مجلة جامعة الرازي
للعلوم الإدارية والإنسانية
RUHMS

عملية محكمة تصدر عن كلية العلوم الإدارية والإنسانية – جامعة الرازي

أبحاث العدد:

- Hydrological Study Analysis and Groundwater Assessment of Hadramawt Aquifers ،May 2022.
- Hydrological Analysis Study and Groundwater Assessment of Sana'a Basin ،May 2022.
- تقييم جودة الخدمات الصحية في مستشفيات الشرطة بأمانة العاصمة وفقاً لأبعاد جودة الخدمة.
- أثر الحوافز على أداء الكادر الطبي في مستشفى القوات الخاصة.
- دور جودة الحياة الوظيفية في الحد من ظاهرة الاحتراق الوظيفي (دراسة تطبيقية).
- واقع البحث العلمي الجنائي في أكاديمية الشرطة اليمنية (دراسة ميدانية على أعضاء هيئة التدريس بالأكاديمية).
- أثر تطبيق إدارة الوقت في تحسين الأداء دراسة حالة على ديوان عام الهيئة العامة للزكاة للعام 2020م.
- تطور الدين العام في اليمن وقياس أثرة على عجز الموازنة العامة للفترة 1994-2016 .

جامعة الرازي

كلية العلوم الإدارية والإنسانية

يونيو 2022م

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مجلة جامعة الرازي – مجلة علمية محكمة – تهدف إلى إتاحة الفرصة للباحثين لنشر بحوثهم العلمية باللغتين العربية والإنجليزية في مختلف العلوم الإدارية والإنسانية

مجلة جامعة الرازي للعلوم الإدارية والإنسانية

مجلة علمية محكمة تعنى بنشر البحوث في مجال العلوم الإدارية والإنسانية

تصدر عن كلية العلوم الإدارية والإنسانية – جامعة الرازي – اليمن

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Hydrological Analysis Study and Groundwater Assessment of Sana'a Basin, May 2022

Compiled by Dr. Abdulwahed Ali Iskander

Abstract:

Hydrological study of Sana'a basin is composed of several sections. The first section introduces the hydrological aspects to be covered and analyzed, which includes parameter of surface water as rainfall, runoff scale in relation to geology composition and soil moisture and characteristic. Background of the study area in terms of location, topography and classification of Sana'a basins are disused in this study. Research objectives pertinent to groundwater resource assessment in Sana'a basin are successfully accomplished in this study through examination of enormous data variables of rainfall and surface runoff data that was collected and covering longtime period for over 70 years. Time series of rainfall are used to reveal rainfall pattern in the concerned area and examine its temporal and spatial distribution at annual, seasonal and monthly averages. Rainfall distribution and other climatic opponents are discussed in relation to other meteorological data. Several formula and models relevant to water assessment are applied and mentioned under methodology section and further explored in the hydrologic analysis segment.

The researcher undertakes thoroughly the hydrological analyses composing of numerous components of water resources availability in order to assess the type and amount of water resources at the surface and underground level within regional basins and local valleys. Catchment areas in relation to rainfall and runoff parameters are used in relation to the mean of annual rainfall to estimate groundwater recharge rates. Comparative analysis is performed to contrast water abstraction with recharge rate in order to establish a baseline defining critical basins within concerned areas and valleys in Sana'a governorate including main basins of targeted project areas. Components of groundwater system and water saving as a consequence of the implementation of the proposed project are consequently discussed in the analysis section. Monitoring and evolutional aspects of the project explore the current situation of water balance by defining the extent of groundwater availability and

depletion at a district level where the result reveals that almost all basins in Sana'a are suffering water balance deficit and continuous depletion. The magnitude of water balance is pictured and charted in a detailed map for the target areas, so as to better control and monitor groundwater use based on location and using sustainable management methods to reserve water resources within the context of objective achievements and practicing water saving activities under the suggested programs for Sana'a Modern Irrigation Projects (MIP) to be implemented in the concerned area. A list of hydro and meteorological devices and equipment needs are defined to support monitoring and evolution processes of the project. Finally, concluding marks and research recommendations are abstracted at the end of the study.

Hydrological analysis assessment revealed that the total annual groundwater recharge into the valleys and basins of Sana'a governorate where the main basins and four sub-basins reach a total recharge amount of 143 MCM /year in 2008 and 162 MCM in 2020 as the recharge aggregated for the 4 main basins and 14 sub-basins in the governorate. The total Irrigated Area from groundwater in Sana'a Governorate was approximately 70,000 hectare in the year 2007, and about 51.000 in 2008. Results of data analysis are exposed and show that water balance in Sana'a basin reach a very critical situation where the difference in the amount of water between charged and discharged in the basins of Sana'a record an alarming indicator, they are accounted for a negative value amounting - 405 MCM, over four hundred millions cubic meter being lost annually (143- 548= -405)

Hydrological analysis results show that the area of irrigated crop from underground water in Sana'a governorate was 50,856 hectares in 2008, representing about 62 % of the total irrigated area in the governorate, which consumes 548 MCM/year of underground water, this tremendous amount corresponds to the total abstraction of water used for irrigation could be minimized. It is a huge volume of water use, particularly with respect to 42 % average in water saving, which equals to 330 MCM/year for total irrigated area, which could be saved, contributing to the augmentation of groundwater recharge. An amount of water equal to 548 MCM/year is consumed for irrigation based traditional use vs. 318 MCM/year using improved irrigation method, which means a deference of 330 MCM/year is accounted for water savaging, assuming that all irrigated land be covered with modern irrigation techniques in Sana'a Governorate.

ملخص: دراسة هيدرولوجية لتقدير المياه الجوفية في حوض صنعاء:

شملت الدراسة الهيدرولوجية لحوض صنعاء والأودية المرتبطة به العديد من المتغيرات القياسية للمياه الجوفية المتوفرة في الأحواض المائية المغذية للمياه الجوفية في محافظة صنعاء بغرض تحديد كمية المياه الجوفية المستخدمة سنوياً في الري الزراعي. من خلال دراسة العلاقة بين متغيرات كمية المياه السطحية والجريان في أودية حوض صنعاء وبين متغيرات المياه الجوفية والمخزون المائي في أحواض المحافظة، قام الباحث بفحص هذه العلاقة مستخدماً نماذج القياس الهيدرولوجي المعتمدة وتطبيق التحليلات الإحصائية المناسبة في حساب كمية المياه المتجددة بالاعتماد على سجلات المناخ والإرصاد الميترولوجية المتوفرة لفترة تزيد عن70 عاماً من الأرصاد الجوية المتعلقة بكمية الأمطار الساقطة، متوسطات الحرارة، البخر والنحت إضافة إلى حساب كمية الجريان السطحي ومعدل الامتصاص بحسب التركيب الجيولوجي وخواص التربة في الحوض والأودية ذات العلاقة بنظام المياه المتوافقة مع التقسيمات الإدارية للمحافظة.

و أن الهدف الرئيس لهذه الدراسة هو توفير البيانات المائية اللازمة وإجراء القياسات المطلوبة لتقدير كمية موارد المياه الجوفية والمتجددة ومقارنتها بالمياه الجوفية المستهلكة للري الزراعي بغرض الحفاظ على المياه الجوفية وترشيد استخدامها وذلك للتقليل من معدل الاستنزاف والفاقد عن طريق تطبيق واستخدام الأدوات والوسائل التكنولوجية الحديثة في عملية الري الزراعي كون هذا القطاع يستهلك/ يستخدم ما نسبته 90% وأكثر من إجمالي المياه المسحوبة من مخزون المياه الجوفية عن طريق الآبار الإرتوازية. لقد تم تصميم برنامج مشروع الري الحديث في اليمن لمواجهة مشكلة استنزاف المياه الجوفية من خلال استخدام التكنولوجيا الحديثة في الري التي أوصى بها خبراء الزراعة والري بأشراف وزارة الزراعة والري وبالتعاون مع وزارة التخطيط بدعم من خبراء البنك الدولي. ولتنفيذ هذا المشروع تم البدء بإجراء دراسات شاملة مكونة من خمسة حقول وهي: الدراسة الهيدرولوجية، والدراسة الهندسية لمكونات الري الحديث، والدراسة الاجتماعية والاقتصادية والبيئية وقد غطت 20 موقعا شملت معظم محافظات الجمهورية اليمنية. شكلت هذه الدراسة الهيدرولوجية لحوض صنعاء أحد مكونات مشروع الري الحديث والتي قام بتنفيذها الباحث بالإضافة إلى قيامه بالإشراف والتنسيق بين أعضاء ورؤساء الفريق الاستشاري لتنفيذ مهام العمل في فروع الدراسات الأخرى المكونة لمشروع الري الحديث، فضلاً عن قيام الباحث بإعداد التقارير النهائية لهذا المشروع.

ولأن الهدف الأساسي للدراسة الهيدرولوجية/ المائية هو تقدير المياه المسحوبة سنوياً من المخزون المائي للأودية المغذية لحوض صنعاء بالمياه ومقارنة هذه الكمية بمعدل التغذية السنوية للحوض المائي من خلال المياه المتجددة، فقد قام الباحث بإجراء تحليلات هيدرولوجية شاملة تطلبت جمعاً ضخماً للبيانات والسجلات المناخية ذات العلاقة والتي شملت بيانات عن كمية الأمطار والحرارة والتبخر والنتح والاستفادة من دراسة ومراجعة كل التقارير والسجلات المتوفرة المتعلقة بالجريان السطحي ودراسة الخصائص الجيولوجية والفزيائية وطبيعة التربة وقابليتها للامتصاص ودرجة الاحتفاظ بالرطوبة ومن ثم القيام بفحص العلاقة بين كل هذه المتغيرات بهدف تقدير الموارد المائية من خلال تطبيق موديلات قياس المياه المعتمدة واستخدام المعادلات والقياسات المعيارية في قياس المياه

وتطبيق الأساليب الإحصائية المناسبة الشاملة لحساب المعدلات والمتوسطات وإجراء تحليلات التباين واستخدام مختلف المؤشرات النسبية المئوية والانحراف عن المتوسط والمؤشرات الدالة لمدى علاقة الارتباط بين المتغيرات والعوامل وغيرها من الحزم الإحصائية المستخدمة لتحليل البيانات القائمة على المسح الميداني وتم حساب وقياس الثبات والمصداقية لعينات الدراسة الممثلة فضلاً عن استخدام البيانات المنشورة وغير المنشورة من مصادر ثانوية متنوعة.

وأظهرت نتائج الدراسة الهيدرولوجية لتحليل الوضع المائي في محافظة صنعاء أن عدد الآبار الإرتوازية في تزايد مستمر وقد وصل عددها إلى ما يقارب 60.000 بئر عام 2008م ويصل متوسط عمق الواحد منها بين 200 إلى 400 متر. وكذل أظهرت نتائج القياسات بأن مستوى المياه الجوفية يهبط بمعدل يتراوح بين 10-15 مترا في السنة، في حين أن معدل التغذية السنوية للمياه الجوفية يبلغ فقط نحو 143 مليون متر مكعب مقارنة بمسحوب مائي سنوي من الأحواض الخازنة للمياه الجوفية يصل إلى أكثر من 400 مليون متر مكعب. وكشفت نتائج الدراسة الهيدرولوجية بأن كمية الأمطار الساقطة على الأودية المستهدفة في محافظة صنعاء يصل إلى 2600 مليون متر مكعب وأن جزءاً كبيراً من هذه الكمية يُفقد بعملية التبخر والنتح وجزءاً يجري بعيداً عن الأحواض وجزء بسيط 4.8 % من هذه الكمية هو فعلاً ما يمد أحواض المياه الجوفية بالتغذية المائية في عملية التجدد وهذا يعني أن هناك فارق سلبي في ميزانية نظام المياه الجوفية يبلغ حوالي 405 مليون متر مكعب من المياه والتي يتم استنزافها سنوياً عن طريق الضخ الإرتوازي من الآبار وهذه الكمية لا يمكن تعويضها بأي حال من الأحوال وفقاً للحسابات الهيدرولوجية والظروف المائية السائدة في المحافظة. ولذلك يرى خبراء الري الزراعي أن بالإمكان التعويض الجزئي لهذا الفاقد عن طريق استخدام وسائل الري الحديث عن طريق الرش والتنقيط وفي نقل المياه وتقليل الفاقد إلى حده الأدنى. وفي هذا السياق يوصي الباحث المختصين الزراعيين البحث عن وسائل إضافية مثل تشييد السدود التي تقوم بوظيفتين في آن واحد فهي من جهة تعمل على زيادة معدل تغذية المياه الجوفية وتتيح فرص أفضل وبتكلفة أقل في عملية الري الزراعي من جهة أخرى.

1. INTRODUCTION

The introduction of the new tube well technologies together with macro agricultural sector economic policies, especially the huge subsides which the sector enjoyed in the form of reduced diesel cost, subsidized credit of pumping technologies, had led to a rapidly increasing demand for irrigation water. Accordingly, irrigated agriculture in Yemen become the largest water user and now is using over 92% of the total water consumption in Sana'a.

