5	10	1718700	433950	●	●		good	○	2.7	175	0.14		66.15	
21	Arisha	16	10	1726200	433325	●			bad		0.6	140.9	0.2		17	
22	Thouma	42	10	1721400	436950	●	●		bad	○	7.1	191.4	0.35		476	
23	Rejam	35	12	1709450	430750		●				106.6	0.1	0.1			
24	Tozan	43	13	1713800	400600	●			bad	○	23.4	200	0.15		702	
25	Al-Rakab- Subaha	15	14	1694100	406575			●	good		0.9	119.7	0.1		11	
26	Beit Redam	21	14	1684250	399600	●	●	●	good		neglected	170	0.4		0.24	
27	Eram	28	14	1709800	403200	●			……		4	200	0.15		120	
28	Rei'an or Al- Lu'lua	36	15	1703450	410250	●			good		261	170	0.03		1300	
29	Artel	18	16	1687250	413880	●	●		good		0.675	234.3	0.15		24	
30	Kamaran	32	16	1688700	413925	●			……		4.1	234.3	0.15		144	
31	Al-Khunazer	9	17	1703250	423950	●			50% achieved		0.5	106.6	0.2		11	
32	Beryan	24	17	1705100	433700	●	●		bad		10.325	106.6	0.15		165	
33	Mukhtan	33	17	1700650	428300	●			good		5.1	194.8	0.2		199	
34	Allujma	10	18	1693950	433500	●			bad	○	1.275	198.8	0.35		87	
35	Dar El-Heid	25	18	1695450	422175	●			good		1.65	194.8	0.35		112	
36	Shahek	38	18	1701275	438400	●	●		good		47.125	170	0.035		280	
37	Shi'b Al-Jawaza	39	18	1696350	425100	●	●		good		1.45	194.8	0.35		99	
38	Ghayman	30	19	1687900	429500	●	●		……		102	194.8	0.035		669	
39	Al-Gished/Al-Higra	2	22	1675000	433325		●	●	good		0.7	122.6	0.2		17	
40	Assirein	19	22	1671000	432225	●			not operated		10.825	122.6	0.15		199	
41	Higrat Al- Dhabaina	31	22	1673725	432940	●			good		0.2	122.6	0.2		5	
42	Ni'edh	34	22	1667150	430300	●			85 % completed		3.69	122.6	0.2		90	
43	Sayan	37	22	1678225	427725	●			15 % achieved		6.8	250	0.2		340	
44	Tharah	41	22	1677800	433100	●	●		bad		5.3	122.6	0.1		65	
45	AlHinnaa		10	1718733	433362		●		Operational					4.7	148	Inventory survey by SBWMP
46	Al Wadi Al Shar		11	1713735	449437				Operational					4.7	148	
47	Wadi Assir - Sh		11	1717808	436943		●		Operational					4.7	148	
48	AlHaroorah		14	1689847	399809				Operational					4.7	148	
49	Bait Mahjiz		14	1703395	401131				Intermittent					4.7	148	
50	Bait na'am		14	1709720	403084		●		Intermittent					3	95	
51	AlSha'ab		15	1701325	403723		●		Temp. Not Use							
52	Sna'a - Althofr		16	1690000	411272		●		Operational					4.38	138	
53	Sna'a - Almasa'		16	1689969	411301		●		Operational					4.38	138	
54	Sna'a - Alma'ae		16	1690205	411370		●		Operational					1.5	47	
55	Hadah - Ala'ash		16	1691975	407972		●		Operational					0.6	19	
56	A'ashash Hadah		16	1692173	408966		●		Operational					4.7	148	
57	Bahran		19	1691939	437928				Dry							
58	Al-Ja'arah		19	1695150	444202				Operational					4.7	148	
59	Khayaran		19	1693893	434424		●		Operational					4.7	148	
														Total:	24,037	

Table 3.9 is the compiled result of the GDI inventory and the SBWMP inventory survey and *Figure 3.8* shows the location of dams. Most of the dams listed by GDI, No.1 to 44 in the table, are constructed to recharge groundwater. According to the remarks of the data sheet by

GDI, discharge from the wells around the dams increases generally whenever the dams fill. 15 dams of them are also used for irrigation and only three dams are used for domestic water. Dams numbered from 45 to 59 are used for irrigation mainly. Most of them may be small-scale reservoirs constructed by rural people. Total volume of the annual flow or yield of dam sites is calculated to be 24 MCM.

Another surface water source is a spring. The result of SBWMP inventory survey showed 145 springs in the Sana'a basin. The locations of the spring are shown in *Figure 3.9*.

51 of 145 springs, 35%, are used for irrigation, 43 springs, 30%, for animal or livestock, and 49 springs, 34%, for domestic water use for rural areas. The yield of spring ranges from 0.01 to 9.26 l/sec and totals 545 l/sec. This amount is equivalent to 17.2 MCM annually. The volume, however, is not likely an actual annual yielding amount, because the yield of spring is fluctuating seasonally. One third to half of the amount, about 6 to 9 MCM may be an acceptable figure.

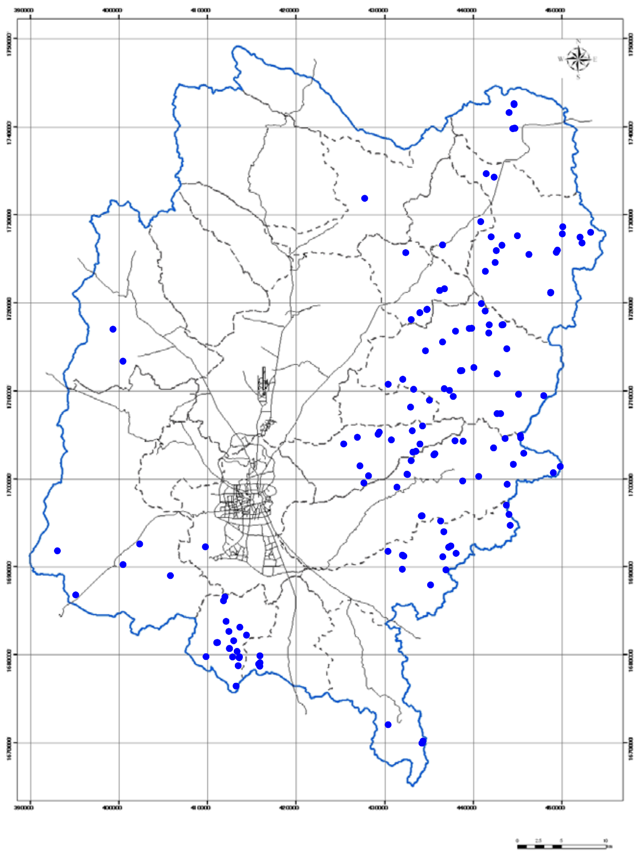


Figure 3.9 Springs in the Sana'a Basin

3.4 HYDROGEOLOGY

3.4.1 AQUIFERS

Geology in the Sana'a Basin is summarized in the section of 3.2.2. General hydrogeological description is also explained in 3.2.2 (*Table.3.2*). As shown in the table, the previous studies have revealed that aquifer developed in the Sana'a Basin can be classified to the four types, namely Alluvial Aquifer, Volcanic Rocks, Tawilah Sandston and Amran Limestone. Based on the result of the well inventory survey (2002), the characteristics of the aquifers are described in the section. The occurrence of predominant aquifer may be indicated by the distribution of boreholes. Yield of boreholes and the depth of boreholes suggest generally the aquifer potential and the depth or thickness of the aquifer respectively.

(1) Alluvial Aquifer

The well inventory survey (2002) recorded 1,110 operational water points developing the alluvial aquifer. 89 of them were boreholes, 988 were dug wells, 27 were Dug/Bore type and 6 springs. Dug wells, naturally, drilled in the alluvial plain and wadi beds in the Sana'a Basin. Boreholes are distributed mainly in the Sana'a plain as shown in *Figure 3.10*.

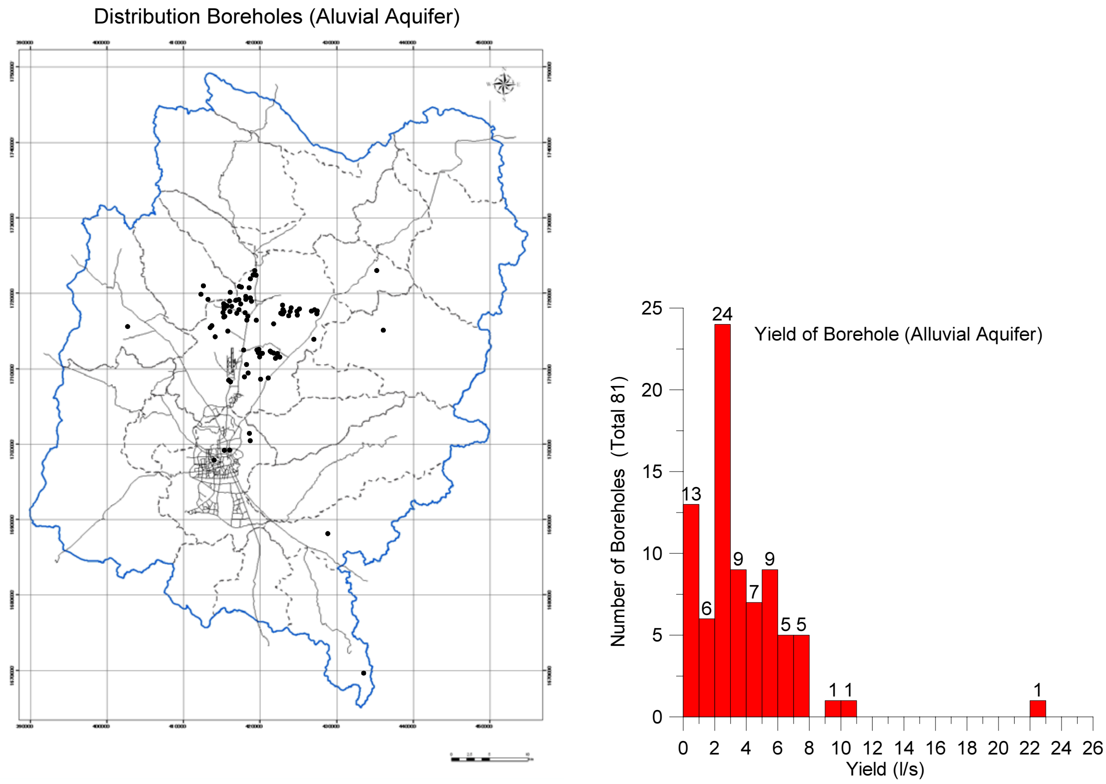


Figure 3.10 Distribution and Yield of Boreholes (Alluvial Aquifer)

Though the yield of boreholes ranges from 0.3 to 23 l/s as shown above, the yield of less than 3 l/s accounts for more than 50% of the whole boreholes.

Figure 3.11 shows the distribution of depth. The depth of boreholes ranges from 64 to 400 m and the depth of dug wells ranges from 3 to 80 m.

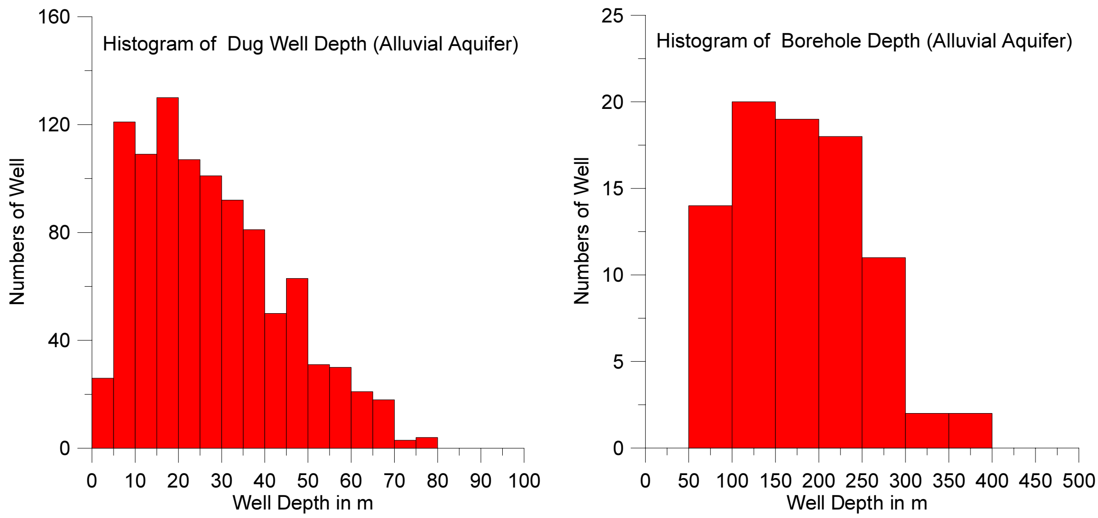


Figure 3.11 Distribution of Well Depth (Alluvial Aquifer)

Groundwater in the alluvial Deposits has been exploited mainly for irrigation use. 778 wells (70.1%) were used for irrigation, and 185 (16.6%) wells for domestic use.

(2) Volcanic Rocks

The well inventory survey (2002) shows that 4,214 operational water points exploited the aquifer in the Basin. 2,812 of them are dug wells, 1,294 are boreholes and others are Dug/Bore (88), Springs (18) and Dam/Pool (2).

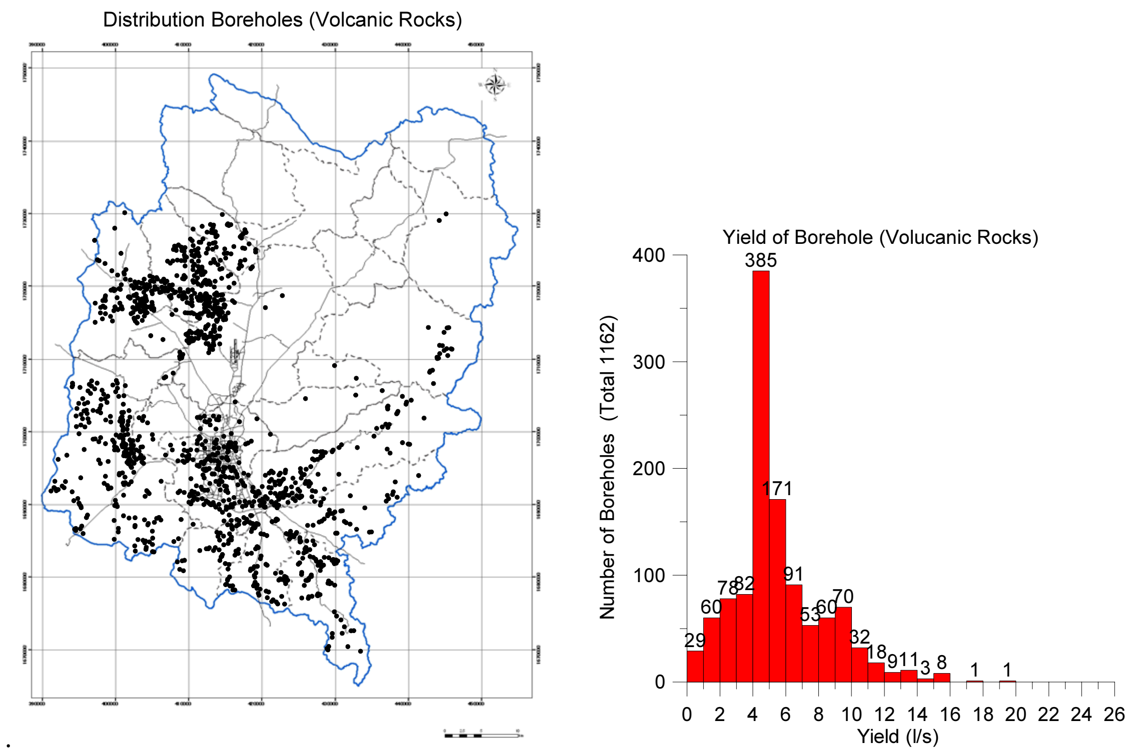


Figure 3.12 Distribution and Yield of Boreholes (Volcanic Rocks)

Figure 3.12 shows the distribution and yield of boreholes. About 48% of boreholes yield between 4 and 6 l/s. Dug wells generally penetrate to volcanic rocks up to 10 to 25 m, as shown in *Figure 3.13*. More than half of boreholes were drilled up to the depth of 150 to 300

m. 3,568 wells (85.1%) and 335 (7.9%) are used for irrigation and domestic respectively.