According to the recent statistics of 2008, the total cultivated area in Sana'a governorate was 136,596 hectare, and the total cropped area was 166,522 ha (5.86% of the country total crops area). The total irrigated area was 82,095 ha, representing 49.3% of the total cropped area in the governorate. The irrigated area from groundwater resource in Sana'a was 50,856 hectare in 2008, representing 62% of the total irrigated cropped area grown in Sana'a or 30.5%

of the total crops area in the Governorate. Water harvesting in Sana'a has played and will continue to play an important role in soil conservation and leaching salty soil by surface spate water coming from the mountain slopes in the uplands. However, agricultural land under water harvesting was subjected to serious soil erosion and soil degradation

The study addresses the hydrological and water resources assessment as well as water saving in Sana'a basin and rainfall catchment areas around the basin.

Sana'a governorate has diverse agro-ecological zones. The major zone is Sana'a Basin areas and several Wadis in Bani Alharith, Dabian, Bani Hushaish, Khawlan, Bani Mattar, and Arhab. Because of this diversity there are distinct agricultural activities of summer and winter crops namely, tropical and subtropical fruits, vegetable crops, feeder natural agricultural crops, essence and medical herbs which depend mainly on groundwater irrigation.

However, Sana'a governorate is situated in one of the poorest country region regarding water resources as the average per capita was hardly over 150 m^3/person/years a decade ago but now is not exceeding 114 m^3. Rainfall of the catchment area of the western highland and groundwater are the only sources of water and because the governorate is mostly predominated by arid climate, the rainfall is highly erratic and variable where standard deviations of the annual rainfall are within the ranges of 33-37% of the means in the semi-arid Sana'a zones. This is coupled with high evapotranspiration potential rates and available surface water can hardly support rain-fed and spate irrigated agriculture.

Hence the focus has been given to binding ground water sources for both agricultural and domestic utilization to the extent of over exploiting it. This fact is authenticated by the pertinent literature, which exhibits a rapid growth rate in population and in expansion of irrigated agriculture from several hundred hectares in the seventies to 82,095 ha as in year 2008. Irrigated agriculture is the dominant water consuming sector. It consumes over 90% of water use in the governorate. A rapid dropdown in ground water levels has been monitored and reported in many Sana'a Wadis and Basins due to the fact that over abstraction and consistent depletion have become the rule rather than the exception. As for example in Sana'a Basin a drop down rate of ground water levels in the range of 50-100 m. has been recorded during the last 40 years.

These ground water levels were said to be more sustainable in the past and this is attributed mainly to the fact that irrigated agriculture practiced was largely based on spate, floods and shallow manually dug wells.

Based on the Agricultural Statistic's Year Book (2008), around 51% of the total cropped area was rainfed, about 31% groundwater irrigated crops, and the remaining 18% of cropped area was irrigated from other sources such as spate/floods, streams, dams and tanks carried on cars.

Flood water harvesting agriculture have played and will continue to play an important role in soil conservation and in controlling quality of soil in terms of salt leaching by surface water at foothills near the mountain slopes of the uplands provided that precautions are taken against erosion and degradation hazards. Despite the fact that the government has launched huge investments to improve spate irrigation, no obvious changes have been noticed on the cropping pattern and their respective yields at macro scale level. This has always been attributed to budgetary constraints for the O&M of the large hydraulic structures associated with this activity in addition to uncertified fund assignment and hasty agro-infrastructure localization.

On the other hand, ground water irrigated agriculture allows much greater flexibility in the cropping pattern and cultivation of high value crops. It produces 75% of the total production from only 30.5% of total cropped area in the governorate. However, groundwater agriculture suffers seriously from over abstraction of water that leads to aquifer depletion in many areas of the region and apart from labor this water becomes the most costly item of the agricultural inputs. Additionally, there is evidence of unlawful practice of water rights and unfair distribution of water sources in behalf of commercial and large size farming.

The overexploitation of water is directly endangering groundwater resources in the concerned areas. All urban and rural areas in Yemen are directly affected and they suffer from various negative consequences of groundwater overexploitation. (Frederic Pleat 2006).

The successful and sustainable exploitation of water resources is threatened by the rapid depletion of groundwater resources. Almost all the important groundwater systems are being over-exploited at an alarming rate. The socioeconomic consequences of groundwater depletion are dramatic because it will become too expensive for use in agriculture and, as a result, regional agricultural economies based on groundwater irrigation are doomed to collapse if the water resources are not adequately controlled. Groundwater availability may be further reduced by groundwater salinization in extensive irrigated areas and groundwater pollution in urban areas and areas of intensive agriculture.

1.1 The Statement of Research Problem:

Groundwater is a valuable resource both in Sana'a and throughout the country of Yemen. Groundwater assessment, a term often defined as a long-term water level measurement involving enormous variable of hydrological data analysis, composing of surface rainfall, runoff water and aquifers characteristic such as geographic, topographic geology natural soil in relation to recharge and discharge. This research study focus on hydrological aspects of Sana'a basins in order to provide reliable measurement tools of water level depletion in concerned areas such as basins, valleys/wadis of Hadramawt where water level declines caused by sustained groundwater pumping is the main issue associated with groundwater use for irrigation that this research aims to tackle.

Since the cultivated area based underground irrigation in Sana'a represents around 49% of total irrigated land and 30.5% of the total cropped area, yet it produces 75% of the total crops production, and contribute 85% of the value of production, hence as a result the demand for irrigation water has rapidly increased over decades and in many areas exceeded available water resources as the water shortages in these areas is supplemented by over abstraction of the groundwater, which resulted in considerable drop in the groundwater table levels including the reach aquifers of Sana'a Governorate. Water harvesting and terraces agriculture is continuously subjected to soil erosion and degradation in the uplands and along valleys banks. The spate agriculture is subjected to valleys' bank erosion and the groundwater agriculture is more affected by the over abstraction of groundwater, which led to aquifer depletion in many areas of the governorate under study. This has ultimately led to the fact that groundwater irrigation water becomes the most costly input item. Therefore an extensive data collection on groundwater and long run measurement in terms of hydrological aspect related to surface rainfall, runoff and recharge variables, which of prime importance to groundwater measurement in order to improve irrigation methods and to sustain groundwater through effective mechanism of irrigation use of groundwater. The contribution of this research study could induce economic progress and a sustainable use of groundwater for agriculture irrigation.

1.2 Research Objectives:

This study defines the objectives of Sana'a through the research study and develops recommendations for monitoring indicators related to physical target particularly water extraction rates in comparison of the targets water saving mentioned for the concerned Projects.

To fulfill the objective of the study, the researcher identify the relevant aspects and design a program set to assist government institutions in promoting groundwater conservation in farming areas and increasing surface and groundwater availability through: (i) **Assessment of current water resources situation**; (ii) **improving irrigation water use efficiency**, thus increasing farmer returns to water and creating the conditions that would allow them to reduce groundwater pumping from aquifers towards sustainable levels; (iii) **improving recharge and protecting water basins and groundwater storage** in order to increase water resources and groundwater availability through the improvement of irrigation water use, water conveyance and irrigation application schemes, groundwater balance protection,; and (v) **supporting the groundwater management framework and institutions** that will have the incentive and capacity to manage local water resources in a sustainable manner and add further measures to improve the water balance.

This study objectives are to analyses of hydrological aspect designed to provide a large extent of data to implement Modern Irrigation Project that is expected to ensure the sustainable irrigation management and to make efficient use of water resources and thereby to sustain groundwater together with increase agricultural productivity in several irrigation sites in the Governorate of Sana'a, thus to make people and water users particularly aware of the consequences of carless action toward water crises. Therefore, the overall objectives of Sana'a Hydrological research study are as follows:

- The main objective of hydrological analysis is to provide sufficient data and information for the target areas in order to improve water management and increase irrigation efficiencies in the study area.

- Assess the extent of current groundwater situation in the basins of Sana'a
- Estimate the level of groundwater in relation to quantities of rainfall, surface runoff and annual recharge of the target aquifers.
- Analyze data with parameters relevant to water availability and consumption as well as water use and management for crops irrigation to be used in monitoring and evaluation before and after irrigation system implementation of modern irrigation.
- Provide a list of equipment and devices, which are needed to assist in carrying out the activities under the proposed project.
- Make recommendations for monitoring indicators related to water extraction rates in comparison with targets water saving.
- The result of hydrological analysis would suggest ways to reduce water consumption used for irrigation and improve water use efficiency particularly in critical basins of the target areas.
- Improve performance of assessment in water savings.

1.3 Methodology, Data Collection and Analysis:

Various methods of recharge estimation have been reported in the literature. The choice of a particular method depends on the type of data available. These methods can be summarized as:

1. Soil moisture balance method, which requires data on rainfall, runoff, evapotranspiration, soil moisture profile and other soil characteristics such as soil field capacity.
2. Modeling techniques in which rainfall, valleys/wadi discharge is included in the overall model. Reliable water level series for various observation wells are needed for model calibration in addition to other groundwater parameters.
3. Simple method in which the water level distribution in the aquifer before and after the wet season are compared. Recharge can then be calculated as a function of the aquifer area, porosity or specific yield of the aquifer and the average rise in the water level.

If the average rise of water table is Delta H (m) and the aquifer area is A (km2) and the aquifer specific yield is Sy, then:

Volume of recharge is = A x Delta H x Sy x 106 m3/year

Since the lock of some data with respect to above parameters, another way is adopted for calculating groundwater recharge, abstraction and storage from the past estimates and trends taking into account the local conditions such as geological and topographic features and other controlling factors. Therefore, the formula used for valleys is adopted from the major regional aquifers and the regional ones from the aggregation order of the whole country for groundwater recharge, for groundwater abstraction and storage several techniques are adopted such as wells inventory, measured average capacity of groundwater pumped wells in terms of m3/hours/ha irrigated from groundwater as fallowing formulas demonstrate;

Volume of recharge is = A* (Rainfall (mm) /1000mm)* 106 m3/year x Coefficient Factor)(1)

Volume of recharge for specific basin is =(∑i-j ÷ Ai) x (Rainfall (mm) /1000mm)* 106 m3/year x Coefficient Factor) (2)

Vol. of Abstraction is\=Water Vol. required for irrigation (m3/ha)* Irrigated area (ha) (3)

Another way to calculate ground water abstraction is to determine the number of wells and their capacity of pumping in (m3 / hours) for each crop requirement of water during the growing seasons multiplied by area of concerned irrigated crop from groundwater as fallows;

Volume of water abstraction is = Average hours of pumping of water * Capacity of pumping in (m3/ hours) * Scheduled irrigation (m3 / hours* irrigation frequency)*Size of area of specific irrigated crops in concerned project (4)

Verification of these analytic methods is proved reliable on grounds that such analysis are based on gauged runoff parameters on the one hand, and on field measurement of water pumped from wells on other hand, as well as measurement of water volume used for certain irrigated crops during its full growing season carried on field units survey by GWSCP, 2007-2009. Furthermore verifying formulas are used to test the accuracy of the results of these estimates as fallows;

1. Estimated runoff and recharge volumes should be or nearly equals:

Mean Annual Rainfall (mm) ÷ 1000(m3)*Area*coefficient factor = the Runoff and recharge volumes of gauged catchments/valleys/basins respectively.

2. Estimated water abstraction should be or nearly equals:

Number of wells in concerned area * Average capacity of pumped wells (m3/ hours) multiplied by the aggregated area of irrigated crop in terms of (m3/ hours/ ha)

Methodology used in this research includes the following tools and techniques:

- Review of secondary sources including statistics, records, reports and references
- Direct observations during site visits.
- Conducting direct interview and discussions meeting method with individual and groups of stakeholders in target areas.
- Questionnaire was designed and distributed to collect data related to study in various issues related to wells pumping and irrigation use of underground water.

The current study approach and methodology is based on the objectives and the specific tasks to be carried out as per the Terms of Reference (TOR) of Modern Irrigation Project (MIP), the researcher along with his team has adopted the following approach for successful completion of the assignment. Inception Report was prepared and submitted to the MAI, GDFI along with the check list and questionnaires in June 2009 for their review and comments before undertaking the Field Visits as a pilot study to test the groundwater and social situation in most of suggested project areas by the consultant team. In August 2009, Interim Report was presented by the consultant chaired by the International Team; the research work was supervised by the current researcher as a. Team Leaders and Project Coordinator of the MIPs in corporation with the members of GDFI Supervision Mission. Field survey was carried out with the help of feedback attached with the Interim Report approval in 1st July to 21st July 2009.

Data is collected from both sources, the primary and secondary data. Large scale data were gathered, arranged, further tabulated, and analyzed by the team of experts assisted by the local enumerators, based on the statistical tools of analysis and application of models are used to make accurate estimation of groundwater recharge and discharge. Long range Final draft report on MIPs was prepared. With the help of MAI, GDFI comments on the draft, the Final Report was prepared and developed by the researcher and was submitted at the end of year 2010. Update and specific modification based on reviews conducted by the Judgment Team of Al-Razi University Journal for Medical Sciences (RUJMS) in June 2022.