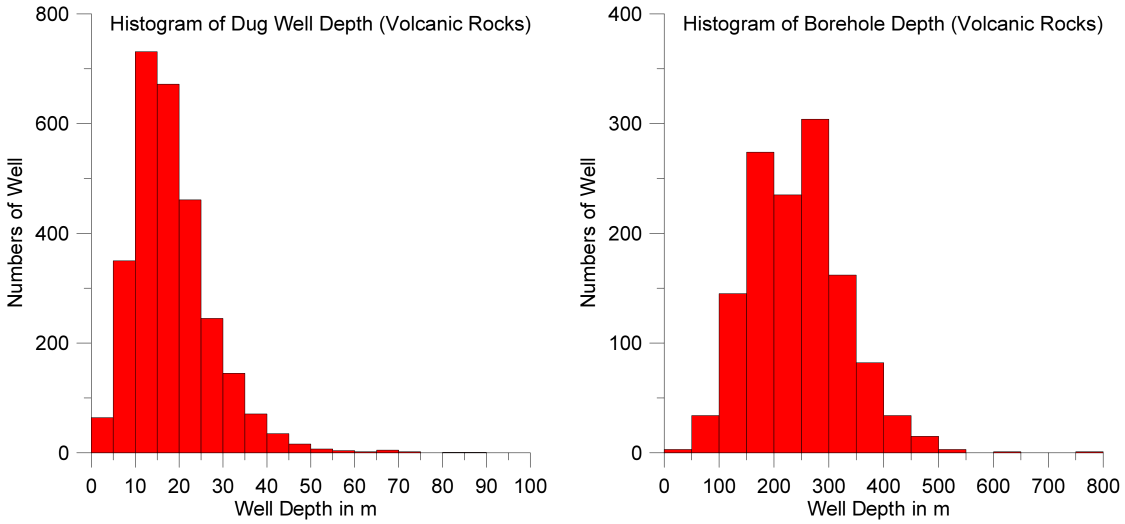


Figure 3.13 Distribution of Well Depth (Volcanic Rocks)

(3) Tawilah Sandstone

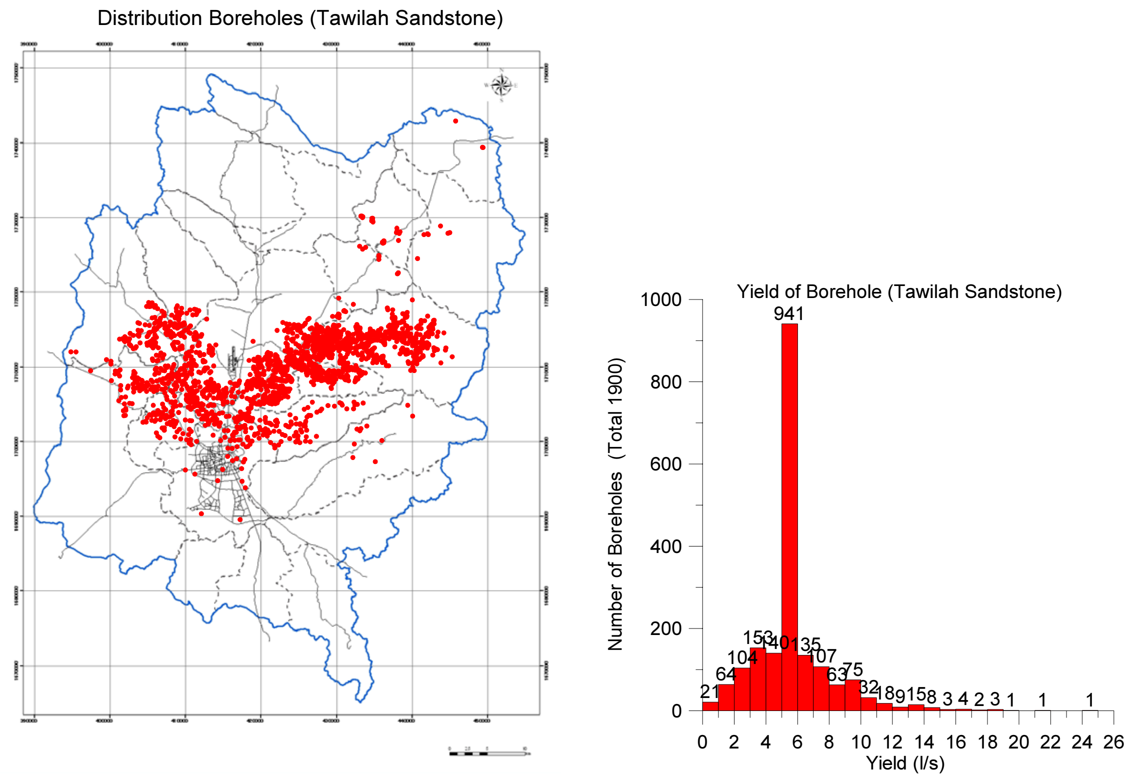


Figure 3.14 Distribution and Yield of Boreholes (Tawilah Sandstone)

According to the inventory survey (2002), 2,778 wells targeted the aquifer. 2,080 of 2,778 wells are boreholes and 630 wells are dug wells, and others are Dug/Bore (67), Springs (1) and Dam/Pool (1).

Figure 3.14 indicates the yield of 5-6 l/s is prominent, it means the Tawilah Sandstone aquifer is the most productive in the Basin generally. 60% of dug wells were drilled up to the depth of 20 m or less and 70% of boreholes were drilled up to the depth of 150 to 300 m as shown in *Figure 3.15* 2,540 (91.4%) of boreholes are used for irrigation and 85 (3.1%) for domestic use. Recently the sandstone aquifer underlying volcanic rocks has been exploited by drilling up to the depth of 1,000 m or less in the south of Sana'a City by Sana'a Water and Sanitation Local Corporation (SWSLC) and Sana'a Basin Water Management Project (SBWMP).

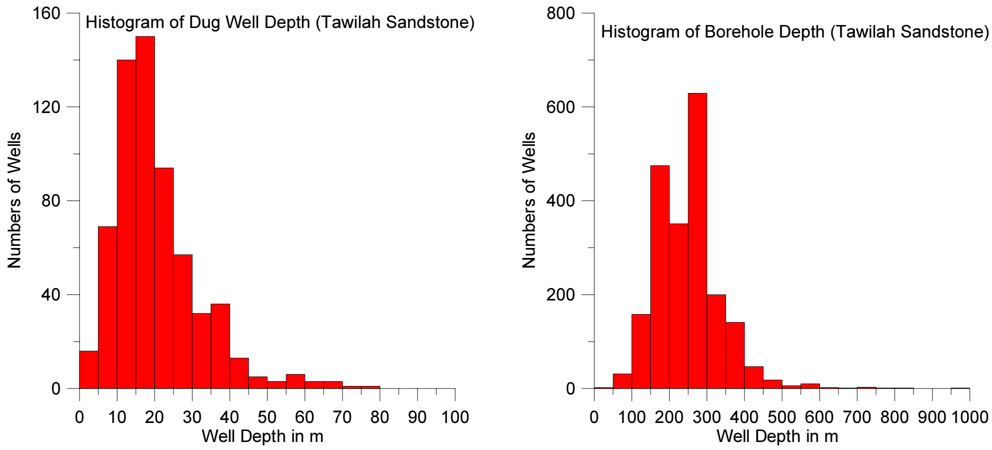


Figure 3.15 Distribution of Well Depth (Tawilah Sandstone)

(4) Amran Limestone

The inventory survey (2002) shows there were 791 operational water points exploiting the limestone aquifer. 460 of them were dug wells, 283 were boreholes and others were Dug/Bore (47) and one spring.

Figure 3.16 shows the distribution and yield of boreholes. The prominent yield is 3 to 4 l/s, 42% of boreholes. 62.8% of dug wells were drilled up to the depth of 10 to 25m and 70% of boreholes were drilled up to the depth of 150 to 350 m as shown in *Figure 3.17* 688 wells (85.8%) were used for irrigation and only 19 (5.7%) were used for domestic.

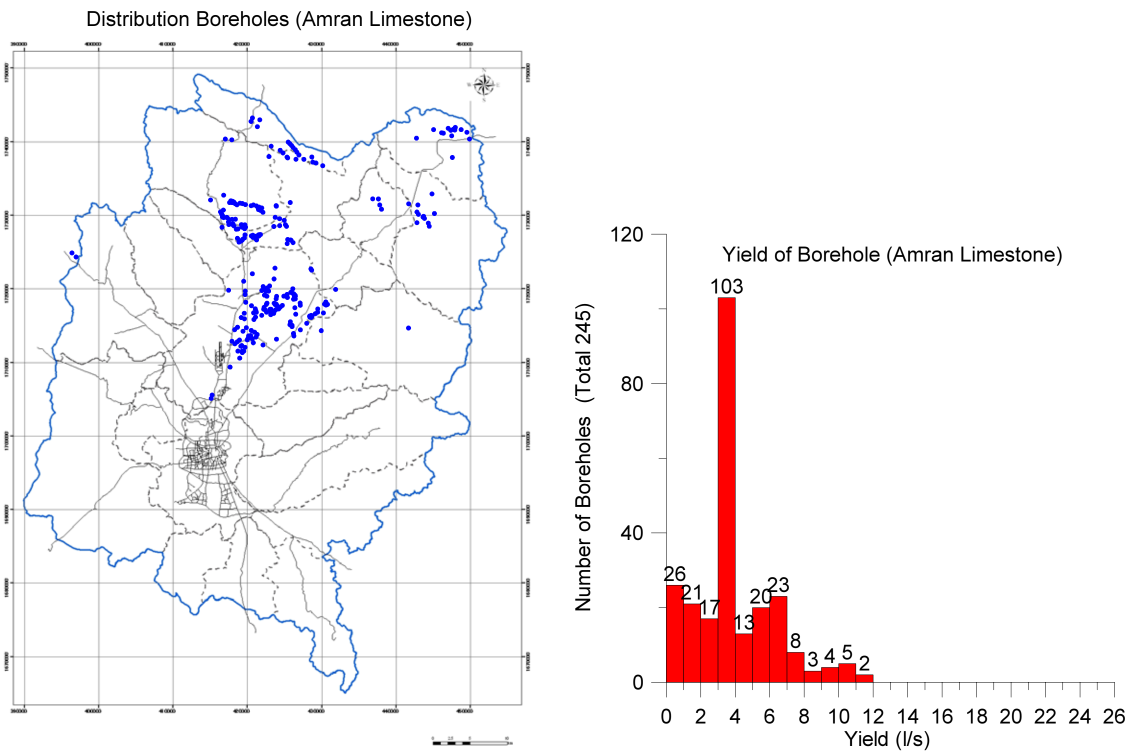


Figure 3.16 Distribution and Yield of Boreholes (Amran Limestone)

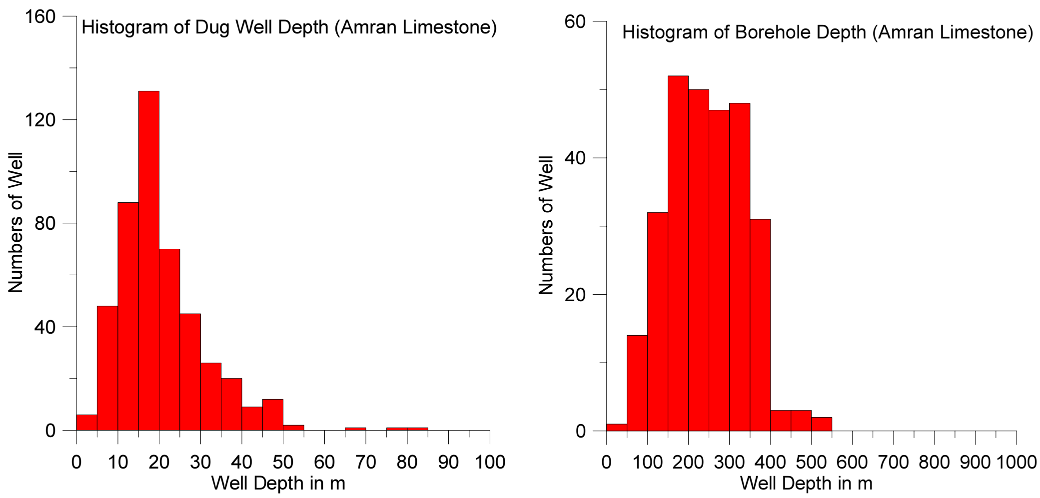


Figure 3.17 Distribution of Well Depth (Amran Limestone)

3.4.2 Groundwater Level

The well inventory survey (2002) recorded also water levels of the total 7,002 boreholes and dug wells, that is, 1,279 wells of Alluvial aquifer, 3,590 wells of Volcanic Rocks, 1,329 wells of Tawilah Sandstone and 645 wells of Amran Limestone. This section describes general condition of each aquifer based on the well inventory survey (2002).

(1) Alluvial Aquifer

Figure 3.18 shows the groundwater level of Alluvial aquifer. The map of the depth to water (left) indicates the water level of the central plain is generally 20 m or more, which means some shallow dug wells drilled in the past may not reach the water table now. The contour map of water level (right) shows that the water table slops first to the Sana'a Plain from the mountainous area to the west, south and east of the plain, and then slopes gently from south to north and northeast along the central low area.

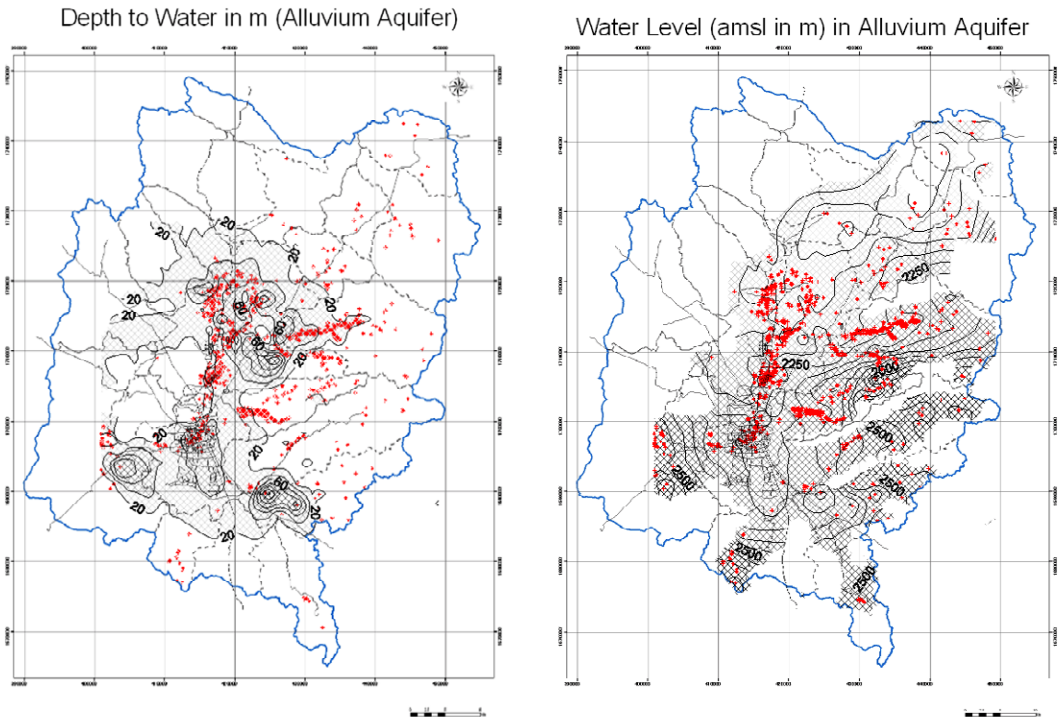


Figure 3.18 Water Level (Alluvial Aquifer)

(2) Volcanic Rocks

Figure 3.19 show the groundwater level of Volcanic Rocks. The map of the depth to water shows that the water level in the western mountain area is more than 100 m deep and the water level is less than 50 m in the eastern mountainous area. The elevation of water table inclines generally toward the north from the southern area in the Basin.