The following methodology was adopted in response to the scope of work and to successfully complete the outlined tasks within the prescribed and adopted time frame.

a. Sample Area Selection:

Selection of sample at the first stage involved a preparation of systematic list for all groundwater and wells pupping users in each wadi/Muderiah collected from the Agriculture Well Survey and Census. The next stage this data was arranged and stratified into categories according to their locations, in respect of existing pumping wells and groundwater irrigation areas. This selection method is accounted for 9 villages in 9 districts (ii) Representative villages of pumped groundwater (iii) Representative villages of grown crops pattern. The final procedure was to choose three villages from each of these three categories. This process ends with selection of groundwater users representing each project area, which considered collectively for the whole targeted area of the research study. Consequently, nine Districts in Sana'a were selected from Sana'a Governorate covering the project areas and another set of water units groups were selected from each project area in the concerned Governorate corresponds to the number of districts in the Governorate covering the main project areas. The study sample area covers 11 District, they are Alharga-Harad, Algar-Abs, Qazan-Abs, Algar-Abs, Qazan-Abs, Alhgawrah-Hrd, Hiran, Banialhadad-H, Algar-Abs, Alhgawrah-Hrd and Hiran.

b. Selection of Water Users and Households Sample:

Selection process of households sample in this study consist of a list includes the total number of households in each of the selected area which were collected from the Agricultural Census, published in 2004, from this list a number of households were randomly selected for each sample representing the project areas in order to generate primary data in consistent with the approved household questionnaire. However, in a few cases some of the households were not readily available for providing the information as needed and in some cases the sharecroppers did not want to face the interview and has the opinion that this may hostile the relation between the sharecropper & landowner. Therefore, in such cases, those households were replaced by the available respondents, who were ready to cooperate with the survey. Around 17 farmers from each target project were selected. Finally, average of 15-17 farmers from each project area was interviewed. This makes a total of over 200 samples of farmers from all district of the governorate as a representative sample of households, which were selected for this study.

c. Review and Analysis of Available Data

During the initial stage of the study, it was of prime importance that all relevant available data and reports concerning the Groundwater Irrigation Improvement as well as the Government policy documents are evaluated. Thus, all available data and reports were collected from different primary and secondary source, in addition to relevant maps, drawings, reports and publications. The Review of literature includes large volume of data in geography, geology, hydrology (catchment areas, runoff, and floods) and metrology, climatology (rainfall, maximum & minimum temperature, relative humidity, sunshine hours, radiation, evaporation, evapo-transpiration, soil quality and moisture)as well as water resources availability (availability of surface water, groundwater from aquifer layers, rate of abstraction, depletion of groundwater, recharge, pumping wells and water balance) and in geomorphology aspects. Consequently, tabulation based data analysis and treatment were developed and presented in consist manner using suitable statistical data tools such as averages, means, standard deviation from the mean, coefficient, data extrapolation in based on historical/temporal trends and on spatial context developments.

In summary, the methodology used in this study includes several techniques. Review of secondary sources including statistics, records, reports and references, Direct observations during site visits, Conducting physical measurement method to gauge streaming water flood, rainfall, surface runoff and estimating recharge, furthermore, questionnaire was designed to collect unavailable needed data related to the study various issues.

1.4 Assumptions and impact indicators:

(a) About 1.5 MCM/year, volume of water will be saved, based on Hydrological Analysis;

(b) At least 22% increase in agricultural productivity per unit of water use, based on Economic Benefit/Cost Analysis; and

(c) (c)A number of families, representing 0.05% of the households in the concerned governorate of the project will be benefiting from the investment, based on Social Study as well as Economic Study, FAO and current MIPs social survey.

Monitoring indicators:

Monitoring indicators for groundwater levels, abstraction and recharge are set at regional basins, local/sub-basins and at district levels. These indicators are presented in detailed tables, figures and maps. Progress toward the project development objectives will be evaluated based on these key indicators. A monitoring and evaluation program has been prepared to monitor progress, including water saving and its impact on aquifer sustainability.

2. HYDROLOGICAL ANALYSIS:

This research study of hydrological analysis is composed of seven main sections and each section includes many sub-sections. The first section deals with the background of the hydrology work program to achieve the objectives of hydrological study. The second section discusses the geographical settings in terms of location and topographic feature of the site and situation of target area as it related to administrative division of the concerned governorate. The third section explains rainfall data collection and methods of analysis. Time series of rainfall are used to reveal rainfall pattern in the concerned area and examine its temporal and spatial distribution at annual, seasonal and monthly averages as well as its relations with relevant climatic and other meteorological data. The fourth section analyzes the components of water resources availability in order to assess the type and amount of water sources at the surface and underground level within regional and local aquifers. Catchment areas in relation to rainfall and runoff parameters are used to estimate groundwater recharge rates. Comparative analysis is performed to contrast water abstraction with recharge rate in order to establish a baseline defining critical basins within concerned governorate and main basins of targeted project areas. Components of water resources assessment including groundwater system and water saving as a consequence of the implementation of the proposed project are discussed in section five. This section also deals with the monitoring and evolution aspects of the project. In this section the components of groundwater system, magnitude of water levels in the basins of project areas and evaluation of current water balance by defining the extent of groundwater availability and depletion at a district level. The magnitude of water balance is pictured and charted in a detailed map for the Sana'a project, so as to better control and monitor groundwater use based on location and using sustainable management methods to reserve water resources within the context of tasks achievements and practicing water saving activities under the suggested programs for Sana'a Modern Irrigation Projects (CT-MIP) to be implemented in the concerned area. A list of hydro and meteorological devices and equipment needs is developed to support monitoring and evolution processes of the project. The cost of required equipment and devices for monitoring purposes, its distribution over the first five years of project life as well as the economic and financial analysis are summarized in section six. Finally, concluding marks and consultant recommendations are abstracted in section seven also at the end of each project component.

2.1 Background of the Study Area:

Agriculture in Sana'a has a significant effect on the local and on the country economy as it serves for foodstuffs and livelihood support. The majority of the area's population (up to 90%) lives in the rural areas and about 78% of them are employed in agriculture where traditional farming prevails. Almost over 90% of the total water consumption in Sana'a governorate is used by irrigation sector, of which 62% depends on groundwater. This is envisaged to lead to over-abstraction of groundwater as it evident in the serious depletion of ground water levels.

Based on the Agricultural Census published in 2004, the number of pumped wells in Sana'a reached around **59,693**. Ground water levels have dropped dramatically from 150 m to 300m, particularly, in the main wadis basins during the last 40 years, this depletion is equal to a yearly rate between 2 and 7 meters..

The groundwater use for irrigated agriculture proved more efficient in the cropping patterns and is therefore directed towards maximizing yield of high quality in many neighboring countries; however, it is still quite low under traditional irrigation systems in Yemen. Hence, the government of Yemen is presently becoming deeply concerned about the introduction of the new tube-wells and motor-pumps innovation with a view to investing such technologies mainly in the agricultural sector. This attitude has been reflected in government–supported strategic policies and plans that aim at improvement and modernization of transporting irrigation water through pipe conveyance and using on-farm irrigation methods while conserving water and protecting its good quality. One of the main objectives expressed in the Mid-Term Sustainable Development Plan for Agricultural Food Security and Poverty Reduction, based on MDGs 2006-2010, and public investment programs in agriculture sector 2007-2010 is to improve the efficiency of water use for irrigation up from 40%, through introduction of modern irrigation technologies while preserving water resources and improving integrated water management.

The hydrological analysis proves that about 1.5 MCM/year of groundwater will be saved as a consequence of implementing the current MIP in Sana'a.

This Final Report defines the objectives of the twenty projects and sets the hydrological parameters and the procedures by which climatic, meteorological data and hydrological variables of surface and groundwater has been assessed and monitored to achieve the objectives and carry out the study tasks.

2.2 Hydrological Study Objectives:

The overall objectives of hydrological study of Sana'a basins are to reducing groundwater abstraction and hence improving ground water levels, in purpose of alleviating poverty, increasing crop production, insuring food security, and enhancing sustainable livelihood of low-income farming households.. These objectives conform to specific objectives of hydrological study as follows:

- Assess the extent of water saving from pumped aquifer supplies resulting from the implementation of the 20 projects.
- Suggest ways and procedures to be used by the project to ensure that the reduction in pumped groundwater would reduce aquifer depletion.
- Collect data with parameters relevant to water availability and consumption as well as water use and management for crops irrigation to be used in monitoring and evaluation after implementation.

- Provide a list of equipment and devices which are needed to assist in carrying out the activities under the projects.
- Make recommendations for monitoring indicators related to water extraction rates in comparison with targets water saving mentioned for each one of the study area. The main objective of hydrological analysis is to provide sufficient data and information for the project areas in order to improve water management and increase irrigation efficiencies in the project area. The project contribution could impede progress and economic development in the country. The project would aim at expanding irrigation improvement and modernization at the farm level and implement participatory groundwater management and conservation advisory services. By achieving above objectives (as economic study emphasizes), the project would:
- Reduce water consumption used for irrigation and improve water use efficiency particularly in critical basins of the project area through the installation of piped distribution network (with PE/PVC) and improving conveyance of groundwater and the installation of localized irrigation systems (Drip and Bubbler).
- Promote the use of improved conveyance of groundwater for irrigation and localized on-farm irrigation system
- Further improve the productivity of pumped water and overall farm productivity through creating of post-installation irrigation advisory service (IAS) for advising the farmers on efficient and optimal irrigation practices to optimize use of groundwater, energy and labor savings as well as to increase yield. The irrigation advisory service will also be responsible for general evaluation of the performance of the irrigation systems implemented under the project and for assessment of savings of water, and mproving farmer's income by increasing the crop yield.

Hydrological component, objectives and the planned activities have been achieved through three phases of project work progress: the first phase of work attained was reported during the first half of the year in 2009, the outputs of the second phase have been executed during the next four months in the same year and reported in the Interim Report submitted in August, 2009. This report was developed based on the technical comments and suggestions made by GDLR&FI,MAI and submitted as a progress report. The third phase work of hydrological analysis results are reported in the Draft Final Report (DFR) and was submitted in December, 2009. Second version of DFR has been developed and submitted before submission of Final Report Summary of the 20-projects including hydrological studies in 2010, however data concerned to groundwater assessment has been updated to year 2020, and certain modifications on hydrological study have been executed in 2022.

2.3 GEOGRAPHICAL SETTINGS:

Geographical settings section disuses the location and topographic features of the study area and exposes Administrative Division and shows the classification of Sana'a basins and valleys.

2.3.1 Location and topographic features:

Sana'a Governorate is located in the Central Highland Region and Sana'a City is, the national capital of Yemen, situated in the center of the governorate. The governorate is bordered by Amran and Al-Jawf Governorates from the north, Dhamar from the south, Al-Hodaiedah and Al-Mahwit Governorates from the west, and Mareb Governorate from the east. It is extends in from northern Dhamar to the southeast Amran. Its area estimated at 38,605 Km^2. It is consists of 13 Districts. The Governorate as a part of Central Highland Region of the Yemen Mountain Massif, its elevation ranges from 3000 m to 3500 m.a.m.s.L. In contrast to western mountains, the landscape is less dissected and characterized by lower relief amplitude and common occurrence of almost flat to undulating extension land called Highlands.

2.3.2 Administrative Division:

Sana'a Governorates consists of 13 Districts, the third order of administrative division of the country. The governorate as an administrative unit has a distinctive boarder in common with its neighboring governorates. Its 13 districts vary in climatic and soil features as well as in the area extent. Khawlan and Nehm Districts, occupy the eastern portion of the governorate, are relatively the largest districts in the governorate. The other districts are Hamdan, Arhab, Bani-Haushaish, Sanhan, Bani-Bahlawll, Belad-Arraws, Bani-Mattar, Alhaymah-Addkhiliah, Alhaymah-Alkharigaiah, Manakhah, and Sa'afan. These districts are labeled in the map of Sana'a Governorate shown in Figure 2.1-a and 2.1-b.

Figure 2.1a- Sana’a Main Wadis and Water-shades

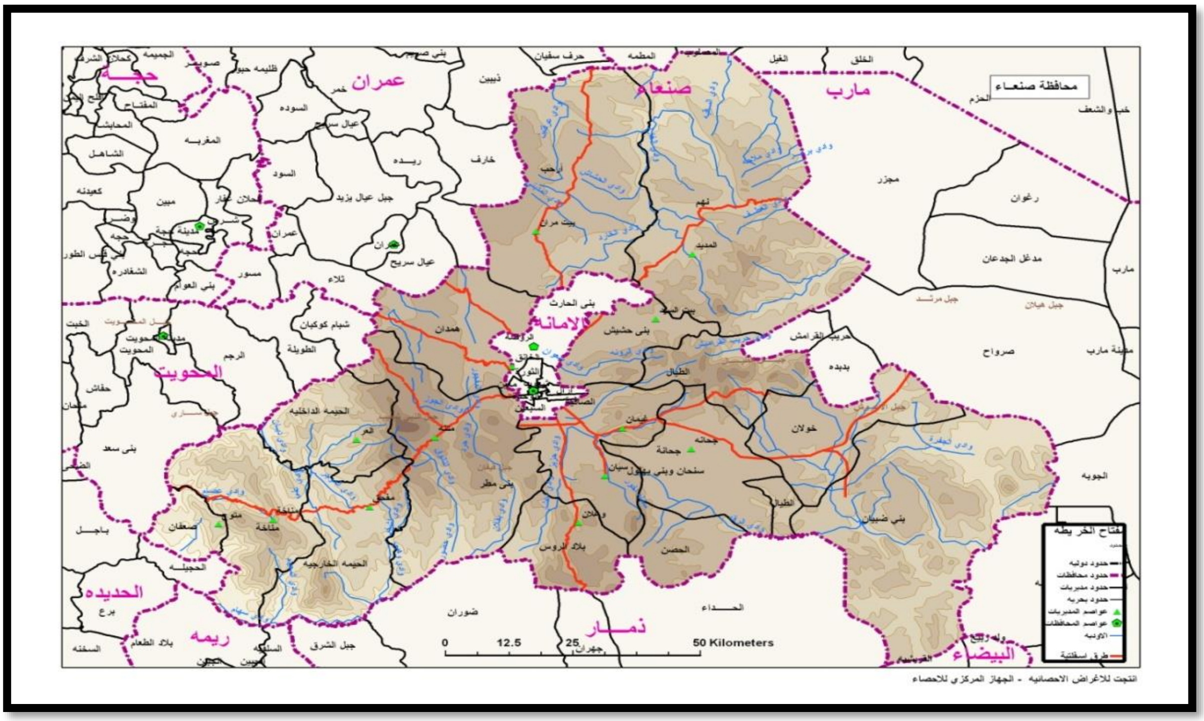
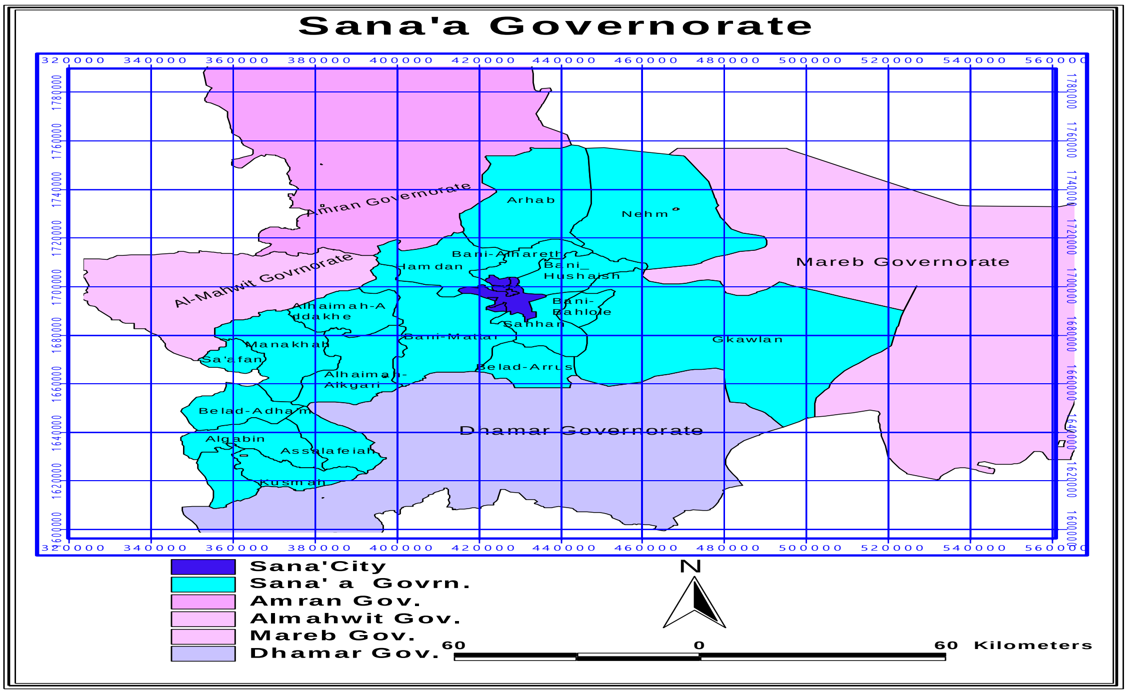

محافظة صنعاء
عمران
صنعاء
مارب
الامانة
المحويت
الحديده
ريمه
ذمار
البيضاء
0
12.5
25
50 Kilometers

Figure 2.1: Location Map and Administrative Division, Sana'a Governorate



Source: Base map referred to MOPIC and MAI, Dhamar Research Center. Details Developed by Dr.A-W A. Iskander, GIS Unit,

2.3.3 Classification of Aquifers:

There are four main basins in addition to several sub basins scattered in the governorate of Sana'a. The main basins are Sana'a Basin, Khawlan, Blad Arrus, Qaa Albawn and Bani Alharith basins. Sana'a Basin is categorized as one of the Highest Hazard basins not only in the governorate, but also in the country at large. Since the central plains are in the Highest Hazard Category. With respect to agricultural practice, these basins/plains are the most important in the Governorate. The entire governorate should be considered in as of Hazard basins. The average depth of wells ranges from 200m to more than 400m.

The soil texture varies from small to medium quality in the governorate, the best soil quality is common in the beds of valleys and in Qa'a plains and basins. The areas of Sana'a plains contain important agricultural zones, due to numerous wadis namely, Wadi Almlwk, Qa'a Albone, Sanhan plain, Wadi Blad Arrus and Wadi-Dhahr. Most of the plains are inward-drained confined by the adjoining mountains and hilly hinterland. Sometime slopes areas, topography and rainfall amount support spate irrigation to be practiced. These wadis also provide recharge to the porous and permeable quaternary sedimentary aquifers of the plains. The area is composed of old alluvium from the wadis. They are divided by rocks out crops at their marginal areas.

3. CLIMATE

Rainfall data analysis is described under this section. Rainfall patterns, spatial and temporal distribution as well as seasonal pattern of rainfall are examined in Sana'a Governorate. Other metrological data are analyzed hereafter. Due to its location in the central part of Highland Region, the governorate topography forms parts of Highlands and high plateau. Rainfall there is characterized as much similar to that of highland regions. Mean annual precipitation is moderately variable both in time and in space, being strongly affected by inter-annual variations and by altitudes. The rainfall is hardly adequate to produce rain-fed of moisture tolerated crops in the valleys and plains of the governorate, consisting largely of cereal grains cultivation. But, fruits and vegetables are produced using groundwater irrigation.

The rainfall data described under this section includes rainfall pattern, spatial and temporal distribution as well as seasonal pattern. Also metrological data are analyzed hereafter. The average rainfall is 125-167mm/year, temperatures vary between 10^0-28^0 C, evapotranspiration is 1485 mm/year, and the annual average of relative humidity is about 44% as the case prevails in mountains of central and northern uplands regions. The mean annual precipitation is highly variable both in time and in space, being strongly affected by inter-annual variations and by altitudes. The average elevation ranges from 2500m to 3600m a.m.s.l. in west of Sana’a.

3.1 Rainfall Data

There are only 2 rainfall stations in Sana'a with continuous long records of over 50 years. The rainfall series of long records has several interruptions. For the purpose of this investigation, mean annual rainfall data have been collected from various sources for stations representing the whole governorates for at least the period (1972 – 2008). The data have been updated to include more recent years. The available data has been analyzed to reveal the general rainfall pattern as well as temporal and spatial variations of rainfall over the governorate and its districts where the proposed Dams Network project well be sited. The following sections discuss the rainfall pattern, temporal and spatial variations in Sana'a Governorate where the nineteenth modern irrigation project (S-MIP) is to be developed.

3.2 Rainfall Pattern

Rain is the main form of precipitation in Sana'a Governorate, but hail is not uncommon and it is slightly snowing in January at the mountain summit of Gabal-Annabi-Shua'ib. Rain storms are dominantly convective in the region. As a result, their areal extent tends to be limited, in spite of the fact that the general circulation that sets the general conditions for the occurrence of rainfall is of a sub-regional scale. During summer periods of intensive convergence of trade winds, several rain storms may develop, bringing rainfall to extensive areas of highland. But in Sana'a Basins there is a regional great difference in the amounts of rainfall over short distances with shorter seasons. The general observation for most individual storms is that they cover only a limited area, no more than several tens of square kilometers. Local effects are strongly controlling the spatial patterns of rainfall in the different regions of Yemen. The location and higher elevation effects of Sana'a in the north is clearly feasible in the air moisture and rainstorms in many occasions.

Table 2.1 illustrate the mean annual rainfall of Sana'a, the mean catchment area for 35 years since 1972 with nearly complete records and associated chart shows the mean rainfall for longer period (76 years from1932 to 2007) as indicated in Figure 2.2. Data analysis of the last 35 years is based on observations of Sana'a Airport Station. The mean annual rainfall of the first 12 years is about 194 mm/year, with a variation of 78 mm/yr. The mean annual rainfall in the second 12 years is 164 mm/yr, while the value for the last 11 years is markedly higher than previous decade but lower than first decade; nearly 158 mm/yr indicating a gradual increase in rainfall average over previous decade. The overall mean of rainfall for the 35 years is 125mm/year. Based on spatial orthographic features, rainfall decreases from south-to-north. The overall mean of rainfall there is around one and half times of the amount in the costal areas. The average deviation from the mean for the three periods are about 74, 55, and 55mm/year respectively, which represent a gradually inter-annual decrease toward a lower rainfall variation from year to year in the last decades.

Unlike lowland of coastal plains, northern central highland implies that a relation between rainfall amount and variation extent in temporal terms is wider and far away from liner relationship. It is predictable from the past trend that a higher average of rainfall tends to occur once every 30 years in the past and once every 5-7 years recently as it is noted in the bar-chart of figure 3.2 . These exceptional years indicate a little ups-downs departure from the mean for the past and more deviation in the recent years.

Table 2.1: Annual Rainfall Pattern, Sana'a 1972-2007

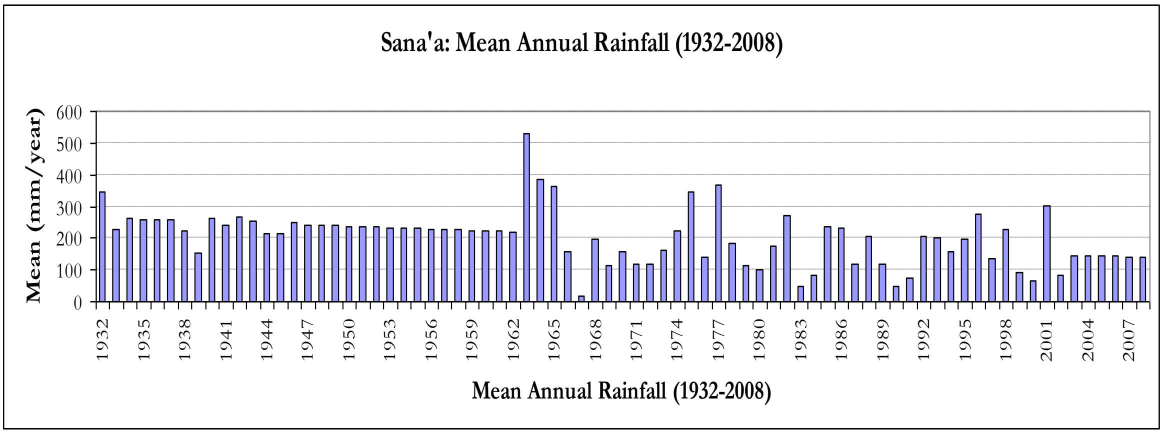
Year	Rainfall (mm/y)	Year	Rainfall (mm/y)	Year	Rainfall (mm/y)	Total 1972-2007	
						Average	Deviation
1972	116.5	**1984**	82.8	**1996**	277.3	190.1	79.0
1973	163.9	**1985**	236.9	**1997**	134.8	200.4	38.9
1974	224.8	**1986**	233.3	**1998**	227.4	184.3	3.2
1975	345.5	**1987**	117.9	**1999**	91.9	192.9	106.9
1976	141.2	**1988**	204.5	**2000**	63.9	129.4	48.4
1977	367.2	**1989**	118.7	**2001**	302.2	177.1	96.0
1978	185.9	**1990**	48.8	**2002**	83.4	92.6	53.2
1979	112.9	**1991**	72.4	**2003**	146.0	148.3	25.4
1980	99.6	**1992**	205.0	**2004**	146.6	171.5	36.4
1981	176.1	**1993**	203.2	**2005**	144.1	168.0	20.3
1982	270.8	**1994**	158.2	**2006**	142.4	193.6	53.6
1983	50.1	**1995**	198.3	**2007**	140.7	143.2	53.1
Mean	194.4		163.4		158.4	125.1	14.9
D.F.M	73.7		54.7		55.3	61.2	8.3

Note: Data for 1981-1987 is based on Rusaba Station and data from 1972-1980 is (unavailable) extrapolated.