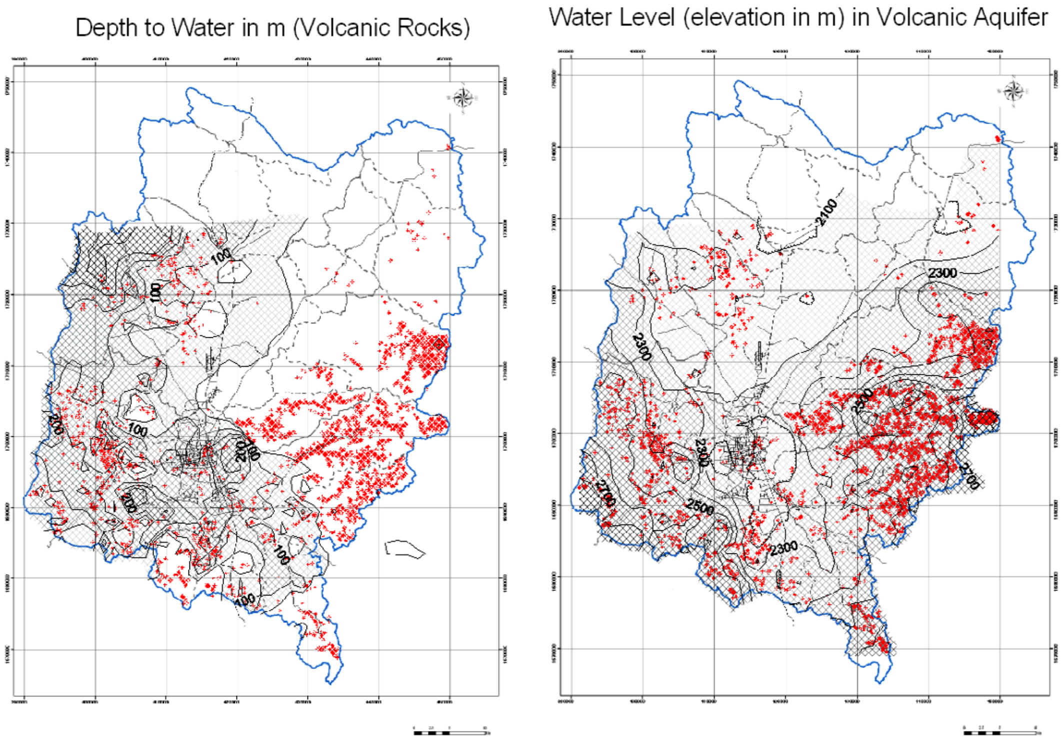


Figure 3.19 Water Level (Volcanic Rocks)

(3) Tawilah Sandstone

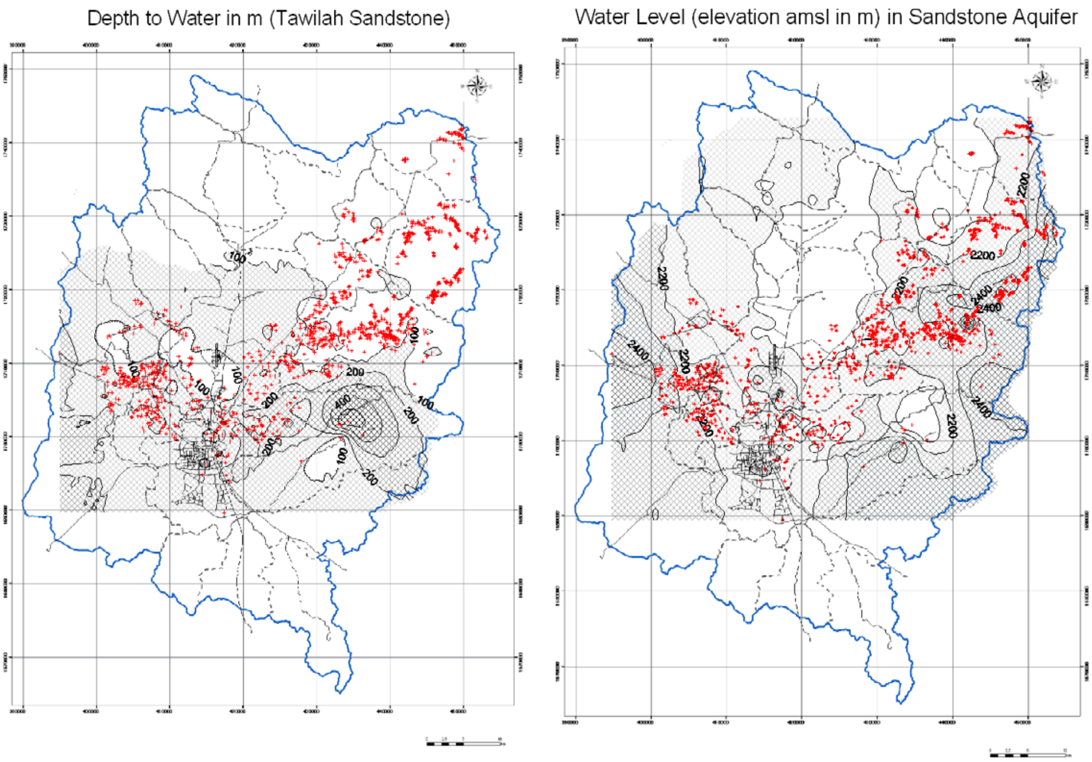


Figure 3.20 Water Level (Tawilah Sandstone)

Figure 3.20 show the groundwater level of Tawilah Sandstone. The map of the depth to water indicates that the water level in the central to southern area is generally more than 100 m deep and the water level in the northeastern part is less than 100 m. The contour map of water level shows that the water table slops from both sides of the mountainous area to the lower plain and then slopes toward the north.

(4) Amran Limestone

Figure 3.21 shows the groundwater level of Amran Limestone. The map of the depth to water shows that the water level in the northeastern area is generally less than 50 m deep and the water level in the north central part is more than 50 m. The contour map of water level indicates that the water table seems to slope from the northeast toward the south central, which is the opposite direction of other aquifers.

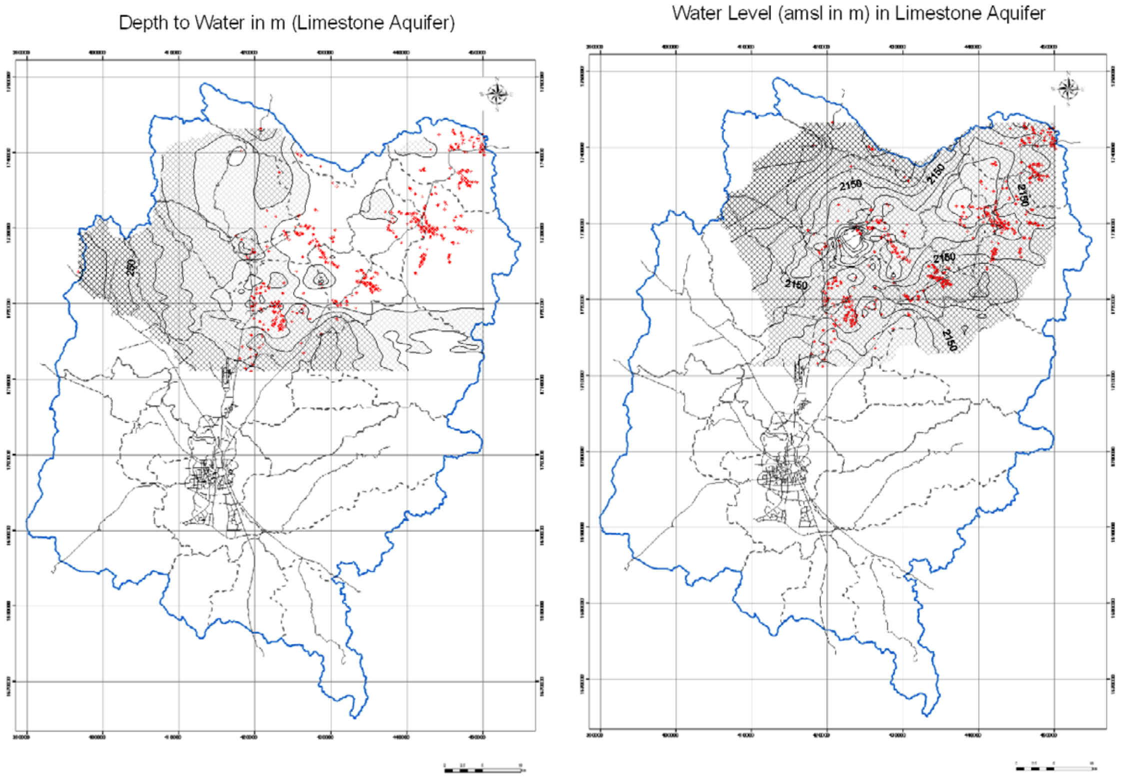


Figure 3.21 Water Level (Amran Limestone)

3.4.3 Aquifer Properties

The some previous studies carried out the pumping tests. SAWAS Technical Report No.5 (1996)[11] summarized the results of the previous pumping tests, which is shown in *Appendix.1*. The recent drilling results also have been added to the table.

(1) Transmissivity

The value of transmissivity indicates groundwater supply potential of the aquifer. SAWAS (1996) collected 12 values of Alluvial aquifer, 16 values of Volcanic Rocks, 62 values of Tawilah Sandstoen and 5 values of Amran Limestone. Additionally 15 values of Tawilah Sandstone drilled recently were added. Though the values of transmissivity ranges very widely from 0.25 to 2,000 as shown in *Appendix1*, *Table 3.10* indicates Tawilah Sandstone is the most productive aquifer. Transmissivity of Volcanic Rocks look to be scattering widely, it may suggest that the productivity of aquifer is probably affected by the scale of fissures or fractures in the rocks. Only five results of Amran Limestone seem to be not enough to indicate its characteristics.

Table 3.10 Transmissivity of Aquifers

(1) Alluvial aquifer

Transmissivity	Number of Wells		Groundwater supply Potential
10	3	(25.0%)	Low
10=< <100	8	(66.7%)	Intermediate
100=<	1	(8.3%)	High
	12	(100.0%)	

(2) Volcanic Rocks

Transmissivity	Number of Wells		Groundwater supply Potential
<10	8	(50.0%)	Low
10=< <100	5	(31.3%)	Intermediate
100=<	3	(18.8%)	High
	16	(100.0%)	

(3) Tawilah Sandstone

Transmissivity	Number of Wells		Groundwater supply Potential
<10	1	(1.3%)	Low
10=< <100	27	(35.1%)	Intermediate
100=<	49	(63.6%)	High
Total	77	(100.0%)	

(4) Amran Limestone

Transmissivity	Number of Wells		Groundwater supply Potential
<10	2	(40.0%)	Low
10=< <100	2	(40.0%)	Intermediate
100=<	1	(20.0%)	High
Total	5	(100.0%)	

(2) Hydraulic Conductivity (Permeability)

Hydraulic Conductivity is the rate of flow through a unit cross section under a unit hydraulic gradient, which is the coefficient of permeability of a layer. The values of hydraulic conductivity indicate that permeability is mostly moderate in aquifers in the Sana'a basin.

Table 3.11 Hydraulic Conductivity of aquifers

(1) Alluvial aquifer

Hydraulic Conductivity (m/day)	Number of Wells		Permeability
<0.1	1	(9.1%)	Low
0.1=< <1	5	(45.5%)	Moderate
1=< <10	4	(36.4%)	
10=<	1	(9.1%)	High
	11	(100.0%)	

(2) Volcanic Rocks

Hydraulic Conductivity (m/day)	Number of Wells	Permeability

<0.1	3	(20.0%)	Low
0.1=< <1	6	(40.0%)	Moderate
1=< <10	4	(26.7%)	
10=<	2	(13.3%)	High
	15	(100.0%)	

(3) Tawilah Sandstone

Hydraulic Conductivity (m/day)	Number of Wells		Permeability
<0.1	4	(5.6%)	Low
0.1=< <1	34	(47.9%)	Moderate
1=< <10	30	(42.3%)	
10=<	3	(4.2%)	High
	71	(100.0%)	

(4) Amran Limestone

Hydraulic Conductivity (m/day)	Number of Wells		Permeability
<0.1	2	(40.0%)	Low
0.1=< <1	0	(0.0%)	Moderate
1=< <10	3	(60.0%)	
10=<	0	(0.0%)	High
	5	(100.0%)	

3.4.4 GROUNDWATER QUALITY

The well inventory survey (2002) collected the data of EC, pH and temperature of water from 7,786 wells. In addition, SAWAS (1996)[12] conducted water quality analysis for 327 wells and collected the chemical analysis results of the previous studies.

Based on the above results, the characteristics of groundwater quality in the aquifers are generally described in this section. The issues concerning contamination are described in the section of 3.7.

(1) EC, pH and Temperature

1) Electric Conductivity (EC)

Almost 90% of groundwater has the EC value of 1,500 or less microS/cm as shown in *Figure 3.22*, or the water quality is generally good. And the figure also indicates that deeper wells have most likely a better water quality. The EC values more than 2,500 microS/cm appear mostly in the shallow wells with the depth of less than about 50 m. This may suggest that the shallower aquifer is possibly polluted in some areas.

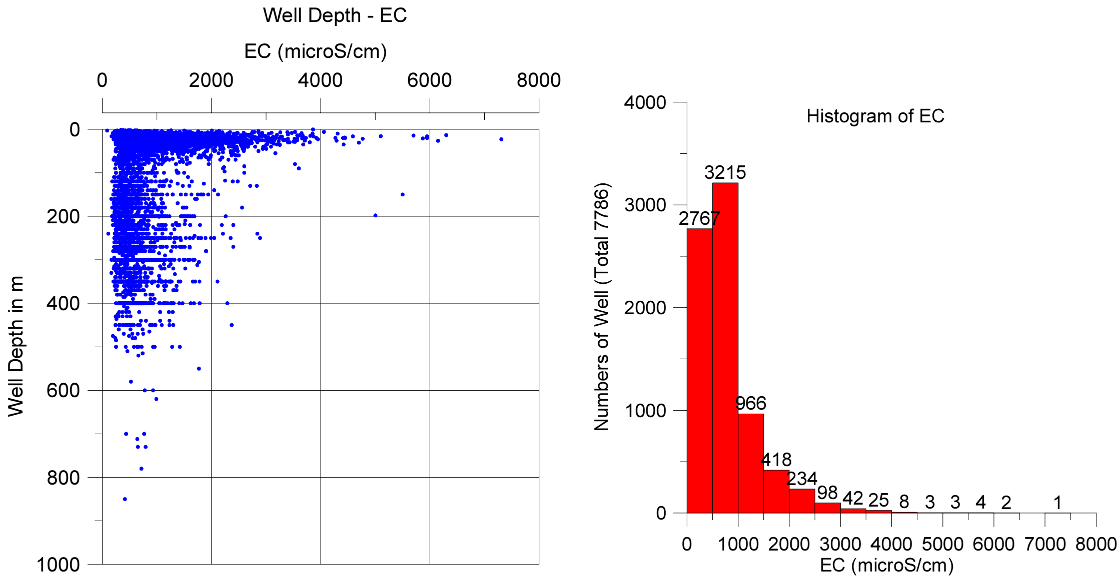


Figure 3.22 Relationship between Depth and EC, and Histogram of EC

Figure 3.23 shows the general tendency of the distribution of EC in the Sana'a Basin. The EC distribution of both dug wells and boreholes shows that there is a north-south long and narrow area around AR Rawdah and along the airport to the north of Sana'a city where the relatively higher EC values appear. AR Rawdah was the town where a sewage pond was once located and there is a wastewater treatment plant at the north end of the airport. Groundwater quality looks to be worse in the northeast area than the other area in the Sana'a basin. This issue is mentioned later again in the section of 3.7.