Sources: Agro-Climate in Yemen General Authority of Agricultural Research and Guidance, Dhamar Center,2005

MAI, 2008Year Book Statistics, March, 2009 and 200-2006 Year Book Statistics, 2000-2006

Figure 2.2: Annual Rainfall Pattern, Sana'a 1932-2008



Source: The General Authority of Meteorology, Sana’a, 2008 and Table 2.1

Sources: Agro-Climate in Yemen General Authority of Agricultural Research and Guidance, Dhamar Center,2005

MAI, Year Book Statistics, 2008, March, 2009

Aden Airport, Climate Data 2005-2008, July 2009

The histogram above shows variation of limited amplitude for the first 30 years (1932-1962), but it gets wider thereafter (1963-2008). This deviation is partially attributed to unsystematic time series recording at the concerned stations.

3.3 Temporal Variations of Annual Rainfall

Annual rainfall mean varies from year to year and from location to location even in the same region or governorate. Table 3-1 shows the mean of annual rainfall at Sana'a Airport station for 35-year period while the histogram plotted the mean for 76 years from 1932 to 2008. Most rainfall stations in Yemen have incomplete records which makes it difficult to study temporal rainfall trend with high validity. However, the analysis of Sana'a rainfall records have relatively long series of nearly complete observations which has been allow studying temporal variation with some certainty.

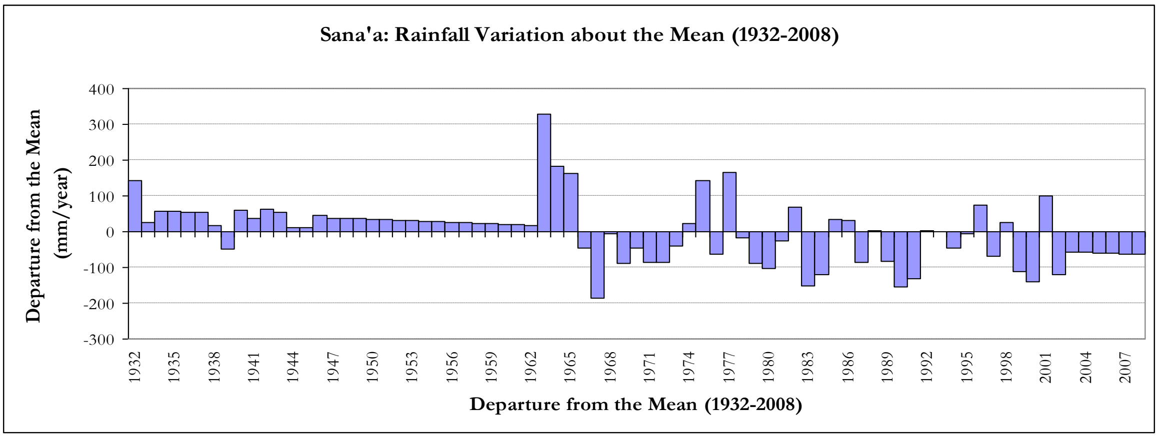
The rainfall observations started in 1932 and continued until 2007, with nearly complete years during the mentioned period except for some years of missing records between 1948 and 1962. Statistical analysis reveals that the long time series has a rainfall average total of 203 mm/year, with a total variation of 65 mm/year .The coefficient of variation is 0.319, which constitutes a considerable value as compared to that of coastal areas. This coefficient implies that the inter-annual variability is insignificant particularly, over the flat plains of Sana'a basin.

In spite of some missing data (12 years prior to 1962), the series is suitable for the analysis of rainfall variations at Sana'a for at least a half of a century. Unavailable records are statistically extrapolated using linear regression models.

The variation about the mean ('departures from the mean') enable to draw some conclusions. The most important is that there is significant long-term trend, but there is somewhat a defined cycles of dry years occurs at least every 3-5 years even though a fluctuation above and below average rainfall is presented.

The coefficient of variation of the annual rainfall series tends to increase with increasing rainfall average (see the mean as compared to variation at the bottom of table 3.2). This mean that varies from year to year is most pronounced at the most arid sites, at least in relation to the average rainfall. This inconsistency is less at the wettest locations in the governorate such as in Arhab, Bani-Alharth and Bani-Dhabian districts as is shown graphically under spatial rainfall pattern section in figure 2.3.

Figure 2.3: Rainfall Variation about the mean, Sana'a 1932-2008



Source: The General Authority of Meteorology, Sana'a, 2008 and Table 2.1

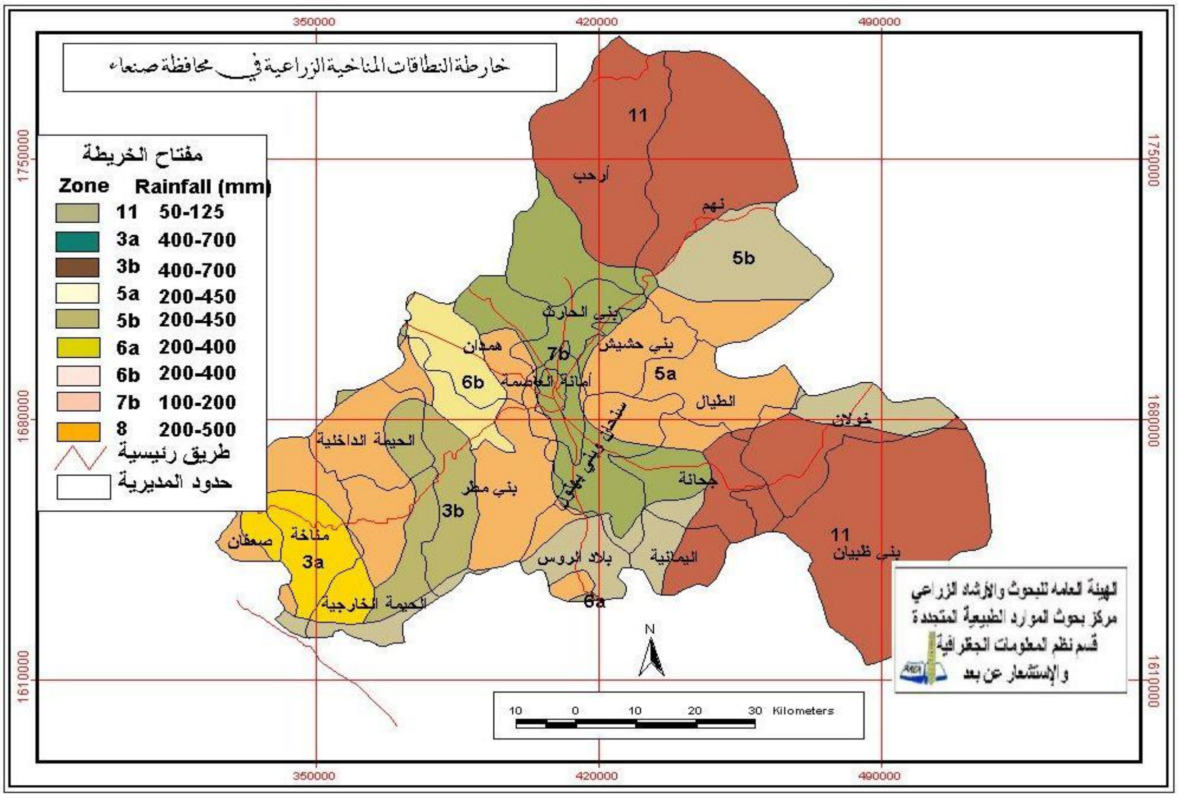
3.4 Spatial Variations of Annual Rainfall

The spatial pattern of annual rainfall varies from place to place. The controlling topographic factors, however, are strong enough to make distinct patterns that are fairly stable for long-term averages of annual rainfall. Figure (2.4) of agro-climate and associated table key shows the spatial pattern distribution of average annual rainfall mapped for Sana'a governorate during the period 1972 through 2003. This standard period was chosen as the period for which as many rainfall stations as possible have nearly complete records and scattered all over the governorate.

There are 9 distinctive agro-climate zones in Sana'a governorate shown in the isohyets map in Figure 2.4. The Isohyets Agro-Climate Zone map (figure 2.4) for the governorate developed by the General Authority of Agriculture Research (GAAR) gives a clear and consistent picture of the spatial distribution of annual rainfall in the governorate even with many associated constrains. Even though the general direction of rainfall zones extend in north-south axes, but spatial concentration of higher rainfall mean (400-700 mm/yr) are more likely to fall over the eastern portion of the governorate with areal extent ranges

10-12 km. as figure 2.4 portrays. Moderate rainfall averages are found in most districts of the governorate while rainfall below 200 mm/year is dominant in north-eastern and south-eastern areas of the governorate, namely in Arhab, Bani-Alharth and Bani-Dabian districts.

Figure 2.4: Spatial Rainfall Distribution, Sana'a Governorate



Source: The General Authority of Agricultural Research and Guidance, Department of Geographic and Information System and Remote Sensing, Sana'a, Yemen, 2010.

3.5 Seasonal rainfall pattern

Sana'a governorate demonstrates a two well-defined seasonal rainfall pattern as is shown in the line-graph below in figure 2.5. Based on 36 years of observation, it is clearly seen that two seasons dominate the annual rainfalls distribution pattern. The first rainy season occurs in Spring (March-May) with seasonal mean of 64 mm/year represents 38 % of total annual rainfall and the second occurrence is in the Summers (July-September) with rainfall mean of 67 mm/year, represents 40 % of the annual rainfall. The highest monthly rainfall average occurs in April 38.6mm and August 38.2mm. However, months of January and November are mostly dry, having only 1-2 mm of rainfall. The correlation coefficient of variation between the two seasons is -0.314 indicating to inverse seasonal relationship.

Figure 2.5: Seasonal/ Monthly rainfall pattern, Sana'a: 1980-2008

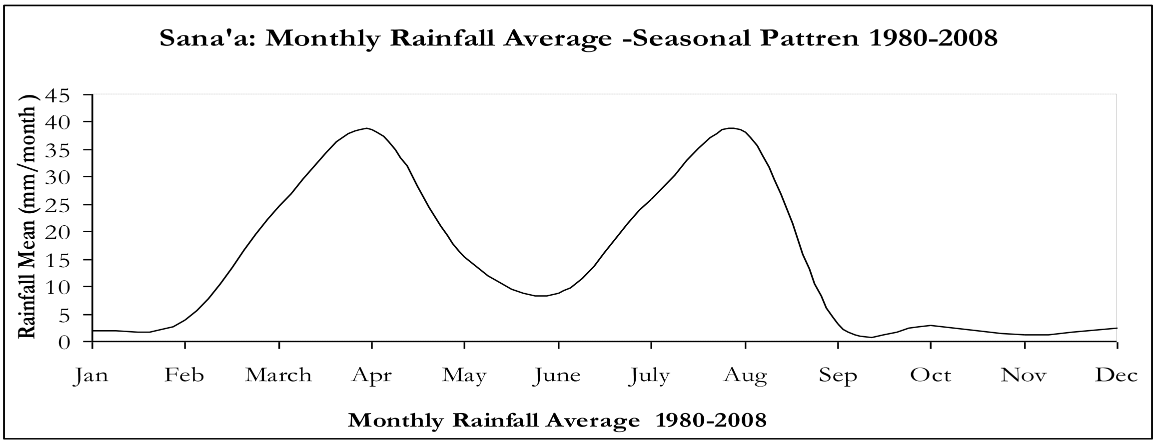
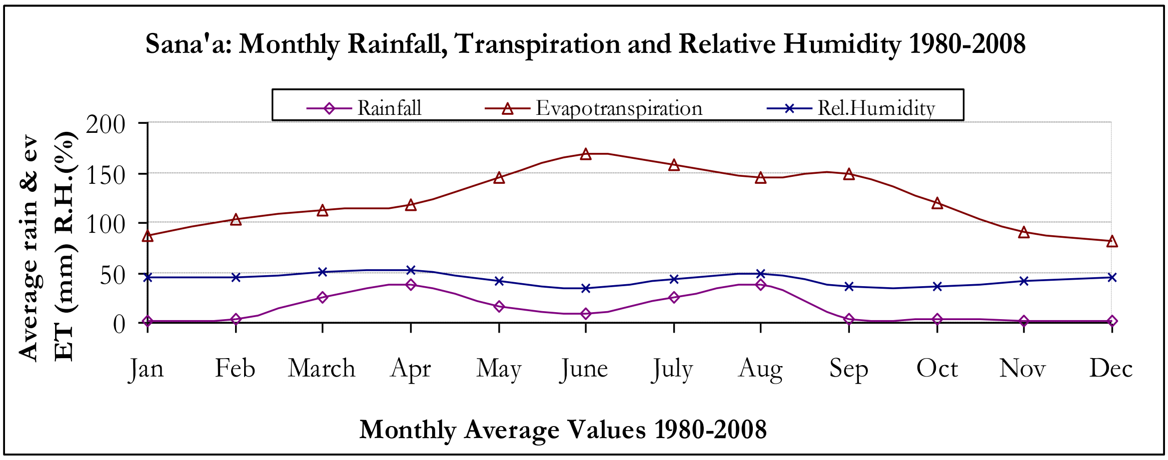


Figure 2.6: Monthly Evapotranspiration vs. rainfall pattern, Sana'a: 1972-2008



Source: The General Authority for Research and Agriculture Awareness, Guidelines of Agro-Climate in Yemen 1881-2004, 2005

-Agricultural Statistics Book. MAI, 2003, 2004, 2006, 2008.