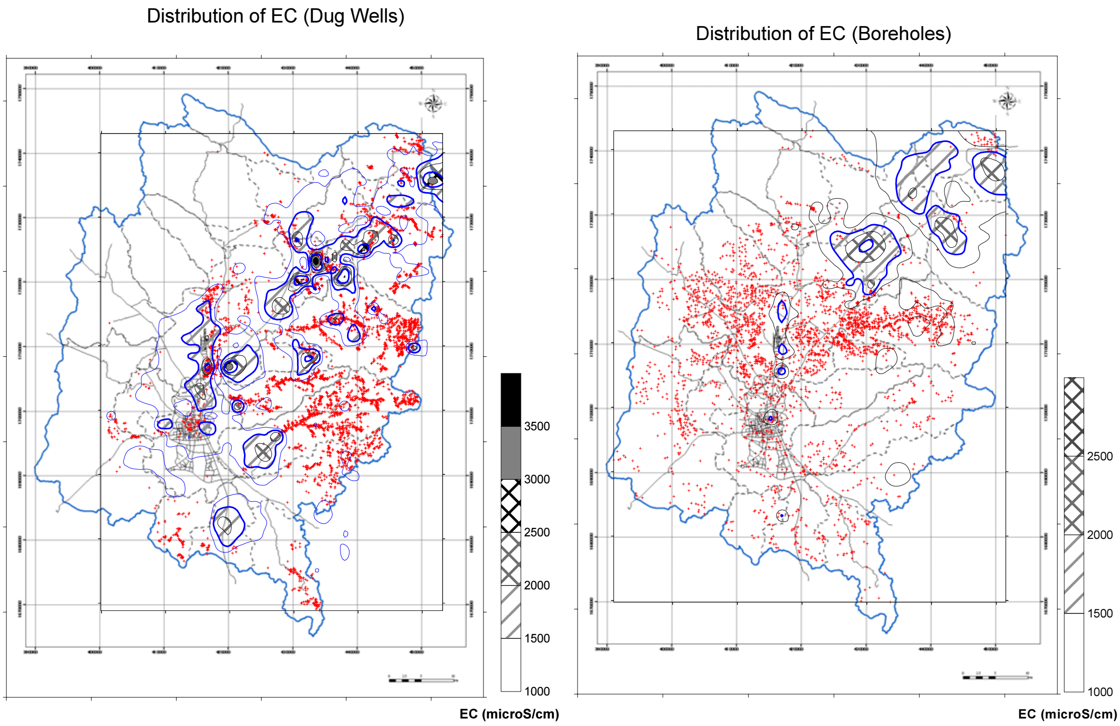


Figure 3.23 Distribution of EC

2) PH

The values of pH ranges mostly from 6 to 10, as shown in *Figure 3.24*. The histogram does not indicate any special tendency except that the mean value is 7.8 to 8, which is a little alkaline. In detail, water from volcanic rocks and limestone generally shows a little higher mean value of pH, about 7.9, than sandstone and alluvium, about 7.7. Depth and pH is also not related specifically.

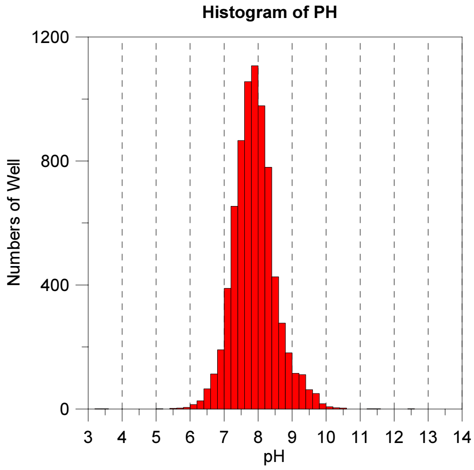


Figure 3.24 Histogram of pH

3) Temperature

The average temperature of groundwater is 22.6 C, though it ranges from 10.3 to 55.2 C. *Figure 3.25* shows the general tendency that a deeper aquifer has a higher temperature.

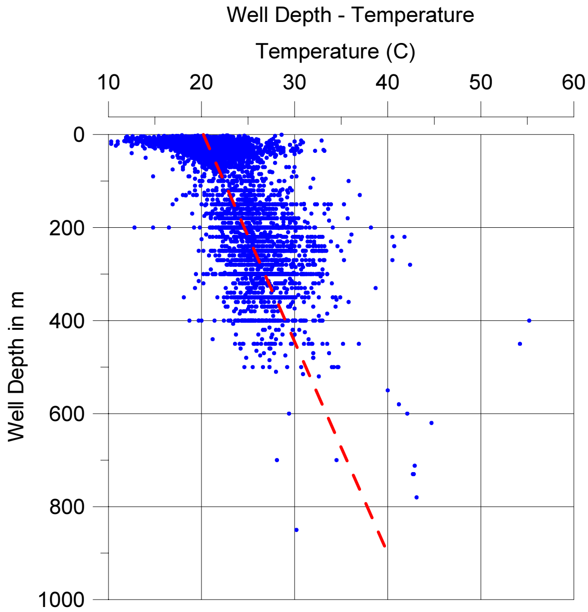


Figure 3.25 Well Depth and Temperature

(2) Result of Chemical Analysis

A detailed explanation about the result of groundwater chemical analysis has been described in SAWAS Technical Report No.13 (1996). The out line is briefly described with the Piper diagram in this section.

Figure 3.26 is the Piper diagrams showing the groundwater quality in the Sana'a Basin. In Alluvial aquifer, the cation composition is generally dominated by calcium and chloride dominates in the anion composition, that is, they are Ca Cl type of groundwater. Similarly, groundwater in the Sana'a basin is approximately classified to some types as below. The data of groundwater from Amran Limestone was not available.

Alluvial Aquifer; Ca HCO3-Cl type, Ca Cl type, Ca Mixed-anion type

Volcanic Rocks; Ca HCO3-Cl type, Ca Mixed-anion type
Na HCO3-Cl type, Na Mixed-anion type
Ca-Na HCO3-Cl type, Ca-Na HCO3-Cl type

Tawilah Sandstone; Ca HCO3-Cl type, Ca Cl type, Ca Mixed-anion type
Mixed-cation HCO3-Cl type, Mixed-cation Mixed-anion type

According to the figure, alluvial aquifer is characterized by relatively higher calcium and chloride, Volcanic Rocks aquifer is characterized by lower magnesium and relatively low sulfate, and Tawilah Sandstone aquifer is characterized by relatively higher calcium and mixed anion.

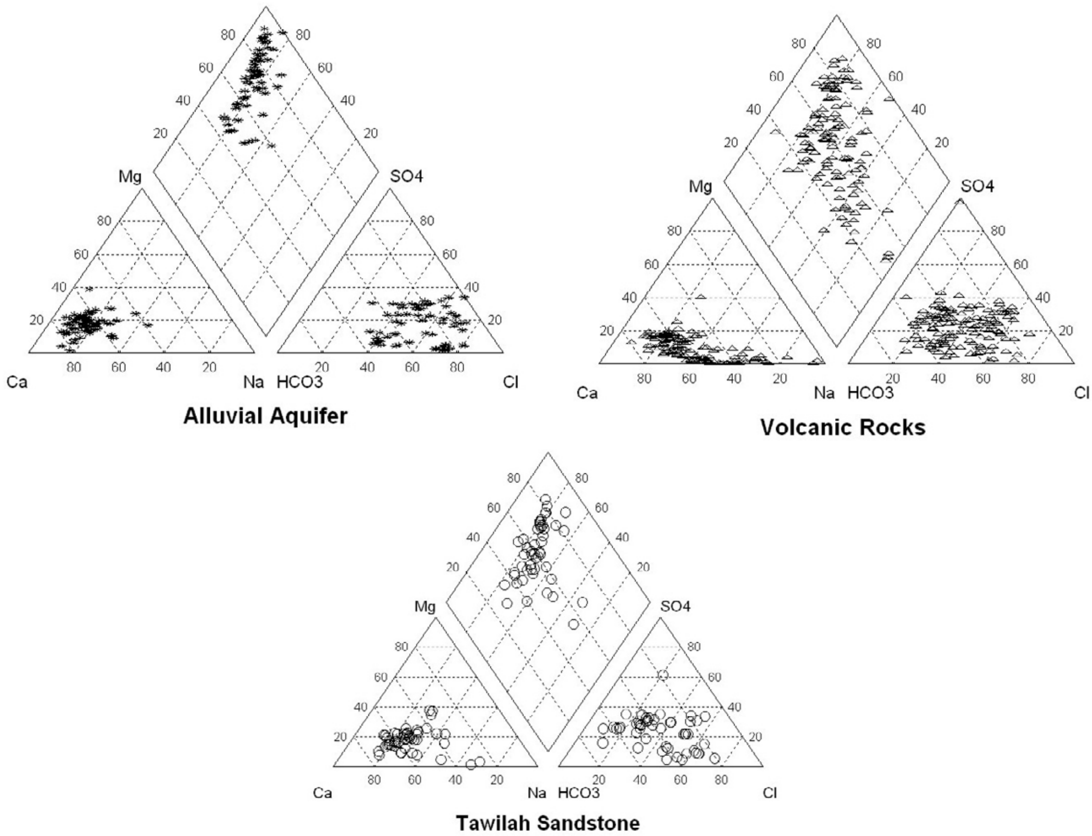


Figure 3.26 Piper Diagrams of Groundwater in the Sana'a Basin

(3) Fluoride

SAWAS Technical Report No.13 (1996) and GARWSP data collected by the Study team indicate some water samples have higher concentration of fluoride than the maximum permissible limit (MPL) of the national standard for drinking water. MPL is 1.5 mg/l and the highest desirable limit (HDL) is 0.5 mg/l. Fluoride in high concentration may cause "mottled enamel" in children's teeth.

Totally 202 samples with the concentration data of fluoride were collected and located. The concentrations of fluoride in 107 of 202 wells, 53%, were 0.5mg/l or less. 67 wells (33%) were in the fluoride concentration between 0.5 and 1.5mg/l. 28 other wells (14%) were in the fluoride concentration of more than 1.5 mg/l, including five wells more than 5 mg/l. *Figure 3.27* shows the distribution of the fluoride. Higher concentration of fluoride may be related to minerals in the volcanic rocks.

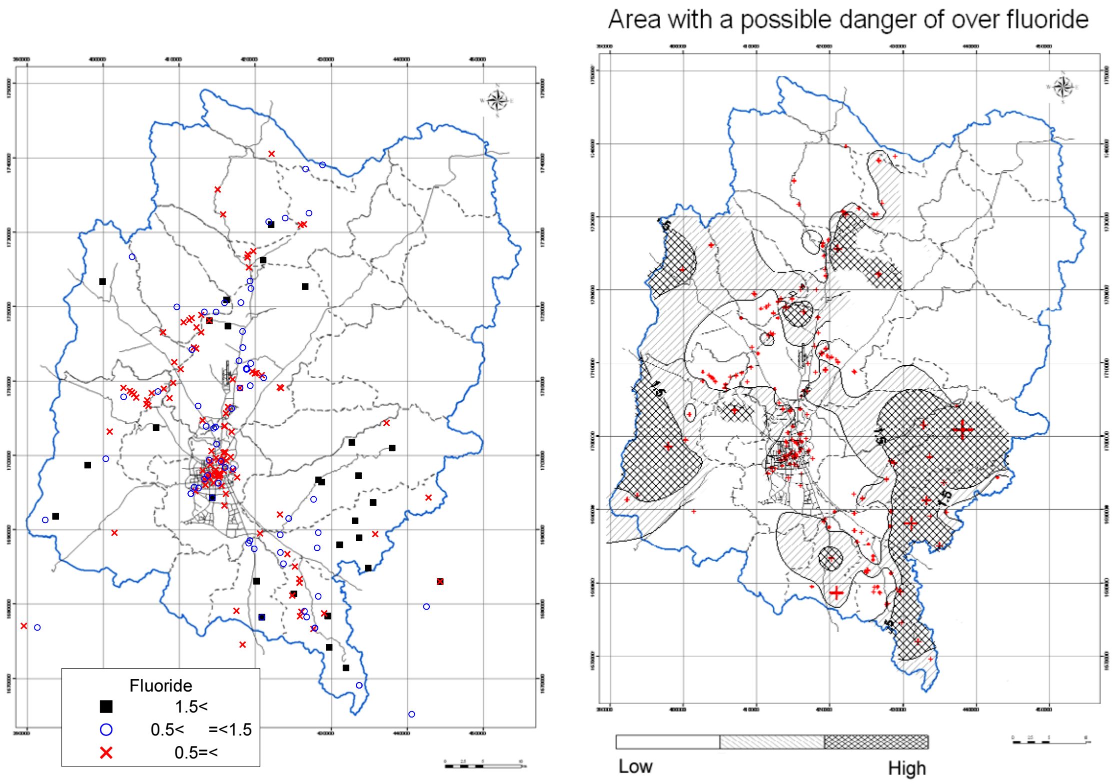


Figure 3.27 Distribution of Fluoride

3.5 WATER RESOURCES POTENTIAL IN SANA'A BASIN

3.5.1 GROUNDWATER RECHARGE

(1) Is it recharged?

WEC (2001)[13] cited some observable facts as evidence of the occurrence of recharge as follows,

- The very fast groundwater study in the Basin showed a water level rise in the Alluvial aquifer, Volcanic Rocks and Tawilah Sandstone for the period between 1965 and 1972. The rise was occurring when the over-pumping in the central part of the plain had already become a considerable subject.
- Reanalyzing the water level data collected during 1980's shows clear evidence of "water mound" following rainy seasons, which eventually disappears as the additional volume of water spreads across the aquifers.
- Rural habitants reported on a number of cases that water table had risen considerably due to the construction of small dams.

Several previous studies assumed that groundwater recharge occurred in the area of sandstone outcrop and wadi beds.

A recent survey of the isotope composition, which is mentioned in Foster (2003)[14], revealed evidence of contemporary (post-1965) natural recharge of the Quaternary Alluvial Aquifer. Although there is no definitive evidence in the current data of contemporary recharge having reached the Cretaceous Sandstone Aquifer, the report noted that the results do not yet exclude the possibility of modern recharge to the Cretaceous Sandstone Aquifer.

The Study team has considered that the natural recharge to the deeper aquifer is most probably occurring since:

- In the Sana'a Basin, the outcrop of the Sandstone is distributed widely from west to east in the central zone. And the volcanic rocks outcropped in the western and southern part of the Basin.
- Rainfall is considered able to infiltrate directly to these outcrops through the rich fissures and cracks of the rocks. There are a lot of springs flowing out from the rocks.
- The drilling works, especially the recent deep drilling up to 1,000 m, shows that there are many fractured zones in the rock underlying the wadi beds and the quaternary deposits.
- The monitoring well located in the Western Well Field, where the Tawilah Sandstone aquifer is exploited, shows the momentary increasing of the water level as shown in *Figure 3.28*. (A water level fluctuation may be caused by not only natural recharge and also various factors. Therefore it is important to monitor continuously water level, rainfall, pumping discharge and so on, in order to clarify the relationship of them.)

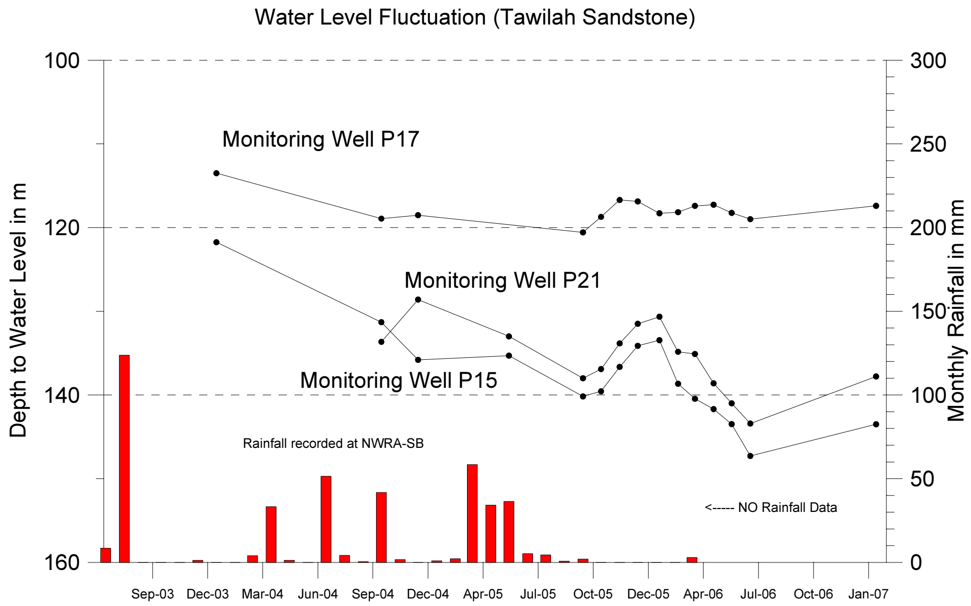


Figure 3.28 Fluctuation of Groundwater Level (Tawilah Sandstone)

(2) Estimation of Recharge

1) Previous Studies

Since 1970, several previous studies have estimated the amount of groundwater recharge in the Sana'a Basin. Adopted methods of the estimation can be grouped into two types, one is the method based on the Darcy Law, another one is the method using recharge coefficient.