* Data from 1990-1996 is extrapolated

Monthly rainfall in relation to evapotranspiration and relative humidity is described in figure 2.6 reveals that higher monthly rainfall are intersected with high rates of transpiration and relative humidity, indicating the effects of temperature on air and moisture capacity.

4. Meteorological data

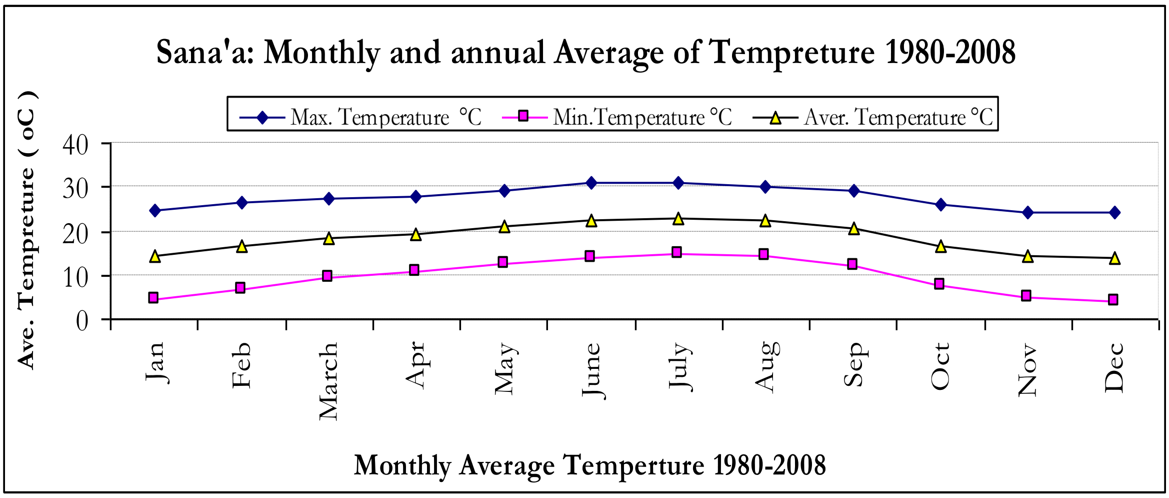
Meteorological variables other than rainfall are observed at most of the meteorological stations in Yemen. These are daily sunshine duration, temperature, relative humidity of the air and wind velocity. The average monthly values for these variables from 1980 to 2008 are shown in Table 2.2.

The accuracy and reliability of these meteorological data may be uncertain for part of the records. Careful checking and verification of quality assessments are certainly performed in order to get an accurate analysis results. (Irrigation, 2003, 2004, 2006, 2008)

4.1 Temperature:

The average monthly temperature in Sana'a governorate is 18.7, ranges from a minimum of less than 4°C in December to a maximum of about 31 °C in July. Figure 2.7 presents monthly temperature along with maximum and minimum averages. A strong spatial variation associated with elevation and distance from interior basins to western slopes of the governorate within the Central Highland Region.

Figure 2.7: Monthly Temperature, Sana'a Governorate 1980-2008



4.2Relative Humidity:

Temporal and spatial variations in relative air humidity are insignificant at annual level (43.6 %), but it is pronounced at monthly averages in the value ranges from minimum 35 % in June to 52 % maximum in April as Table 2.2 and associated figures describe.

Table 2.2: Meteorological data, Sana'a Governorate 1983-2008

Meteor-Climatlogical Par.	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual Aver.
Max. Temperature °C	24.7	26.3	27.4	27.7	29.4	31	30.9	30.3	29	25.9	24.3	24.3	27.6
Min.Temperature °C	4.4	6.8	9.5	10.9	12.6	13.8	15	14.6	12.1	7.8	4.8	3.9	9.7
Aver. Temperature °C	14.5	16.6	18.5	19.3	21	22.4	23	22.5	20.5	16.8	14.6	14.1	18.7
Relative Humidity (%)	46	46	50	52	42	35	43	49	36	37	42	46	43.7
Wind Speed (m/sec.)	2	2.2	2.3	2.3	2.6	3	3	2.9	2.7	2.3	1.8	1.8	2.4
Sunshine (hour/day)	9.9	9.5	8.5	8.3	9.6	8.3	7.5	8	9.3	10.5	10.5	9.5	9.1
Rainfall (mm/month)	1.9	3.9	24.6	38.6	15.5	8.7	26	38.2	3.2	2.9	1.3	2.4	167.2
Evapotranspiration (mm/month)	88	104	113	118	146	170	158	145	149	120	92	81.3	1485

Sources: MAI, General Authority of Agriculture Research in Yemen, 18881-2004, Dhamar Research Center,2005

Ministry of Agriculture and Irrigation, 2003 Year Book Statistics, 2004 and 2008 Year Book Statistics, 2009

MAI, Final Report, Indian Consultant, 2006

Sources: Agro-Climate in Yemen General Authority of Agricultural Research and Guidance, Dhamar Center,2005

(Irrigation M. o., Groundwater and Soil Conservation Project (GWSCP), 2007-2008)

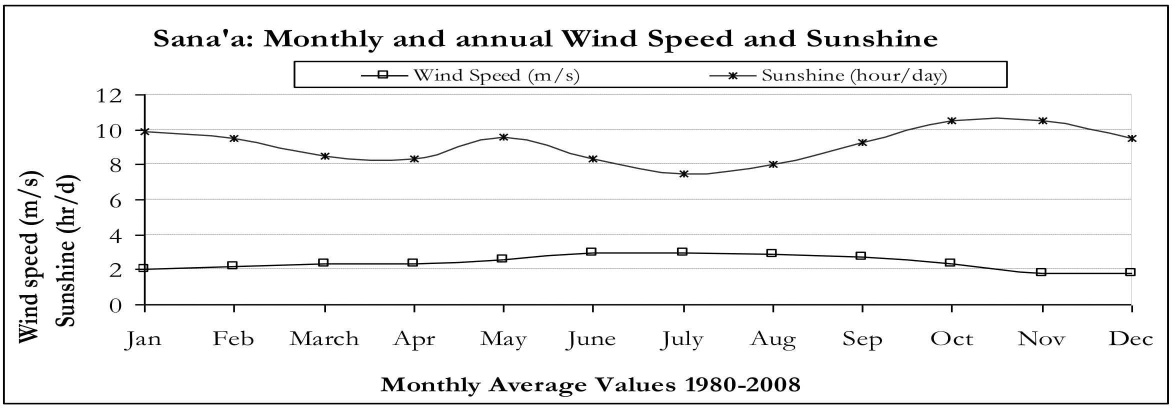
4.3 Sunshine:

The records of sunshine duration shows that clear skies are predominant in Sana'a Governorate during most of the year. The monthly average values of sunshine in the Governorate range from 7.5 hours per day in July to 10.5 hours per day in October and November, which corresponds to 62 -88% of the theoretical maximum. Clear skies in the winter cause much losses of daily temperature during nighttime by bare land solar reflection.

4.4 Wind Speed:

The average wind speed in most of Yemen ranges from low to moderate, except on the coast and at well exposed locations in the mountain zones. It is believed that a significant part of the differences has to be attributed to local effects. Figure 2.8 illustrates monthly wind speed as meter per second along with sunshine curve. The average monthly wind speed in Sana'a ranges from 2 meter per second in January, April and September to 2.9 m/s in the month of August and the annual average is 2.4 m/s as is seen in the line graph as constant due to insignificant differences.

Figure 2.8: Monthly Sunshine and wind speed, Sana'a Governorate 1980-2008



4.5 Evapotranspiration:

The potential evaporation and evapotranspiration records in the Metrological table for Sana'a during the period (1983-2008) shows that either the monthly or annual average ranges from a minimum of about 81-88 mm in December and January to a maximum of around 158 mm in July as is compared to 120 mm and 196 for the western costal area of Tehama in Alhodaiedah. The annual average in Sana'a is 1485 mm/year. Figure 2.9 compares monthly evapotranspiration average with rainfall average along with relative humidity in Sana'a governorate. Figure 2.10 also compares Sana'a with the other governorates in the country in respect to evapotranspiration.

Figure 2.9: Monthly Evapotranspiration vs. rainfall pattern, Sana'a: 1980-2008

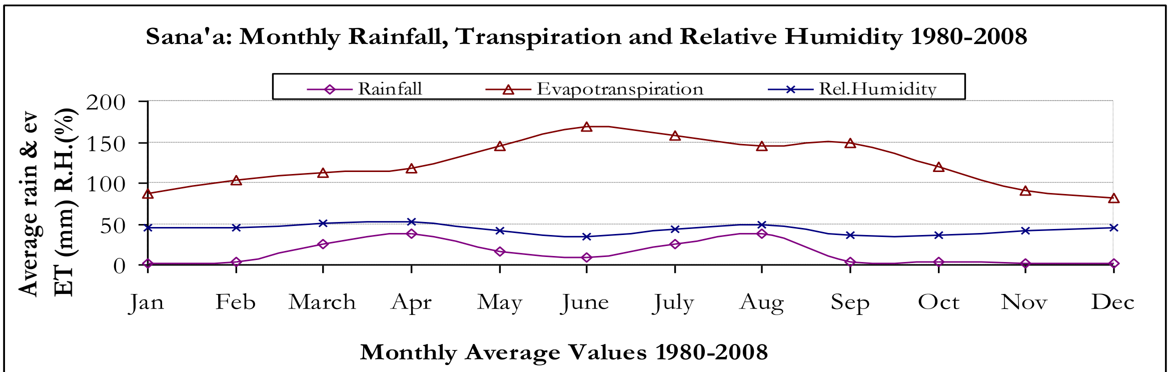
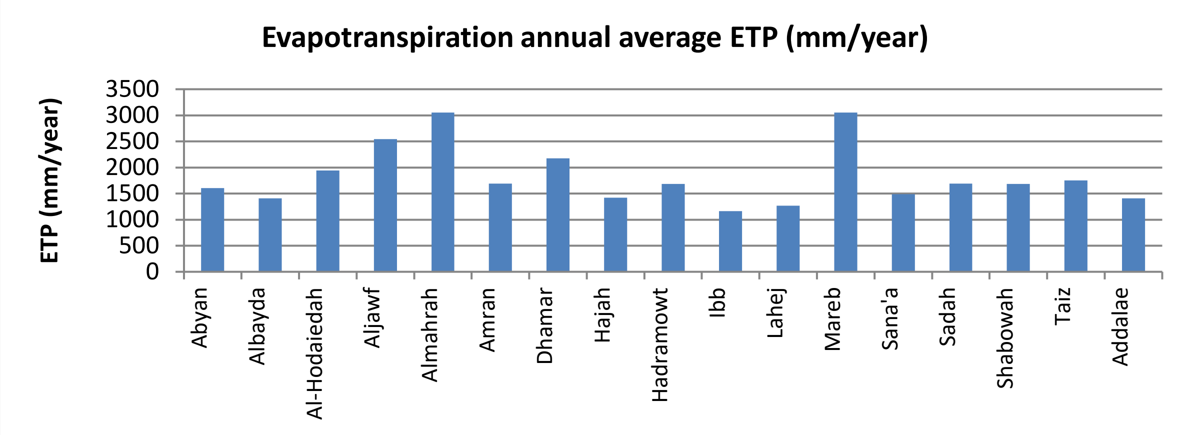


Figure 2.10: Annual Average Evapotranspiration at Project Locations(Sana'a Basin).



5. WATER RESOURCES ASSESSMENT

Due to insufficient rain-fed agriculture, many areas depend on groundwater for supplement irrigation by overexploitation of deep aquifers which are consequently in depletion of groundwater table.

Several Parameters are used to assess water availability. The most important are means of annual rainfall in catchment producing areas and in absorbing areas for considerable time span, runoff and recharge volumes in mm/year and in MCM/year, number of pumped wells and their mechanical capacities in terms of m^3/ hours of water discharge. Other variables are also employed such as water level in a basin and water application for irrigated crops according to traditional versus modern use for all types of cropping pattern. Data of water applications amount in m^3 per crop type for each hectare of irrigated Field Units by GWSCP proved to be reliable as compared to the number of active wells and their capacity of pumping and drops in water tables in concerned areas and basins. Irrigated areas from groundwater were measured on Field Units covering 18 Yemeni Governorates.

Methods of data analysis include statistical models, historical linear regression trends and forward extrapolation in addition to verifying formulas in order to test validity of data analysis. Data input of these parameters and related variables are organized and tabulated analytically and aggregately according to three spatial levels: first, at regional and local levels, then, at basin and wadi levels, and finally at districts and governorates or administrative division levels.

The purpose of these geographical partitions is to enable concerned authorities to functionally plan, manage and control water resource and guide project implementation process properly with clear advisory and sustainable work bases.

5.1 Surface Water and Runoff Scale

The runoff process is controlled by several factors; considering the conditions encountered in Yemen, the main factors are:

(a) Size and shape of the catchment;
(b) Rainfall characteristics, such as intensity, spatial and temporal distribution of rainfall;
(c) Rates of potential evaporation and evapotranspiration;
(d) Terrain characteristics of the catchment area such as slopes; properties of soils, rock outcrops and vegetation;
(e) Presence and properties of regional groundwater systems;
(f) Land use and other human interference.

Table 2.3 gives an explanation of runoff producing and runoff absorbing zones as distributed over the territory of Sana'a Governorate. The runoff producing zones are subdivided into zones with a permeable surface and those where outcropping rocks are more or less impermeable. Relevant data has been updated and some other catchment areas of highland region are divided by governorate and its territories are added to the model. Certain modification of runoff coefficient values is carefully managed in relation to topographic features and soil coverage based on mean annual rainfall figures aggregation and relative areal extent representation. This may be of interest for better understanding the differences in runoff regimes; the aggregation level of the map did not allow other relevant terrain features to be incorporated, such as terrain slope and presence of vegetation and terraced agriculture, which is recommended to be investigated and covered in future projects. There is no estimation for either runoff or recharge has been done in the highland region by previous reports and studies except for certain basins in Sana'a, Amran and Sa'adah, therefore, the base estimation of the current hydrological study for Sana'a is executed using various models. Careful check out and examination also have been performed to test the validity of analysis and the results are shown in (Table 2.3) below.

Sana’a basins and wadis presented in table 2.3 include four sub-basins/plains as potential locations for the Sana’a Modern Irrigation Dam Network Project (S-MIDNP). Dam network of 330 hectares should be executed in suitable sites for the concerned improvement project. Sana'a Basin is one of the large-scale example of runoff absorbing zone in the central highland region, although it is insignificant as runoff absorbing zone due to its urban area, it is the largest runoff producing zone in its surrounding and nearby areas.

Review on previous reports indicates that surface water (runoff) in Sana’a Basin, not including the other government basins, was estimated at 41 MCM/year in 1984 and 38MCM/year in 1995 (WRAY-35).

The total catchment areas producing runoff in Sana’a governorate is estimated at 11,987 sq. km., which produces a runoff volume of 158 MCM/year as in 2008. About 90% of this amount or 147 MCM/year is absorbed contributing to the aquifers recharge in Sana'a governorate as shown in table 2.3 below.

The summary table of runoff-recharge component demonstrates the catchment area, mean annual rainfall in mm and in MCM, runoff volumes in million cubic meters, and runoff coefficient in addition to recharge volumes.

Table 2.3-A: Mean Annual Runoff for Runoff producing catchments, Sana'a Basins

Project name	**Northern Highland Plains**	**Catchment Area**	**Mean Annual Rainfall (1980-2008=28yr)**		**Mean annual runoff (1984-2008)**				**Recharge Volume**	
		(Km2)	mm/yr	Mm3/yr	2008 mm/yr	2008 Mm3/yr	1984 Mm3/yr	1994 Mm3/yr	2008 mm/yr	2008 Mm3/yr
Sana'a	**Coefficient**				**0.0608**	**0.0608**	**gauged**		**0.904**	**0.904**
	Sana'a Basin	3250	197	640	12	39	41	38	11	35
	Khawlan-Blad Arrus	3473	320	1111	19	68			18	61
	Qaa Albawn	264	386	102	23	6			21	6
	Bani Alharith area	5000	150	750	9	46			8	41
Total (38,605)		***11987***	***263***	***2604***	***16***	***158***	***41***	***38***	***14***	***143***
Mean		**2997**	**263**	**651**	**16**	**40**	**41**	**38**	**14**	**36**

Note: Mean annual rainfall is referred to the average catchment producing areas while recharge is referred to absorbing areas

Sources: Ministry of Agriculture and Irrigation Compiled from different tables presented in "Water Resources, Report-35, 1996"

The Table is compiled from various sources.

The volume of annual rainfall falling over the catchment areas that drained toward Sana'a basins, specifically to the Basin of Sana'a and Qaa' Albawn, Bani-Alharth, and other wadis in the governorate is estimated at 2,604 MCM/year of which around 6% is runoff to these areas, which corresponds to 158 MCM/year surface flow and 143 MCM/ year ground infiltration as in 2008.

The following table which is updated to the year of 2020 in order to show current data of annual rainfall and related runoff and recharge. The figures of 2020 are not far from those of 2008 where less than 6% of rainfall is account for recharge and slightly more than that is estimated for surface runoff water.

Table 2.3-B: Mean Annual Runoff for Runoff producing catchments, Sana'a Basins 2020

Project name	Northern Highland Plains	Catchment Area	Mean Annual Rainfall (1980-2008=28yr)		Mean Annual Rainfall (2008-2020=12yr)		Mean annual runoff (2008-2020)				Recharge Volume 2008-2020			
		(Km2)	mm/yr	Mm3/yr	mm/yr	Mm3/yr	2008 mm/yr	2008 Mm3/yr	2020 mm/yr	2020 Mm3/yr	2008 mm/yr	2008 Mm3/yr	2020 mm/yr	2020 Mm3/yr
Sana'a	**Coefficient**						**0.0608**	**0.0608**	**0.0628**	**0.0628**	**0.904**	**0.904**	**0.914**	**0.914**
	Sana'a Basin	3250	197	640	201	653	12	39	199	41	11	35	11	37
	Khawlan-Blad Arrus	3473	320	1111	350	1216	19	68	305	76	18	61	18	70
	Qaa Albawn	264	386	102	360	95	23	6	395	6	21	6	23	5
	Bani Alharith area	5000	150	750	170	850	9	46	160	53	8	41	9	49
Total (38,605)		*11987*	*263*	*2604*	*1081*	*2814*	*63*	*158*	*1059*	*177*	*58*	*143*	62	*162*
Mean		2997	263	651	270	703	16	40	265	44	15	36	15	40

Sources: Ministry of Agriculture and Irrigation Compiled from different tables presented in "Water Resources, Report-35, 1996"

The Table is compiled from various sources in addition to metrology data by the General Authority of Air and metrological statistics 2021

Outcome analysis of surface water assessment is then depends on geographic, topographic and soil cover features. Differences on estimation rely on specified value of coefficient and any slight modification on this value is reflected in a considerable yield or under estimation of groundwater recharge. It is believed that current estimate value is accurate since it depends on catchments aggregation and segregation of wider extent covering the whole country and then assigned to main regions and sub-basins and wadis.

5.2 Sources of Irrigation

Irrigated area in Sana'a governorate has increased from 43% to 49 % of total cropped area (38,112-81,994 ha) between 2007 and 2008. However, cropped area irrigated from groundwater has decreased from 69,763 hectares to 50,856, represents 27% shrink in one year which indicate to a welcome trend in the context of groundwater sustainability, but the percentage of irrigated area from groundwater is still high 30.5 % of total cropped area or 62% of irrigated area in 2008. The increase of irrigated area is accounted for other sources of irrigation particularly, the spate irrigation (floods), despite the overall decrease trend in the cropped area as 2008 is compared to 2007, as shown in Table 2.4. It is a good indicator that irrigated area from wells has been recently retreated for the sake of groundwater sustainability.

Table 2.4 : Cropped Area by Sources of Irrigation, Sana'a: 2007- 2008

Year	Sana'a Cropped Area (Ha)	Cropped Area by Source of Irrigation (Ha)						Irrigated Area	
		Rains	Wells	Floods	Streams	Dams	Tanks	Area (Ha)	% to Total
2007	176,454	88,231	69,763	410	2,850	14,300	900	38,112	43
2008	166,522	84,427	50,856	16,552	3,297	9,707	1582	81,994	49
2008%	100%	50.70	62%	20%	4%	12%	2%	100	49%

Source: Economic Benefit/cost analysis, FAO,2008

2008 Agricultural Year Book Statistics, MAI, May 2009

6. GROUNDWATER SYSTEMS

Studies on groundwater in different areas in Yemen are frequently far from uniform as TON report noted. The main aquifers basins and variations are analyzed and compared on a national scale, then in regional and sub-regional levels with attention to re-interpret the available information with implementation of several but consistent methods for tabular organization and classification.

There are four medium alluvial aquifer systems scattered over Sana'a plains, which constitute aquifers of considerable water absorption capacity and their productivity is generally high to moderate. A brief description of the main groundwater recharge systems for the governorate is as follows:

Many of Highland Plains constitute small, but relatively favorable areas for groundwater development. The most important groundwater basins in

Sana'a are the Sana'a Basin, Bani-Alharith, Qa'a Albawn, Khawlan and Blad-Arraws Plains. They will be briefly described below.

Based on several studies carried out during the last 20 years (including Italconsult, 1972; Mosgiprovodkhoz, 1986; Bloemendaal et al., 1994a; TS-HWC, 1992i), the Sana'a basin is characterized by a complex groundwater system. Hydrogeological, important units are the Quaternary alluvial deposits, the Tertiary Yemen Volcanic, the Cretaceous Tawilah Sandstones and -perhaps- the Kohlan Sandstones. An important source of groundwater in the past was produced from the alluvial deposits, but serious declines of the groundwater levels have reduced their production. The Tawilah Sandstones have become the most significant extracted aquifer unit since they were explored in the early 1970s. Flow in this aquifer is believed to be through fissures and pores (mixed aquifer type). Probably, Kohlan aquifer supplies groundwater in the northern part of Sana'a Basin as the Tawilah sandstones are not present there, due to erosion. South of Sana'a the Tawilah Sandstones are overlaid by a complex of Tertiary volcanic rocks and intercalated alluvial sediments. Productive wells have been sunk in the Tawilah Sandstone in the southern zones of the urban area, but further south the volcanic/alluvial complex is the only significant aquifer known. High rates of abstraction have severely affected the water table levels in the Tawilah Sandstones. Groundwater quality is generally good in the Sana'a basin, but polluted zones have been observed in the urban area and north of Sana'a city, where incomplete treated sewage water is infiltrating. A review of hydrogeological studies and data related to the Sana'a basin indicate to hazard situation regarding this issue.

There are large differences between the aquifer complexes present in different parts of the country, in addition to the great variations in hydrological conditions, which leads to a great diversity of groundwater systems.

6.1 Groundwater Recharge Estimation

The main source of aquifer recharge in Dhamar plains is by infiltration of runoff surface water from upper rainfall catchments drain into wadis' beds and fused into Sana'a Basin. Direct recharge from rainfall falling on to the area is generally important unlike western and southern lowland areas due to relatively rain moisture nature of the soil column during rainy seasons. Only when rainfall with high intensity occurs during few days, it is possible for the soil profile to be fully saturated and produce recharge to the groundwater basin below.

Various methods of recharge estimation have been reported in the literature. The choice of a particular method depends on the type of data available. These methods can be summarized as:

Volume of recharge is = A x Delta H x Sy x $\boldsymbol{10^6}$ $\boldsymbol{m^3}$***/year***

Verification of these analytic methods is proved reliable on grounds that such analysis are based on gauged runoff parameters on the one hand, and on field measurement of water pumped from wells on other hand, as well as measurement of water volume used for certain irrigated crops during its full growing season carried on field units survey by GWSCP, 2007-2009. Furthermore verifying formulas are used to test the accuracy of the results of these estimates as fallows;

1-Estimated runoff and recharge volumes should be or nearly equals:

*Mean Annual Rainfall (mm) ÷ 1000(m3)*Area *coefficient factor = the Runoff and recharge volumes of gauged catchments/wadis/basins respectively,*

2- Estimated water abstraction should be or nearly equals:

*Number of wells in concerned area * Average capacity of pumped wells (*m^3*/ hours) multiplied by the aggregated area of irrigated crop in terms of (*m^3*/ hours/ ha)*

The outcomes of recharge analysis of Sana'a plains are shown in previous table 2.3 and reproduced in Table 2.5, which designed to demonstrate groundwater recharge in relation to rainfall and runoff in the main basins of the governorate. Valleys/ wadis and plains of alluvial soils absorbing capacity are donated to uptakes between up to 90 % of runoff volumes and transmit it to underground with coefficient of 0.904. The results of analysis are shown in table 2.5. The total recharge of the main four sub-basins in is 143 MCM / year. The sub-basins vary in the recharge yields according to the size of catchment area, the rainfall mean, despite the constant value of coefficient adopted for the runoff-rainfall and recharge-runoff components as Table 2.5 describes.