The former one is the calculation of groundwater flow through the aquifer using the width and thickness of the aquifer, transmissivity and hydraulic gradient.

The latter one is the estimation using the rainfall in the area, the area or size of the surface, and recharge coefficient decided according to the surface conditions such as geology and land use.

The method using the Darcy Law is based on the transmissivity obtained from the results of few pumping tests and the assumed simplified shape of the aquifer though the geological structure is complicated in the Basin. Therefore, it is unclear whether the assumed values used for estimation reflect the actual characteristics of the aquifer. The recharge coefficients used for the estimation, also, are the empirical values, which are not obtained experimentally.

Consequently, the values of groundwater recharge have been calculated very roughly. In fact, the obtained valued range widely from 28 to 63 MCM annually as shown in *Table 3.12*.

Table 3.12 Estimation of Groundwater Recharge in the Sana'a Basin

Study	Term	Organization	Consultant	Method	Estimated Rechareg (Mm^3/y)
Water Supply for Sana'a and Hodeida. Sana'a Basin Groundwater Studies	1970-1973	NWSA	Italconsult	Darcy	59
Water Supply for Sana'a Phase 2	1980, 1983	NWSA	Howard Humphreys & Sons	Darcy	45-28
Sana'a Basin Water Resources Scheme	1986	MAF	Mosgiprovodkhoz	Recharge Coefficient	63
Assistance to the High Water Council in the Preparation of a Water Master Plan	1988-1992	HWC	Individual Experts	Recharge Coefficient	42
Sources for Sana'a Water Supply (SAWAS)	1987-1996	NWSA	TNO Institute of Applied Geoscience	Darcy	35
Sana'a Basin Water Resources Management Study (SBWRM-PPT)	2001	NWRA	Sana'a University, WEC	Recharge Coefficient	46

2) Recent Estimation of Groundwater Recharge in Sub-Basins

Norman and Mulat (2007) have recently estimated the amount of groundwater recharge in each sub-basin using the hydrological water balance equation of $\boldsymbol{R - (E + Q) = dS}$.

Where; R: rainfall (mm) = daily rainfall (1991 - 2003) data of the nearest observation station

E: evapotranspiration (mm) = estimated by ITC (1989)

Q: runoff (mm) = estimated by SCS Curve Number method

The daily change in soil moisture storage, dS, is calculated by the above equation and accumulated to estimate the average annual change of storage. Then, the following assumptions are adopted.

- The 90% of the soil moisture storage (dS) is consumed by plants and transpired or directly evaporated from the soil. The other 10% recharges the aquifer.
- The 40% of the runoff generated in the catchments is either directly used for irrigation, evaporate from reservoirs, or flow downstream in case of big floods. The other 60% recharges the aquifer.

Finally, the amount of groundwater recharge in the Sana'a basin has been calculated at 50.7 MCM/year in total. *Table 3.13* shows the detailed estimation of each sub-basin.

Table 3.13 Estimated Groundwater Recharge in Sub-basins

No	Sub Basin	Estimated Recharge (MCM)
1	Wadi al Mashamini	0.86
2	Wadi al Madini	2.73
3	Wadi al Kharid	1.76
4	Wadi al Ma'adi	1.71
5	Wadi A'sir	4.27
6	Wadi Khulaqah	1.54
7	Wadi Qasabah	0.83
8	Wadi al Huqqah	1.36
9	Wadi Bani Hwat	5.58
10	Wadi Thumah	1.00
11	Wadi as Sirr	3.81
12	Wadi al Furs	0.79
13	Wadi al Iqbal	2.31
14	Wadi Zahr & al Ghayl	7.11
15	Wadi Hamdan	0.82
16	Wadi al Mawrid	1.54
17	Wadi Sa'Wan	1.41
18	Wadi Shahik	4.12
19	Wadi Ghayman	1.24
20	Wadi al Mulakhy	1.66
21	Wadi Hizyaz	1.92
22	Wadi Akhwar	2.32
Total		50.7

Source; Dr. A.Norman and Eng. W. Mulat (2007), Water Balance and Hydrological Monitoring

3) Conclusion

As described above, the groundwater recharge in the Sana'a basin has been estimated at about 50 MCM/year based on the various assumptions. Even the results are very rough estimation, the adopted assumptions are passably reasonable from hydrogeological points of view. The actual natural recharge is most likely settled into the estimated range, 28-63 MCM annually, in the rough.

3.5.2 GROUNDWATER STORAGE

Storage of groundwater, S_t, can be estimated with the equation of $S_t = AHS_y$., where, A is the area of aquifer, H is saturated thickness and S_y is specific yield, or effective porosity.

TS-HWC (1992)[15] estimated the storage of groundwater in the Sana'a basin using this equation. They supposed that the depth of 250 m was the maximum depth that the groundwater storage could be commanded, and about 50% of this commandable storage could be extracted, or usable. Besides the specific yield was assumed at 0.1 for Alluvial aquifer, 0.01 for Amran Limestone and 0.03 for Tawilah Sandstone. Consequently, the estimated volume of commandable storage was 6,047 MCM and the usable storage was 3,221 MCM in the Sana'a Basin. Please note, however, that the assumptions used to derive these estimations are fairly rough figures as they themselves mentioned it.

WEC (2001) has revised the above approach with the updated water levels, and estimated the storage volume of each groundwater province in the Sana'a basin. As a result, the commandable storage and the usable storage were calculated 10,424 MCM and 5,212 MCM respectively. They mentioned that the volume obtained by TS-HWC should be very conservative estimates because of the water levels applied to calculations were over-estimated. The assumptions such as specific yield remain in rough and ready estimates.

3.5.3 SURFACE WATER

Although surface runoff has not been measured for the present, the runoff volume of surface water has been estimated as described in the section of 3.3.6. *Table 3.14* shows the summarized figures of the annual flow of each sub-basin. Annual Flow is the values totaled by yield of dams/pools and springs in the basin. In addition, Annual Runoff was calculated based on the runoff coefficient suggested by WRY-35 (1995) and rainfall applied in SBWMP, Norman and Mulat (2007). In the Wadi Al Kharid, the accumulated annual flow is several times as much as the annual runoff estimated with the runoff coefficient. It seems to reflect there are springs yielding 0.2 m^3/s near Samnah in the Al Kharid Basin.

At any rate, most of them, flow or runoff water, have been used for irrigation and/or other purposes, and some of them infiltrate to wadi bed finally.

Table 3.14 Annual Flow/Runoff of Sub-Basins

Zone	Sub-Basin	Annual Flow (10^3m^3)	Rainfall (mm)	Catchment (km^2)	Runoff coefficient	Annual Runoff (10^3m^3)
1	Wadi Al Mashamini	412	171	76.5	0.055	719
2	Wadi Al Madini	-	191	211.5	0.055	2,222
3	Wadi Al Kharid	11,078	191	136.7	0.055	1,436
4	Wadi Al Ma'adi	1,033	185	111.5	0.055	1,135
5	Wadi A'sir	5,071	229	210.2	0.055	2,647
6	Wadi Khulaqah	1,588	229	75.9	0.055	956
7	Wadi Qasabah	-	191	64.6	0.055	679
8	Wadi Al Huqqah	-	187	120.7	0.055	1,241
9	Wadi Bani Huwat	-	242	322.4	0.055	4,291
10	Wadi Thumah	1,226	191	77.6	0.055	815
11	Wadi As Sirr	2,223	202	219.1	0.055	2,434
12	Wadi Al Furs	196	242	45.8	0.055	610
13	Wadi Al Iqbal	850	187	204.4	0.055	2,102
14	Wadi Zahr & Al Ghayl	617	279	364.8	0.055	5,598
15	Wadi Hamdan	1,300	217	63.7	0.055	760
16	Wadi Al Mawrid	659	210	179.6	0.055	2,074
17	Wadi Sa'wan	1,193	223	95.4	0.055	1,170
18	Wadi Shahik	1,815	202	236.9	0.055	2,632
19	Wadi Ghayman	1,519	210	143.8	0.055	1,661
20	Wadi Al Mulaikhy	550	249	69.8	0.055	956
21	Wadi Hizyaz	296	249	80.5	0.055	1,102
22	Wadi Akhwar	938	173	125.4	0.055	1,193
	Total	32,563				38,435

3.5.4 TREATED WASTEWATER

Sana'a Wastewater Treatment Plant (WWTP) is located in a sensitive area adjacent to the International Airport with design capacity to treat 50,000 m^3/day of sewage water which comes from the city of Sana'a

According to data from Sana'a Water and Sanitation Local Corporation, who operates the WWTP, the quantity of sewage water have reached the WWTP in 2005 and 2006 is shown in

Table 3.15.

Table 3.15 WWTP Influent for 2005 and 2006

Year	WWTP influent
2005	11.0
2006	16.0

Unit: million cubic meters

Actually the WWTP is operating overloaded as explained in section 5.7.2 and the wastewater improperly treated is discharged to the wadi via a lagoon. The treated water flows by gravity to the downstream through an open channel and farmers are using this water to irrigate their lands. A very small amount of treated water is also used to water trees lining streets and green areas in the city.

Upgrading of WWTP to treat all influent wastewater to an acceptable quality following international standards for reuse in agriculture and watering trees is ongoing. Plans for construction of two new treatment plants are under preparation. One is with daily treatment capacity about 500 m^3/day, with objective to treat sewage brought by tankers from cesspits of the city and other with treatment capacity of 105,000 m^3/day. Details are explained on section 5.7.2.

Consequently, at least, treated wastewater cannot be accounted as a source of water. In the near future, however finishing the upgrade of present WWTP and construction of new treatment plant, the treated water could be accounted as a source of water for irrigation and the expected quantity is a minimum of 18.3 to a maximum of 56.6 MCM/year

3.6 WATER BALANCES IN SUB-BASINS

The water balance in the Sana'a Basin was generally calculated by the previous studies. The results were very rough estimation in the whole Sana'a Basin. The two types of somewhat detailed water balance evaluation in sub-basins have been provided recently by the parts of SBWMP, one is the hydrological approach adopted in Norman and Mulat (2007), which is mentioned in the previous section of 3.5.1, and another one is based on the satellite imagery analysis, GAF (2007).

3.6.1 HYDROLOGICAL APPROACH OF WATER BALANCE ANALYSIS

The estimation of groundwater recharge by the hydrological approach is explained in the 3.5.1. The water balance was calculated by the recharge minus the abstraction from well. The groundwater abstraction was obtained from the result of well inventory survey (2002). *Table 3.16* shows the result. Norman and Mulat (2007) have not counted the return flow from irrigation and sewage. A certain portion of the water applied to an irrigated area is not used up as consumptive use, but infiltrates, eventually reaching the water table. It may amount of as much as 20 to 40%[16] of the volume of water used for irrigation. On assumption that the ratio is 30%, the revised values are calculated and are shown in the same *Table 3.16*.

Table 3.16 Water Balance in Sub-Basins by Hydrological Approach

	Sub-Basin	Recharge (Mm^3)	Abstraction (Mm^3)	Water Balance (Mm^3)	Return Flow (30%) (Mm^3)	Consumed Volume (Mm^3)	Revised Balance (Mm^3)	Comsumed Ratio /Recharge
1	Wadi Al Mashamini	0.90	0.85	0.05	0.26	0.60	0.30	0.66
2	Wadi Al Madini	2.73	2.92	-0.19	0.88	2.04	0.68	0.75
3	Wadi Al Kharid	1.76	3.36	-1.60	1.01	2.35	-0.59	1.33
4	Wadi Al Ma'adi	1.71	2.67	-0.96	0.80	1.87	-0.16	1.10
5	Wadi A'sir	4.27	6.93	-2.66	2.08	4.85	-0.58	1.14
6	Wadi Khulaqah	1.54	2.12	-0.58	0.64	1.48	0.06	0.96
7	Wadi Qasabah	0.83	2.12	-1.29	0.64	1.48	-0.65	1.78
8	Wadi Al Huqqah	1.36	17.36	-16.00	5.21	12.15	-10.79	8.91
9	Wadi Bani Huwat	5.58	60.87	-55.29	18.26	42.61	-37.03	7.64
10	Wadi Thumah	1.00	3.25	-2.25	0.98	2.28	-1.27	2.27
11	Wadi As Sirr	3.81	39.06	-35.25	11.72	27.34	-23.53	7.17
12	Wadi Al Furs	0.79	13.60	-12.81	4.08	9.52	-8.73	12.02
13	Wadi Al Iqbal	2.31	17.46	-15.15	5.24	12.22	-9.91	5.29
14	Wadi Zahr & Al Ghayl	7.11	16.51	-9.40	4.95	11.56	-4.44	1.62
15	Wadi Hamdan	0.82	7.47	-6.65	2.24	5.23	-4.41	6.36
16	Wadi Al Mawrid	1.54	35.40	-33.86	10.62	24.78	-23.24	16.04
17	Wadi Sa'wan	1.41	8.82	-7.41	2.65	6.17	-4.76	4.37
18	Wadi Shahik	4.12	10.41	-6.29	3.12	7.29	-3.16	1.77
19	Wadi Ghayman	1.24	4.23	-2.99	1.27	2.96	-1.72	2.39
20	Wadi Al Mulaikhy	1.66	2.96	-1.30	0.89	2.07	-0.41	1.25
21	Wadi Hizyaz	1.92	3.17	-1.25	0.95	2.22	-0.30	1.16
22	Wadi Akhwar	2.32	8.44	-6.12	2.53	5.91	-3.59	2.55
	Total	50.7	270.0	-219.2	81.0	189.0	-138.2	(4.02)

Source; Modified Norman and Mulat (2007)

The above table also shows the consumed volume ratio per recharge amount in the sub-basin. The results are classified to four classes. The first one is the group with the ratio of over 10. The second is the group with the ratio between 5 and 10, the third is the ratio of between one and five, and the fourth is the ratio of less than one. The worst two groups are as follows:

1st Group: The two sub-basins where groundwater consumed volume is suspected more than 10 times of the recharge amount.

Wadi al Mawrid: The city of Sana'a is located in this sub-basin. Most of the abstracted groundwater is used for domestic use.

Wadi al Furs: This is the smallest sub-basin, but there are many wells along the wadi beds in the area.

2nd Group: The five sub-basins where groundwater consumed volume is suspected 5-10 times of the recharge amount.

Wadi al Huqqa, Wadi Bani Huwat, Wadi as Sirr, Wadi Hamdan, Wadi al Iqbal

3.6.2 WATER BALANCE ESTIMATED BY SATELLITE IMAGERY ANALYSIS

Table 3.17 Water Balance Estimated by Satellite Imagery Analysis (2004/05)

	Sub-Basin	Rainfall (04/05)		Eta Irrigated Crop	Agriculture Water Use (irrigation)	Effective Rainfall (Mm^3)			Balance (Mm^3)		
		(mm)	(Mm^3)	(Mm^3)	(Mm^3)	Min.		Max.	Min.		Max.
1	Wadi al Mashamini	290	22.6	0.4	0.6	1.3	-	1.5	0.7	-	0.9
2	Wadi al Madini	292	62.3	1.8	3.0	3.5	-	3.9	0.5	-	0.9
3	Wadi al Kharid	193	26.7	1.2	2.0	1.5	-	1.5	-0.5	-	-0.5
4	Wadi al Ma'adi	202	22.5	0.5	0.9	1.3	-	1.3	0.4	-	0.4
5	Wadi A'sir	251	52.4	3.1	5.1	2.9	-	3.1	-2.2	-	-2.0
6	Wadi Khulaqah	180	13.6	0.9	1.6	0.7	-	0.7	-0.9	-	-0.9
7	Wadi Qasabah	251	16.2	1.0	1.6	0.9	-	1	-0.7	-	-0.6
8	Wadi al Huqqah	261	31.4	5.8	9.7	1.8	-	2.3	-7.9	-	-7.4
9	Wadi bani Huwat	206	67.4	19.5	32.4	4.0	-	5.4	-28.4	-	-27.0
10	Wadi Thumah	210	16.2	0.5	0.8	0.9	-	1.0	0.1	-	0.2
11	Wadi as Sirr	247	54.0	9.9	16.5	3.1	-	3.8	-13.4	-	-12.7
12	Wadi al Furs	185	8.5	3.4	5.7	0.5	-	0.5	-5.2	-	-5.2
13	Wadi al Iqbal	305	61.9	7.9	13.1	3.6	-	4.4	-9.5	-	-8.7
14	Wadi Zahr & al Ghayl	366	132.1	6.5	10.9	11.8	-	11.8	0.9	-	0.9
15	Wadi Hamdan	297	18.9	4.1	6.8	1.1	-	1.4	-5.7	-	-5.4
16	Wadi al Mawrid	268	48.0	3.5	5.8	2.7	-	3.1	-3.1	-	-2.7
17	Wadi Sa'wan	228	21.9	4.0	6.7	1.3	-	1.5	-5.4	-	-5.2
18	Wadi Shahik	293	69.9	4.1	6.9	4.0	-	4.4	-2.9	-	-2.5
19	Wadi Ghayman	290	41.6	2.2	3.7	2.4	-	2.7	-1.3	-	-1.0
20	Wadi al Mulaikhy	327	22.8	1.4	2.3	1.3	-	1.6	-1.0	-	-0.7
21	Wadi Hizyaz	268	21.9	1.1	1.8	1.2	-	1.4	-0.6	-	-0.4
22	Wadi Akhwar	276	34.7	1.0	1.6	1.9	-	2.1	0.3	-	0.5
	Total Sana'a Basin		867.2	83.7	139.5	53.9	-	60.5	-85.6	-	-79.0

Source: Modified GAF (2007)

Using the irrigated area and the actual evapotranspiration estimated by the satellite imagery analysis, the amount of water for agriculture use, which was supposed to be abstracted all by wells, were calculated with the assumption of the irrigation efficiency of 60%. (The water amount was recalculated as explained in the 5.4.2.) Effective rainfall, that is, the amount of rainfall that could be used by vegetation, was estimated as the sum of infiltration of overland flow in wadi and the infiltration of precipitation after heavy rainfall event. Overland flow was estimated by the runoff coefficient, 5.5%, supposed by WRAY-35 (1995). The infiltration after heavy rain was estimated by the method introduced by the U.S. Department of Agriculture's Soil Conservation Service. Then, the water balance was obtained by the effective rainfall minus the amount of water use for agriculture. *Table 3.17* shows the results.

As explained above, this water balance is obtained only using the water use for agriculture (irrigated). The other water usages should be included in this calculation naturally. Therefore, *Table 3.18* is prepared after revising with the results of Chapter 5.

As a rough standard to compare the results, the ratio of the volume of water use to rainfall in the area was calculated. The higher ratio means the higher water consumption comparing with the natural replenishment, which is probably corresponding to rainfall. There are five sub-basins where the ratio is between 20 and 40%, two sub-basins where the ratio is between 50 and 70%.

One sub-basin has the ratio around 175%.

Five sub-basins where the ratio is between 20 and 40% are Wadi Huqqah, Wadi As Sirr, Wadi Al Iqbal, Wadi Hamdan and Wadi Sa'wan. Two sub-basins where the ratio is between 50 and 70% are Wadi Bani Huwat and Wadi Al Furs and the sub-basin with ratio of 176% is Wadi Al Mawrid where Sana'a City is located. Two sub-basins, Wadi Al Furs and Wadi Al Mawrid, are listed in the 1st group of the higher ratio of consumption to recharge by the hydrological approach, too. Wadi Huqqah, Wadi Bani Huwat, Wadi As Sirr Wadi Al Iqbal and Wadi Hamdan are listed in the 2nd group described in the previous section.

These seven double listed sub-basins as 1) Wadi Huqqa, 2) Wadi Bani Huwat, 3) Wadi As Sirr, 4) Wadi As Furs, 5) Wadi Al Iqbal, 6) Wadi Hamdan and 7) Wadi Al Mawrid are considered to be in a very critical condition of groundwater resources.

Table 3.18 Modified Water Balance Estimation based on the Satellite Imagery Analysis (2004/05)

No.		Water Use: Agriculture (Mm^3)	Water Use: Urban Water Supply (Mm^3)	Water Use: Rural Water Supply (Mm^3)	Water Use: Industry /Tourism /Others (Mm^3)	Water Use: Total (Mm^3)	Effective Rainfall (Mm^3) Min.		Effective Rainfall (Mm^3) Max.	Balance (Mm^3) Min.		Balance (Mm^3) Max.	Water Use/Rainfall
1	Wadi al Mashamini	0.6	-	0.04	-	0.6	1.3	-	1.5	0.7	-	0.9	2.8%
2	Wadi al Madini	3.0	-	0.10	-	3.1	3.5	-	3.9	0.4	-	0.8	5.0%
3	Wadi al Kharid	2.0	-	0.07	-	2.1	1.5	-	1.5	-0.6	-	-0.6	7.7%
4	Wadi al Ma'adi	0.9	-	0.02	-	0.9	1.3	-	1.3	0.4	-	0.4	4.1%
5	Wadi A'sir	5.1	-	0.03	-	5.1	2.9	-	3.1	-2.2	-	-2.0	9.8%
6	Wadi Khulaqah	1.6	-	0.01	-	1.6	0.7	-	0.7	-0.9	-	-0.9	11.9%
7	Wadi Qasabah	1.6	-	0.03	-	1.6	0.9	-	1	-0.7	-	-0.6	10.1%
8	Wadi al Huqqah	9.7	-	0.09	-	9.8	1.8	-	2.3	-8.0	-	-7.5	31.2%
9	Wadi bani Huwat	32.4	-	0.11	2.38	34.9	4.0	-	5.4	-30.9	-	-29.5	51.8%
10	Wadi Thumah	0.8	-	0.02	-	0.8	0.9	-	1	0.1	-	0.2	5.0%
11	Wadi as Sirr	16.5	-	0.26	-	16.8	3.1	-	3.8	-13.7	-	-13.0	31.0%
12	Wadi al Furs	5.7	-	0.07	-	5.8	0.5	-	0.5	-5.3	-	-5.3	67.9%
13	Wadi al Iqbal	13.1	-	0.19	-	13.3	3.6	-	4.4	-9.7	-	-8.9	21.5%
14	Wadi Zahr & al Ghayl	10.9	-	0.29	-	11.2	11.8	-	11.8	0.6	-	0.6	8.5%
15	Wadi Hamdan	6.8	-	0.06	-	6.9	1.1	-	1.4	-5.8	-	-5.5	36.3%
16	Wadi al Mawrid	5.8	75.6	0.08	2.74	84.2	2.7	-	3.1	-81.5	-	-81.1	175.5%
17	Wadi Sa'wan	6.7	-	0.14	-	6.8	1.3	-	1.5	-5.5	-	-5.3	31.2%
18	Wadi Shahik	6.9	-	0.20	-	7.1	4	-	4.4	-3.1	-	-2.7	10.2%
19	Wadi Ghayman	3.7	-	0.13	-	3.8	2.4	-	2.7	-1.4	-	-1.1	9.2%
20	Wadi al Mulaikhy	2.3	-	0.05	-	2.4	1.3	-	1.6	-1.1	-	-0.8	10.3%
21	Wadi Hizyaz	1.8	-	0.08	-	1.9	1.2	-	1.4	-0.7	-	-0.5	8.6%
22	Wadi Akhwar	1.6	-	0.12	-	1.7	1.9	-	2.1	0.2	-	0.4	5.0%
	Total Sana'a Basin	139.5	75.6	2.21	5.1	222.4	53.9	-	60.5	-168.5	-	-161.9	25.6%

3.7 ADVERSE IMPACT ON GROUNDWATER RESOURCES

3.7.1 PRESENT CONDITION OF ADVERSE IMPACT

An adverse impact on groundwater means an impact resulting in a reduction of the quantity, that is, less yield of existing wells and ending up with the exhaustion of aquifer, and deterioration in groundwater quality, which bring about being unsuitable for domestic, industrial or agricultural use.

(1) Groundwater Level

1) Recent Monitoring Result

A reduction of the quantity shows a fall of groundwater level. Recently NWRA constructed the monitoring network for water levels in the Sana'a basin. There are 33 monitoring wells measured manually every month generally. The number of monitoring wells is planned to increase. In addition, six wells have been installed automatic water level recorder in 2007. *Table 3.19* and *Figure 3.29* shows the locations of these/ monitoring wells.

Table 3.19 Monitoring Wells in the Sana'a Basin

	Code No.	Site Name	District	UTM North	UTM East	Elev.m.	Aquifer	Well Typ
1	P8	W.F.Wes	Ban-Alhar	1704571	412810	2218	Sandstone	
2	O5	W.F.Wes	Ban-Alhar	1707273	411188	2238	Sandstone	
3	P17	W.F.Wes	Ban-Alhar	1708945	409750	2248	Sandstone	
4	P15	W.F.Wes	Ban-Alhar	1709656	409305	2234	Sandstone	
5	P21	W.F.Wes	Ban-Alhar	1710064	410067	2209	Sandstone	
6	F783A	Al Hawri	Hamdan	1715555	411390	2232	Volcanic	
7	A2069	Maribcamp	Ban-Alhar	1714346	4018244	2206	Volcanic	Borehole
8	F 2356	B-alhally	Ban-Alhar	1715014	416162	2192	Volcanic	Dug+Drill
9	F 2357	B-alhally	Ban-Alhar	1715109	416242	2145	Alluvium	
10	F 1446	B-alhally	Ban-Alhar	1718865	416298	2182	Alluvium	Borehole
11	F2131	Bossan	Arhab	1728956	417429	2217	Limestone	
12	F2143	Makarib	Arhab	1730178	421335	2136	Limestone	
13	F 1445	B-Mosaed	Ban-Alhar	1716838	417904	2188	Alluvium	Borehole
14	F1947A	Almasham	Ban-Alhar	1727571	421495	2129	Limestone	Borehole
15	F 2003	W-dogish	Arhab	1729224	425801	2052	Limestone	Dug+Drill
16	C1849	Al-req val.	Ban-Alhar	1711873	424320	2237	Volcanic	
17	C1564	Al-grass	Ban-Alhar	1716018	428437	2239	Sandstone	Dugwell
18	D25	Dharhan	Bani-Hus	1699850	426648	2400	Alluvium	Dugwell
19	C1 146	Alqariah	Bani-Hus	1700113	425179	2367	Alluvium	Dugwell
20	U358A	Aswad	Sanhan	168711	418990	2341	Volcanic	Dugwell
21	U1146A	Rihm	Sanhan	1678618	419008	2400	Volcanic	Borehole
22	B-665A	Maqwalah	Sanhan	1675449	429994	2500	Volcanic	Dugwell
23	B-683	Bit saani	Sanhan	1677294	426909	2502	Volcanic	Dugwell
24	E-2366	Safiat Tamash	Sanhan	1690120	422210	2349	Alluvium	
25	E-2377	Shahik	Sanhan	1701896	439685	2582	Alluvium	Dugwell
26	E-1749	Bani Bahlul	Sanhan	1698001	430469	2460	Volcanic	Dugwell
27	U-427A	Al Nahdeen	Sana'a	1692469	414845	2302	Volcanic	Borehole
28	U-502A	Haddah/azal	Al amanh	1692422	413170	2326	Volcanic	Borehole
29	A878	Almasjed	Bani mater	1692294	401298	2576	Alluvium	
30	A-1038	Raas Alhissin	Bani Matar	1695434	402468	2548	Alluvium	
31	A874A	Aser Almwred	Sana'a	1696814	408818	2411	Alluvium	
32	A-848-A-	Alkhasmah	Bani Matar	1695167	403380	2566	Alluvium	

33	A-691-A	Shamlan	Hamdan	1703827	407993	2342	Volcanic	
Monitoring Wells with Automatic Water Level Recorder								
	Motre well	Wadi Sawan		1704788	432456	-	Volcanic	Borehole
	HS50	Wadi Asir		1711250	427232	-	Sandstone	Borehole
	AS-6	Wadi Al Amanh		1696061	411221	-	Volcanic	Borehole
	ST-7	Wadi Al Amanh		1704200	413910	-	Sandstone	Borehole
	A2069	Wadi Al Amanh		1714346	401824	-	Volcanic	Borehole
	Lualuah	Wadi Hamdan		1701177	400882	-	Volcanic	Borehole

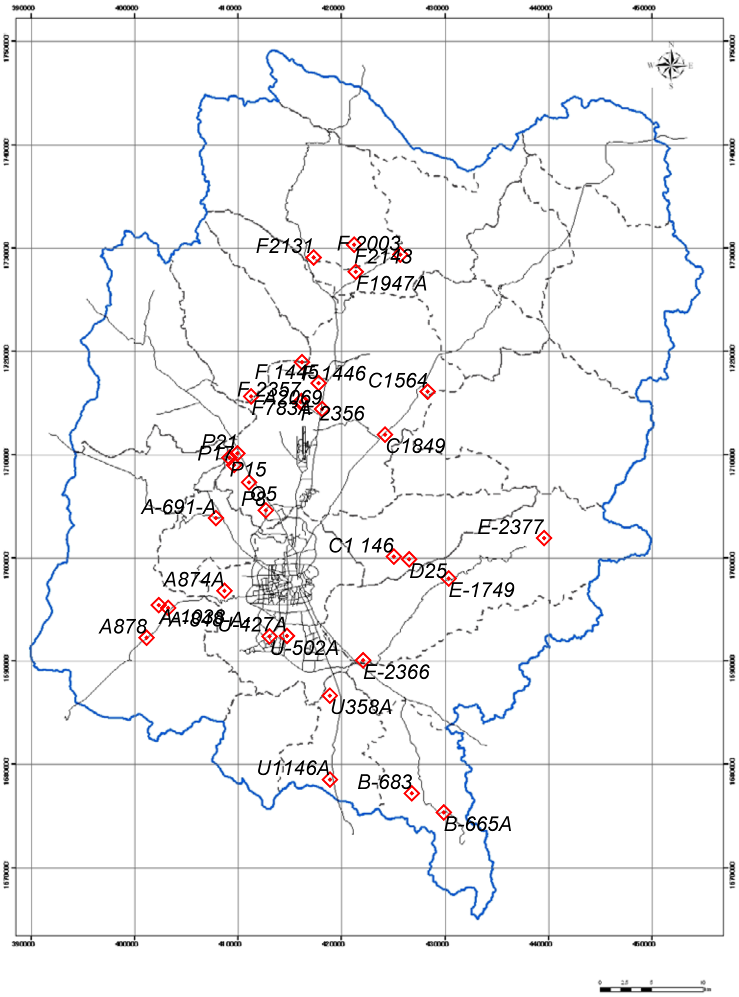


Figure 3.29 Locations of Water Level Monitoring Wells

The result of monitoring is tabulated in *Appendix 2*. *Figure 3.30* shows the fluctuation of water level from August 2003 to January 2007. The figure illustrates the change of water levels clearly especially from September 2005 to June 2006, because the periodical well-regulated monitoring had been continued during the term whereas the other periods with only scattering measurement. It indicates the importance of continual and regulated monitoring. From 2003 to 2007, however, it is not clear whether the water levels have a tendency of decline or not. Only a few wells, i.e. P8, P15 and P21, located in the sandstone well field, which is Western Well Field for the Sana'a water supply system, look to show a tendency of water level decline, though P18 was measured only four times during the period.

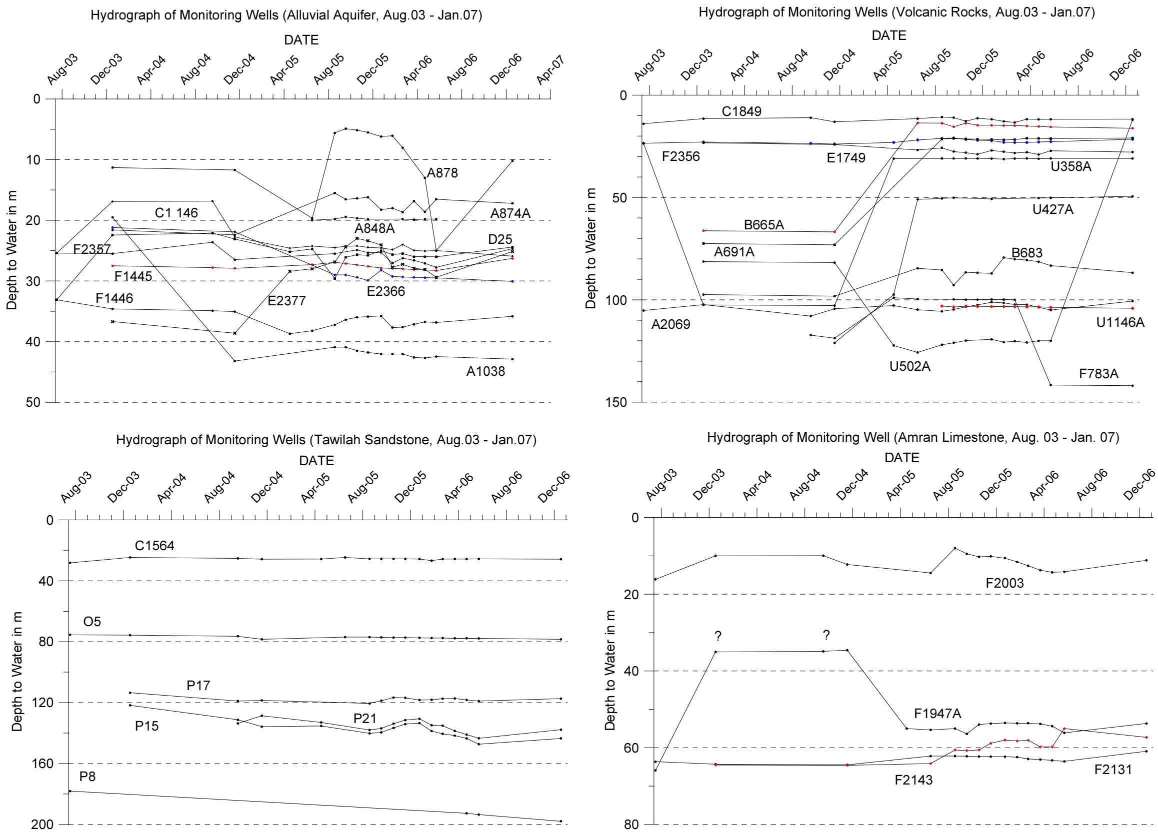


Figure 3.30 Hydrograph of Monitoring Well

2) Long-term Tendency of Water Level Change

<Water level of the western well field>

Howard Humphreys & Sons (1980)[17] shows the static water levels of the wells constructed in the Western Well Field measured in October - November 1979. *Table 3.20* show the comparison of water level between 1979 and 2007.

Table 3.20 Water Level Change between 1979 and 2007 in Western Well Field

Well	Elevation (mamsl)	Depth to Water (m) Oct-Nov. 79	Water Level (m-amsl) Oct-Nov. 79	Depth to Water (m) Jan. 07	Water Level (m-amsl) Jan. 07	Difference (m)	Annual Falling Water Level (m/year)
P8	2231.87	47.32	2184.55	197.87	2034.00	-150.55	-5.54
P15	2224.54	55.29	2169.25	143.49	2081.05	-88.20	-3.25
P17	2216.35	45.95	2170.40	117.40	2098.95	-71.45	-2.63
P21	2215.87	53.54	2162.33	137.79	2078.08	-84.25	-3.10
O5	2211.13	33.07	2178.06	78.42	2132.71	-45.35	-1.67

Although the recent monitoring shows not so clearly a decline of water level in the Sana'a basin as described in the previous section, *Table 3.20* indicate at least the water level of Western Well Field has dropped for these several decades. P8 that showed the largest falling of water level, -150 m for 28 years, is located in the almost center of the Well Field, so the result may reflect the well has been affected by pumping of surrounding production wells. P15, P17 and P21 are located at the northwest end of the Well Field, and there are few production wells around O5.

The expected thickness of the Tawilah Sandstone in the area of Western Well Field is only 400 m, which underlies the Alluvial deposits with the thickness of about 10 m. The range from 140 to 200m of the depth to water showing in the above table means that the thickness of the aquifer has decreased up to 60 to 70% of the original saturated thickness. It is recommended that the drawdown in an aquifer should not exceed around 50 to 60 % of the saturated thickness[18], not to cause any adverse impact such as the deterioration of quality. If the decline of the water level will continue with the annual rate of 3.1-5.5 m as shown in the above table, the water table will reach the critical level in 6 to 10 years.

<Another observable fact about water level>

Figure 3.31 shows the distribution of the depth of boreholes drilled from 1970s to 2002. The shaded area indicates where the drilled depth of more than 300m dominates. The area has clearly expanded with the times. It is considered that there are some reasons. One is the technical one that a depth of borehole became deeper with improved drilling technology, and boreholes have been drilled in highland areas where a borehole was not drilled before. Most of the areas with 400m or more drilled depth shown in the figure seem to be such highland areas. Another main reason is most likely that the depth of 300m or less became not enough to get sufficient water due to a decline of the groundwater level. It may be true especially the surrounding area of Sana'a city.

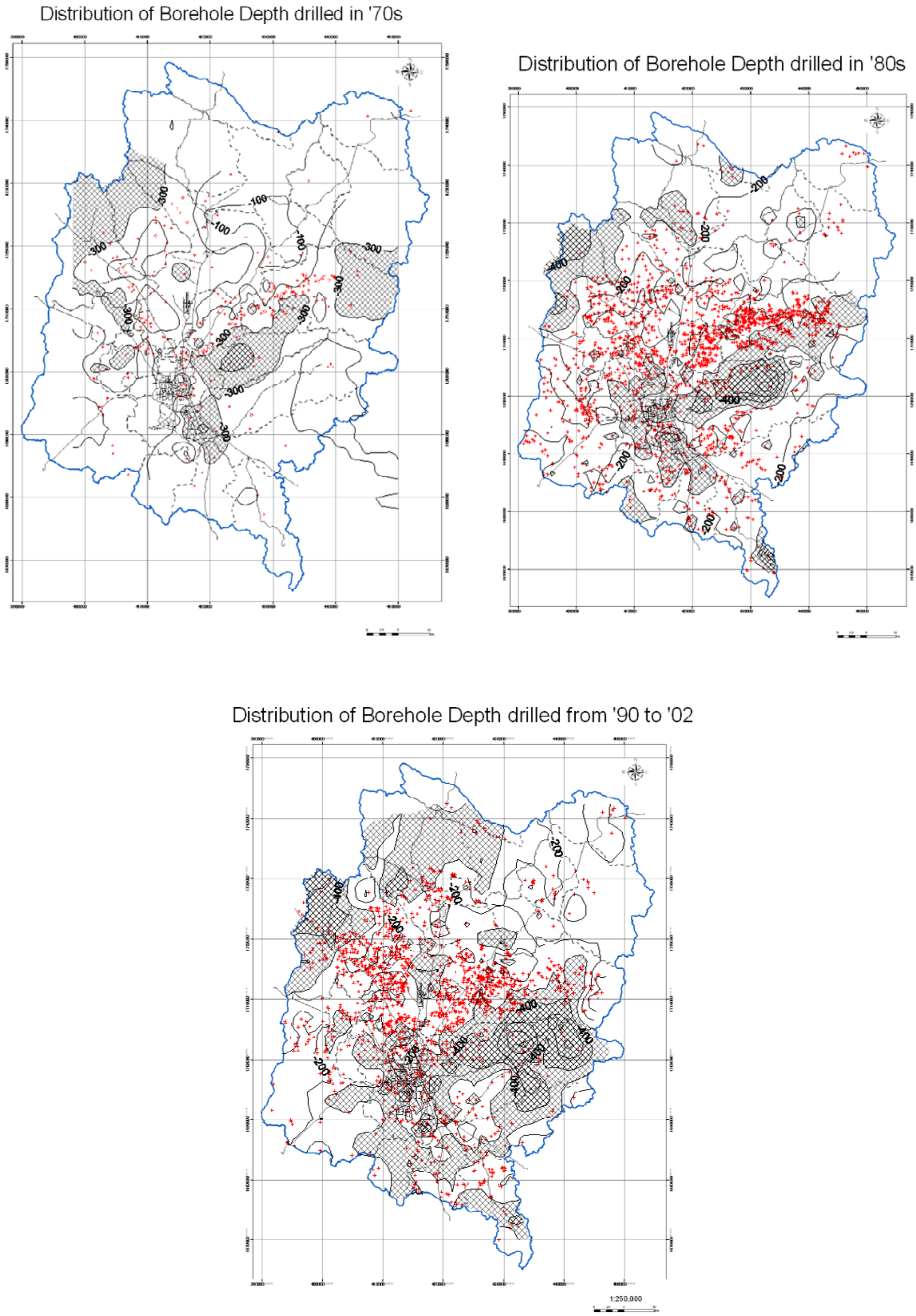
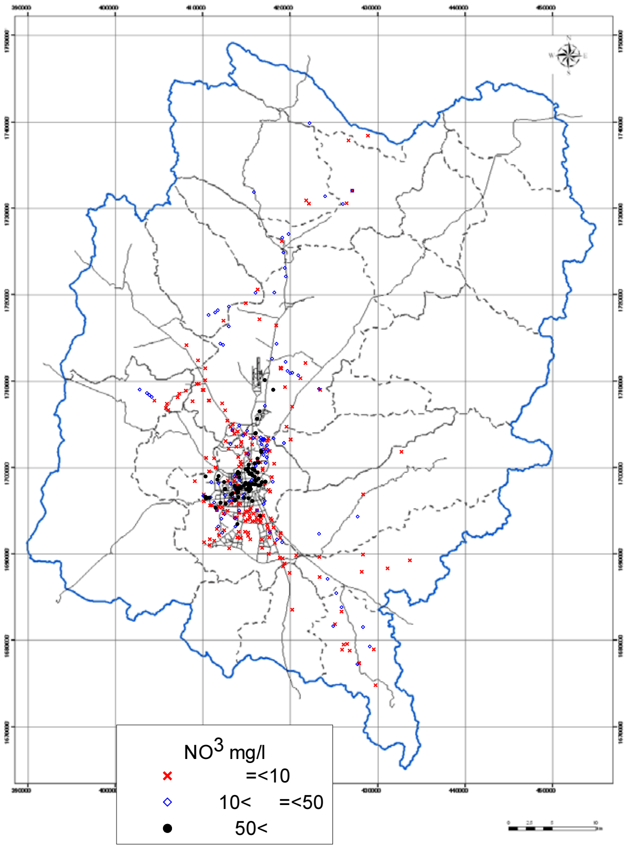


Figure 3.31 Depth of Boreholes drilled from 1970 to 2002

(2) Groundwater Quality

SAWAS Technical Report No.13 (1996) mentioned the possibility of groundwater contamination in the Sana'a Basin. Most possible contamination source is sewage disposal on land at present. *Figure 3.32* shows the distribution of nitrate concentration based on the data measured in 1996 by SAWAS. The highest desirable limit (HDL) of nitrate is 10 mg/l and the maximum permissible limit (MPL) is 50 mg/l in the national standard for drinking water.

The figure indicates clearly that the area of Sana'a city had been polluted by high nitrate, which was considered to derive from a lot of cesspit constructed in the city. The figure also shows there is an area with high nitrate on the north of the Sana'a city, between the north edge of the city and the airport. It was the place where a sewage pond was located once, or Ar-Rawdah.



Data Source; SAWAS (1996)

Figure 3.32 Nitrate Distribution in the Sana'a Basin (1996)

The nitrate data provided by SAWAS were partial in the Sana'a basin as shown in the figure. Well inventory survey (2002) measured the EC values of 7,638 wells in the Basin. EC can be regarded as an indicator of water quality, which is related to the total dissolved solid (TDS) in the water. The data collected by GARWSP indicate the relationship between EC and TDS is roughly shown by the following equation; *TDS (mg/l) = (0.65～0.7) x EC (microS/cm)*

The HDL of TDS is 650 mg/l and the MPL of TDS is 1,500 mg/l in the national standard for drinking water. The values are converted to the EC of 1,000 (HDL) and 2,300 microS/cm (MPL) approximately. *Figure 3.33* shows the distribution of EC in the Sana'a basin based on the data of Well Inventory Survey (2002).

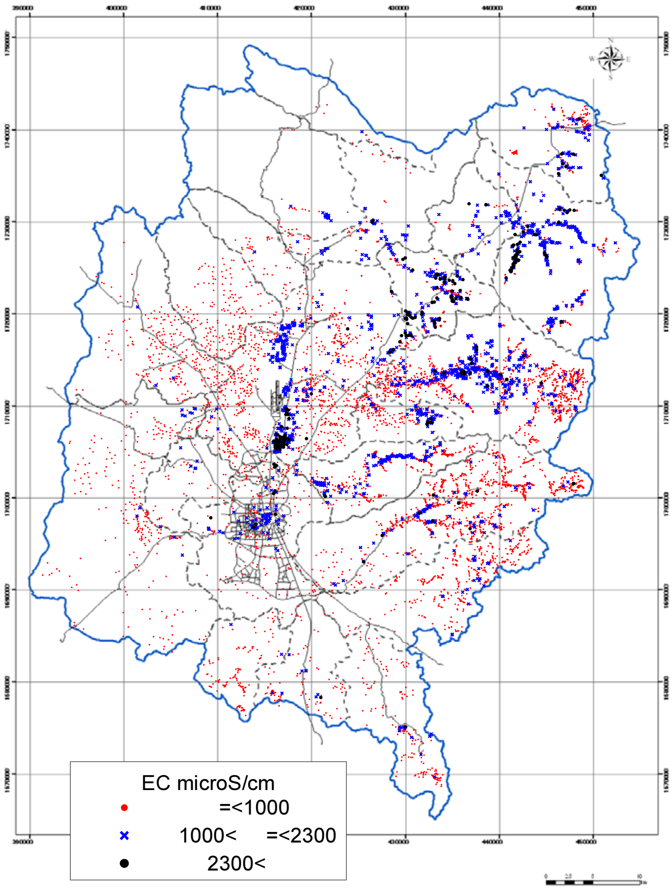


Figure 3.33 Distribution of EC in the Sana'a Basin (2001)

The figure indicates that, addition to the city area, the area along the flow of the Wadi Bani Huwat and other main wadi streambeds in the northeastern part of the Sana'a Basin, namely the upper Wadi Sa'wan, the upper Wadi Furs, Wadi Al Sirr, Wadi Thoma and Wadi A'sirm are probably polluted.

The upstream of Wadi Bani Huwat is the area where the wastewater treatment plant was constructed and started work in 2000, and Ar-Rawdah is located, where a sewage pond was placed once as mentioned before. It suggests that groundwater in this area are most likely contaminated by sewage. Similarly, other wadi streambeds are also highly possible to be polluted by domestic sewage from the surrounding villages, and/or by their agricultural activities, which may use organic fertilizer and leave the storage or disposal of livestock or fowl wastes on land.

3.7.2 Possible Adverse Impact

As described in the previous section, the falling water level in the Western Well Field and the high concentration of nitrate in groundwater has been clearly observed. In addition, the drilling depth of boreholes suggests that the water level around the Sana'a city is falling down and the high EC value indicates the contamination of groundwater in the Basin.

In terms of quantity, or water level, the observable fact about the falling water level is only the record of monitoring wells located in the Western Well Field. As described already, however, the water balance in the Sana'a Basin shows a large deficit for recharge, that is, the storage is decreasing in the basin, especially several sub-basins mentioned in 4.6. Therefore, the falling water level occurs most probably not only in the Western Well Field but also in other areas. The number and the location of monitoring wells are not adequate to grasp the actual condition of groundwater at present. The further monitoring wells are necessary to be installed in other well fields for water supply system and some sub-basins where the large discharge volume as against the recharge is estimated.

In terms of quality, an overall water quality analysis survey has not been conducted in the Sana'a basin since 1996 (by SAWAS), except the well inventory survey in 2001-02, which assessed only EC, pH and temperature. Possible sources of groundwater contamination are not only sewage. There are many other sources having an adverse impact on groundwater quality such as agricultural activities, land disposal of solid wastes (refuse), petroleum leakage and spills, seepage from industrial waste and so on.

Fertilizers and pesticides used for agriculture and the storage and disposal of livestock waste on land effect widely the groundwater quality. YGGMP (2004) has pointed out the possibilities of pollution caused by insufficient waste disposal in the petrol stations, car service shops and the medical units like hospital, laboratory and clinic. The actual condition of groundwater contamination caused by these individual factors has not been clarified yet. YGGMP (2004) reported that the water quality collected the Al-Mashham Dam had been deteriorated since 2003. Though there are neither reports nor record in the other areas, it may be possible the quality of groundwater have become worse from 2001 onward. Therefore, comprehensive survey of groundwater quality in the Sana'a basin is required without delay.

3.8 Non-Conventional Water Sources

Water resources have been conventionally exploited by dug wells, boreholes and small-scale dams or pools for irrigation and domestic water use in the Sana'a basin. In addition to these conventional facilities, several ideas have been proposed by the previous studies to supply water for the area, which are called a non-conventional water source. The non-conventional water sources can be categorized to four groups. The categorized alternative water sources are listed as follow.

1. A large-scale storage dam in and out of Sana'a Basin
   - Wadi Kharid Dam
   - Wadi Surudud Dam
   - Diversion of water from Marib Dam
2. Desalination of Red Sea Water
3. Groundwater Development outside of Sana'a Basin
   - Development of Ramlat Sabatayn Area
   - Development of Wadi al Masilah, Hadramawt
4. Other alternatives
   - Deeper Pre-Jurassic Sandstone
   - Subsurface Dam for Promoting Recharge

SAWAS (1996)[19] evaluated these options except the sub-surface dam that was assessed by

Hydrosult (2002)[20]. The results of the previous reports are summarized in the following sections. *Figure 3.34* shows the locations of the above non-conventional alternative water sources.

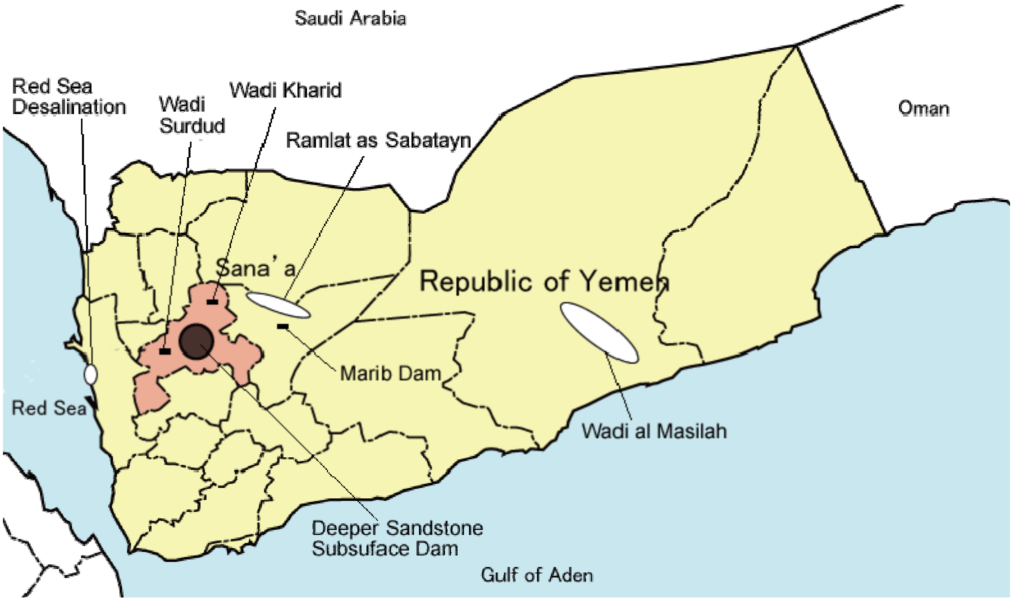


Figure 3.34 Locations of Alternative Water Sources

3.8.1 Storage Dams in and out of Sana'a Basin

(1) Wadi Kharid Dam

Mosgiprovodkhoz (1986) proposed the plan for the Sana'a water supply system originally, and SAWAS Technical Report No.9 (1996) carried out the feasibility study. The result indicated that the average annual catchment yield might be about 11 MCM, or about 350 l/s, and the following works were required.

- A 70 m high rock fill dam, 45 MCM storage reservoir (35 MCM usable)
- Water intake in the upper pool
- Water treatment facilities (20,000 m^3/day)
- 58 km transmission main with a booster pumping station
- Centralized power supply from a sub-station in Sana'a
- Complementary works such as roads, communication systems, workshops, office etc.

The construction cost was estimated at US$87.2 million in total, and the annual cost was estimated at US$10.7 million based on the price level of April 1996. The unit cost was calculated at US$1.32 per m^3.

The environmental assessment has not been carried out, although the environmental impact on the downstream area is predicted.

(2) Upper Wadi Surdud Dam

A pilot study on water resources management of the Wadi Surdud area was implemented in 1991 (WRAY-22, 1991). The study[21] of SAWAS project assumed that a maximum of 500 l/s could be abstracted from the Upper Wadi Surdud. The level of the intake was at approximately 880 m.a.s.l. The proposed intake was a weir with a cylindrical crest and a submerged bucket type dissipator, provided with a scouring sluice, intake sluice and a sand trap.

The construction cost was estimated at US$230.6 million, and the annual costs were estimated at US$32.6 million based on the price level of April 1996. The unit cost was calculated at US$2.03 per m^3.

The environmental assessment has not been carried out, although the environmental impact on the down stream area and the groundwater in Tihama plain is predicted.

(3) Diversion Water from Marib Reservoir

SAWAS[22] mentioned that the existing Marib dam was not able to satisfy the requirements for irrigation in the downstream area on the dam even at that time. In addition, it noted that conclusive decisions concerning the abstraction of water from the Marib reservoir were not expected to be taken in the near future due to the limited availability and high demand for water of the farmers in the Marib area.

Anyway, it is technically possible to abstract large amount of water from the existing reservoir at Marib, and a maximum amount of 1,000 l/s was assumed available from the Marib dam for the Sana'a water supply system by SAWAS.

The preliminary plan was designed for the transport of 500 l/s of raw water from the Marib dam to Sana'a. The total estimated construction cost was US$284 million and the annual costs were estimated at US$37.6 million based on the price level of April 1996. The unit cost was calculated at US$2.33 per m^3.

3.8.2 DESALINATION OF RED SEA WATER

SAWAS Technical Report No.7 noted that the cost of this option might prove to be prohibitive and the transmission system and pumping stations would be very vulnerable to damage and possible sabotage although there are no limits to the amounts of water technically.

The construction cost of the provisional design for the first stage (500 l/s) was estimated at US$900 million, including US$71.6 million for the intake work and desalination. The total annual cost was estimated at US$124.3 million. The unit cost was calculated at US$7.63 per m^3.

3.8.3 GROUNDWATER DEVELOPMENT OUTSIDE OF SANA'A BASIN

Two groundwater development projects have been proposed. One is the development of Ramlat as Sabatayn and another one is the development of Wadi Masilah in Hadramawt.

(1) Ramlat as Sabatayn

There are two large wadis running in the area, namely Wadi Jawf and Wadi Adhana.

The Quaternary alluvial and eolian deposits of Wadi Jawf constitute an aquifer with the thickness of 50 to 70 m in the western part and 10 to 20 m in the Al Hazm area[23]. The Quaternary aquifer is underlain by moderately productive limestone of the Amran Group in the western zone. East of Al Hazm are the western edge of the Mukalla Sandstone with high porosity. The Quaternary deposits are probably connected hydraulically with these productive formations.

The Quaternary aquifer also occurs in Wadi Adhana with the thickness of 50 to 70 m[24]. In the western fringe, it is underlain by the Amran Limestone. About 5 km of Old Marib and further east, it forms one aquifer complex with underlying Mukalla Sandstone. Transmissivity is expected high.

The further detailed study of the development in the area has not been conducted yet, but a feasibility study is planned by NWRA recently.

(2) Wadi Masilah in Hadramawt

A Canadian oil company discovered an aquifer of Mukalla Sandstone in Wadi Masilah during the oil exploration in the area in1990s. The World Bank had proposed it as the water source for the Sana'a water supply system. It, however, was realized that there were many problems such as too long distance, almost 700 km from Sana'a in a straight line, and socio-economic and security issues, although the aquifer was expected to have a potential.

3.8.4 OTHER ALTERNATIVES

(1) Development of Deeper Pre-Jurassic Sandstone

Pre-Jurassic Kohlan Sandstone have been exploited for Sa'dah water supply. The formation was supposed to underlie Amran Limestone in the Sana'a basin. SAWAS project drilled two exploration boreholes with the depth of 1600m in Arhab (Well DS1) and Al Hatarith (Well DS2) located to the northeast of Sana'a. The results were reported in SAWAS Technical Report No.8 (1996)[25].

The first test well (DS1) confirmed the pre-Jurassic sandstone at 1384m below surface. The thickness of the aquifer was only 40 m, which was 10% of the expected thickness. The water had high iron content and smelled H_2S during sampling. The temperature of water was 48 C at the surface.

The second test well (DS2) did not encounter the sandstone formation and it was considered a dry well.

Although, it was considered difficult to use as the source of water supply system due to the water quality and the lower productivity, a design was proposed for the Sana'a water supply system as follows. The well field consisting of four wells with a total capacity of 100 l/s, each spacing of 5,000 m and the depth of 1,400 to 1,500 m, was planned.

The construction cost was estimated at US$60.3 million and the annual costs were estimated at US$4.6 million based on the price level of April 1996. The unit cost was calculated at US$2.43 per m^3.

(2) Subsurface Dam for Promoting Recharge

Subsurface dam may be called a kind of artificial recharge dam. Hydrosult (2002) evaluated the nine sites propose to construct subsurface dams. The nine sites were selected because of the suitable locations for subsurface storage of water in order to reduce the abstraction for irrigation from the deeper aquifer.

The evaluation concluded that the three sites of the nine were the most suitable for the construction of pilot dams, namely Al Asha in Wadi Sawan, and Seil and Al Man in Wadi Dahr.

Assumed reservoir volumes of Al Asha, Seil and Al Man were 0.16, 0.95 and 1.22 MCM respectively. The costs were estimated from US$82 thousand (Al Asha) to US$373 thousand (Al Man).

3.8.5 CONSIDERATION OF THE ALTERNATIVE WATER SOURCES

Information about each alternative is summarized in *Table 3.21*. In these previous studies, capital cost, operation and maintenance cost and water tariff ware estimated on the basis of market price in early 90s. However, quantitative analysis from the view points of social and environmental aspects has not been conducted. It was pointed out that there were some restrictions to be considered prior to the implementation of these alternatives, such as an adverse impact on environment in the up and down streams of dam site, insecurity for the long distance installed pipes and consideration for the people who are living around ground water abstraction area.

Thus, even if the Government of Yemen allocates the budget for one of these alternatives, it is required to study the adverse impact which might be caused by the implementation. Based on the study, the countermeasures to be taken should be considered in both national and basin levels in order to mitigate the expected adverse impact in advance.

Table 3.21 Alternative Water Source

Source	Potential / Production Capacity		Cost**		
	l/s	Mm^3 /year	million US$	annual cost US$	Unit cost US$/m3
Wadi Kharid Dam	250	7.9	87.2	10.68	1.32
Wadi Surdud Dam	500	15.8	230.6	32.62	2.03
Diversion of water from Marib Dam	500	15.8	284.4	37.58	2.33
Desalination of Red Sea Water	500	15.8	902.9	124.28	7.63
Development of Ramlat as Sabatayn	not designed		not estimated		
Development of Wadi Masilah	not designed		not estimated		
Deeper Pre-Jurassic Sandstone	100	3.2	60.3	7.68	2.41
Susurface Dam for Recharge		(1.2)*	0.373		

Source; SAWAS Technical report No.14 and others

*): the maximum designed storage capacity, **): estimated in 1996 except Subsurface Dam (estimated in 2002)

3.9 PROBLEMS AND RECOMMENDATION CONCERNING WATER RESOURCES

3.9.1 PROBLEMS TO BE SOLVED

The present state of water resources was described in this chapter and several problems to be solved were revealed. The problems are:

- As the observed fact, the falling down of water level in the Western Well Field is occurring. Although the water level decreasing has not been confirmed clearly and officially in other areas, it can be considered to have occurred in some areas.
- The long-term tendency of water level change in the Western Well Field indicates that the water table will reach the critical level in 6 to 10 years, if the decline of water level will

continue with the same rate as before.

- The contamination of groundwater is suspected in the Basin, especially in the wadi beds of the northeastern sub-basins in the Sana'a Basin. The comprehensive water quality survey, however, has not been achieved since 1996.
- The water balance estimation in sub-basins indicates that the discharge volume of groundwater is more than 10 times of the estimated recharge volume in some areas. Wadi al Mawrid, Wadi Bani Huwat and Wadi al Furs may be in a very critical condition of groundwater resources.
- Even though the above critical condition is indicated in the areas, the actual volume of groundwater abstraction from wells has not been measured. Additionally, the recharge mechanism is still unclear.
- There are wells with the over fluoride concentration in the Basin.
- The serious issue in relation to the all above problems is that the monitoring system in the Basin is still not sufficiently run at present, though it has shown the progress recently, namely:
    - Some meteorological and rainfall stations have not been operated satisfactorily.
    - No runoff stations, (which is planned by NWRA-SB with the support of SBWMP)
    - Only six wells are installed automatic water level recorders, but others are not planned to be installed it.
    - In general, the wells used for monitoring were not constructed for the purpose originally.
    - Not monitored periodically groundwater quality
    - No plans to install a flow meter on production wells except NWSA wells.

3.9.2 RECOMMENDATION

Monitoring of the hydrological condition is one of the most important factors to do an appropriate management of water resources in the area.

- The monitoring information shall be fully used in the decision-making process for long-term operational strategy of water resources.
- The monitoring information is also essential for the assessment of the effect and satisfactoriness of the implemented activities.
- The monitoring information shall be used to provide a modification or adjustment of the operational plan for water resources utilization and development management.
- The monitoring information shall be open to the public to make them aware of the groundwater condition and to achieve the effective activities to save the resources in cooperation with them.

The following items are recommended.

- Expansion of water level monitoring network including the construction of new boreholes to monitor a specified aquifer
- Implementation of the periodical water quality monitoring and the comprehensive water quality survey in the area

- Investigation of the actual pumping rate of wells used for agriculture and others
- In addition, the continuous monitoring of the pumping rate with the installation of flow meter is necessary.
- The above expansion and implementation are urgently needed especially in the sub-basins of Wadi al Mawrid, Wadi Bani Huwat and Wadi al Furs.
- A periodical report of the monitoring results shall be provided and published by NWRA.
- Construction of the database system consisting of all the monitoring results and its update
- Construction of the aquifer model based on the monitoring results and its update for a future prediction about the water level and quality
- Water supply system shall be provided in rural areas, especially the areas where over fluoride concentration is observed.

Definitely, the recommendation can not be carried out in a short period. The priority level of the items should be decided based on the various factors including not only hydrogeological one but also socio-economical ones. Moreover, of course, the financial resources and the training of the personnel concerned shall be necessary to support the implementation of these items.

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