Table 2.5: Runoff and Recharge by Catchments, Sana'a 1984-2008-2020

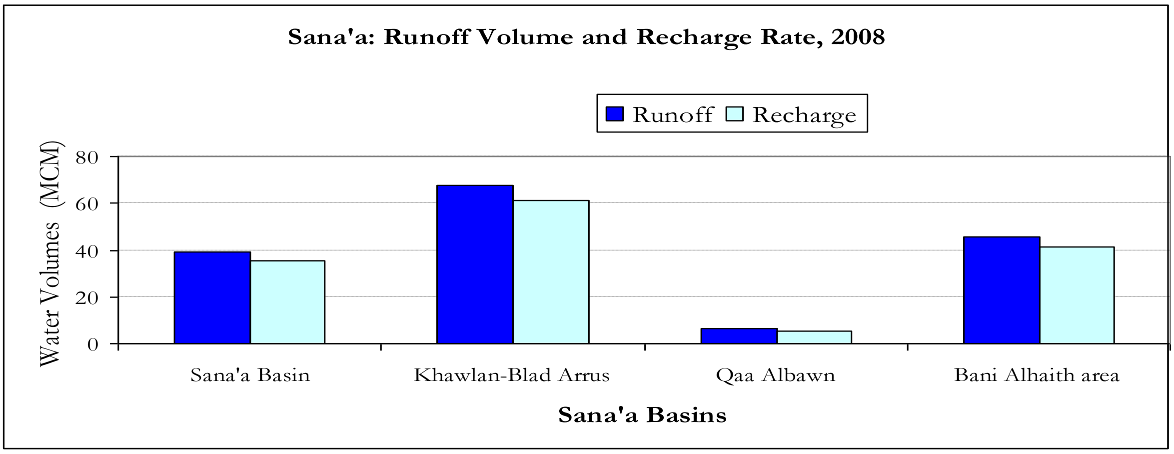
Project name	Northern Highland Plains	Catchment Area	Mean Annual Rainfall (1980-2008=28yr)		Mean Annual Rainfall (2008-2020=12yr)		Mean annual runoff (2008-2020)				Recharge Volume 2008-2020			
		(Km2)	mm/yr	Mm3/yr	mm/yr	Mm3/yr	2008 mm/yr	2008 Mm3/yr	2020 mm/yr	2020 Mm3/yr	2008 mm/yr	2008 Mm3/yr	2020 mm/yr	2020 Mm3/yr
Sana'a	**Coefficient**						**0.0608**	**0.0608**	**0.0628**	**0.0628**	**0.904**	**0.904**	**0.914**	**0.914**
	Sana'a Basin	3250	197	640	201	653	12	39	199	41	11	35	11	37
	Khawlan-Blad Arrus	3473	320	1111	350	1216	19	68	305	76	18	61	18	70
	Qaa Albawn	264	386	102	360	95	23	6	395	6	21	6	23	5
	Bani Alharith area	5000	150	750	170	850	9	46	160	53	8	41	9	49
Total (38,605)		*11987*	*263*	*2604*	*1081*	*2814*	*63*	*158*	*1059*	*177*	*58*	*143*	62	*162*
Mean		2997	263	651	270	703	16	40	265	44	15	36	15	40

Sources: Ministry of Agriculture and Irrigation Compiled from different tables presented in "Water Resources, Report-35, 1996"

The Table is compiled from various sources in addition to metrology data by the General Authority of Air and metrological statistics 2021

Figure 2.11 compares the runoff volumes with recharge rate in 2008 for the concerned sub-basins in the governorate of Sana'a. The differences among plains in the recharge rate indicates the extents of the catchment area and rainfall amounts although local controlling factor affecting the surface runoff water from filtering down into underground recharge are held constant.

Figure 2.11: Runoff Volumes (1984-2008) as Compares to Recharge, Sana'a Gov.



6.2 Groundwater Balance

Looking at the available information on groundwater levels of the main aquifers in Yemen, including Sana'a basins are depleting and increased abstraction have drastically declined groundwater levels to alarming figures. This phenomenon is generally observed in almost all areas.

Estimation of groundwater balance involves determination of several hydrological parameters and many variables involved in each parameter. The most important are those variables related to the mean annual rainfall and runoff volumes, associated with catchment size of producing and absorbing areas that are shown in previous table (2.5). Natural recharge coefficient which depends on scaling down the rainfall and runoff in mm or m/ year with catchment size in m^2 to the quantity in m^3, in addition to topographic coverage and soil features in terms of permeability, porosity, transmissivities and level of slopes.

As Sana'a basins are concerned, the runoff coefficient value is 0.0608 in relation to rainfall while the recharge coefficient is 0.904 in relation to runoff volumes, higher than that of southern recharge areas due to quality deference in soil permeability. These coefficient values are determined on the bases of regional and local parameters of geological as well as hydrological relevant conditions and depends on the past experience and measurements undertaken by several projects. Still the third parameters of abstraction and the availability of accumulated groundwater storage of the concerned basin.

In order to establish a threshold for estimating groundwater abstraction, detailed data on active wells inventory, capacity of their pumping equipment, the average pumping hours of water per year are employed, in addition to historical records of data on water table levels, depth of wells and water in a basin and at least the average dropping rate of water tables are significantly input variables for such estimation. Since the available data is only confined to the number of wells provided by the Agriculture Census of 2002, and to data samples on pumping wells capacity in terms of m3/ *hours* along with water crop requirements and irrigation schedules conducted by GWSCP's on the Field Units, theoretical models have been developed to compensate for some unavailable data. Consequently, several tables are constructed based on field measurement of water use requirement for irrigated crops, which has been scheduled during the full growing season of certain cropping pattern in specific given areas in the governorate.

Table 2.6 demonstrates 6-samples as field units with an area of 9 hectares in Sana'a Governorate. The average water consumed for irrigation using the traditional method is 10, 777 m^3/ha for various types of irrigated crops, however, this average of water use for the same crop pattern is reduced by 42 %, down to

6,232 m^3/ha based on improved techniques of irrigation using modern technologies. The difference in water use is accounted for water saving (4,545 m^3/ha.). Variation of water saving is relevant to method and technologies used for irrigation and cropping type requirement. The water saving ratio increases with crops of more water demanding type and with high water saving technology. For example, higher percentages of water saving associates with coffee and grapes (49-50 %), using drip and bubbler methods of improved irrigation, while 28% of water saving relates to piped conveyance.

Aggregating water saving, for all irrigated crops as measured in the sample, and applying the average to the whole irrigated area in Sana'a Governorate results in around 373 MCM/year of water could be saved in the governorate assuming that all irrigated land be covered with modern irrigation techniques. The highest value of water saving is proportionally related to the size of irrigated area and types of crops as well as technology used for irrigation as is indicated in Table 2.6 by several Field Unite of the samples.

Table 2.6: Water Consumption and Saving, Sana’a Gov., 2008

Sana'a Governorate/Dist.		Croppin g type	Farm sample area	Water Consumption by Irrigation Method			Average Saved Water (traditional versus modern)		
Sample No.	**Project Location**			Traditional	Improved	Irrigation	Sample	Govern.	Percent.
			(ha)	(m^3/ha)	(m^3/ha)	method	(m^3/ha)	(Mm^3)	%
1	Bit-Aziadi	Peaches	2	7,450	4,704	sprinkler	2746	3.51	37
2	Tawar-Khawlan	Sorghum	1	9,302	6,654	pipe conv.	2648	73.55	28
3	Assuhman-Kh	Grape	1	9,785	5,017	bubbler	4768	48.09	49
4	Assuhman-Kh	Tomatoe s	2	7,600	5,280	drip	2320	5.35	31
5	Azzawn-Manka	Coffee	1	22,543	11,301	drip	11242	122.64	50
6	Bani-Mattar	Almond	2	7,980	4,433	drip	3547	18.15	44
Total			**9**	**64,660**	**37,389**		**27,271**	**373.14**	**42**
Average			**1.50**	**10,777**	**6,232**		**4,545**	**45.21**	**42**

Source: Ministry of Agriculture and Irrigation, Groundwater and Soil Conservation Projects, compiled from "Farmer Guideline -Dhamar, January,2008"

Ministry of Agriculture and Irrigation, Agricultural Statistics Year Book,Mar.,2009"

Irrigated from groundwater in Sana'a governorate was 50,856 hectares in 2008, represents about 62 % of total irrigated area in the governorate, which consumes 548 MCM/year of groundwater, corresponds to total abstraction of water used for irrigation. It is a huge volume of water use, particularly with respect to 42 % average in water saving, equal to 230 MCM/year for total irrigated area, which could be saved contributing to the augmentation of groundwater recharge (548 MCM/yr traditional use vs. 318 MCM/yr improved methods) as table 2.7 explains.

Looking into the estimation in view of pumping wells discharge based on their capacity on groundwater abstraction as compared to the amount of water used for irrigated crops as measured on the field units give lower value: 239 MCM/ yr as for wells capacity method versus 548 MCM/yr for irrigated crops method. The difference between the two methods of estimation, namely water crop requirement as measured on the field units and the pumped wells capacity as measured also on the field, is believed to be a function of input units in terms of water as m^3/ hours/ year, where inputs of pumping parameter is confined to one season a year whereas pumping for irrigation may continue throughout the year, specially in the case of Qat cultivation.. Therefore, in such a case, the results of analysis by the two methods could be concise if other seasons were considered in pumping for irrigation. Hence, this analysis proves in two ways to be accurate and the methodology used is valid.

Table 2.7: Groundwater Consumption and Saving, Sana'a Gov., 2008

Sana'a Governorate/Dist.		**Sana'a Cropping Pattern**	**Total Irrigated Areas**	**Sana'a average wells discharge per crop(13-18 m3/hr)**		**Water Consumption and Saving by Irrigation Method**			**Irrigated Area from Groundwater: 2008**	
Sample No.	**Project Location**					Traditional	Improved	Saved	Crop. Area	Water vol
			(ha)	(Mm^3)	(hrs/ha)	(Mm^3)	(Mm^3)	(Mm^3)	(ha)	(Mm^3)
1	Bit-Aziadi	Peaches	1280	65	390	10	6	4	12200	91
2	Tawar-Khawlan	Sorghum	27774	16	427	258	185	74	2800	26
3	Assuhman-Kh	Grape	10085	3	336	99	51	48	600	6
4	Assuhman-Kh	Tomatoes	2305	40	600	18	12	5	4900	37
5	Azzawn-Manka	Coffee	10909	70	806	246	123	123	6300	142
6	Bani-Mattar	Almond	5116	45	250	41	23	18	13148	105
Total		Total	81,994	239	2809	885	512	373	50,856	548
Average		Average	9578	40	468	103	60	44	6,658	68

Source: Ministry of Agriculture and Irrigation, Groundwater and Soil Conservation Projects, compiled from "Farmer Guideline-Dhamar, January,2008"

Ministry of Agriculture and Irrigation, Agricultural Year Book Statistics,Mar.,2009"

7. ESTIMATION OF WATER SAVING BY THE CURRENT PROJECT (D-MIP)

With respect to Sana'a MIP, the amount of groundwater could be saved as a result of the implementation of concerned project is estimated to be about 1.5 MCM/year as a function of multiplying the average water saving (42%) proved by the samples on the field units in the governorate that is 4,545 m^3/ha by the targeted project area that is 330 ha. as is shown in table 2.8 Another countable benefits is from cut-back spending on pumping hours, cost of water, labor wages and so on., in addition to invisible aspects of economic benefits such as stability, sustainability and an efficient use of groundwater for the locals as well as for the nation.

Table 2.8: Sana'a : Project Water Use and Saving Indicators

Sana'a: Average Water use and Saving 2008	Conveyance Pipe System			Modern On-Farm Irrigation System			Total
	Total	Cereals	Cash Crop	Total	Vegetable	Fruits	Area
	Ha	Ha	Ha	Ha	Ha	Ha	Ha
Targeted area(ha)	0.0	0.0	0.0	330	165	165	330
Traditional(MCM/yr)	0.0	0.0	0.0	3.6	1.8	1.8	3.6
Improved(MCM/yr)	0.0	0.0	0.0	2.1	1.0	1.0	2.1
W. Saving(MCM/yr)	0.0	0.0	0.0	1.5	0.7	0.7	1.5
Average W. Saving(%)	0.0	0.0	0.0	42.2	42.2	42.2	42.2

Result of economic benefit /cost analysis by MAI and the FAO is set forth here as it is stated to allow comparison of water saving between the two estimates:

7.1 Critical Basins and Groundwater Abstraction

One of the main aims of the MIP is to reduce groundwater abstraction and recover groundwater levels. Unless groundwater recharge is reasonably estimated this can not be achieved. Water abstraction, recharge estimates and water balance for various groundwater districts in Alhodaiedah are analyzed and the results are shown in Table (3.8) below. However, these estimates can be considered as approximate and hence there is a rational ground to make reliable estimate. Sana'a basins are divided into districts based on factual data obtained from Agriculture Census for wells inventory and from different Year Book Statistics and other sources that are combined with previous tables to produce table 2.11.

Table 2.11: Groundwater Abstraction, Recharge and Water Balance, Sana'a 2008

Series	Sana'a Districts	Total Agricult. Area (ha)	No. of wells	Water abstraction *(wells discharg)*		Groundwater irrigated crops		Water Recharge		Water Balance *(Discharge-Recharge)*	
				Mm³/yr	%	(ha)	%	Mm³/yr	%	Mm³/yr	%
Total Governorate		144900	**59,693**	**548**	**100**	**50,856**	**100**	**143**	**100**	**-405**	**100**
1	**Hamdan**	18730	12342	113.3	20.7	10515	20.7	18.5	12.9	-83.7	20.7
2	**Arhab**	9987	4620	42.4	7.7	3936	7.7	9.9	6.9	-31.3	7.7
3	**Nehm**	5815	3041	27.9	5.1	2591	5.1	5.7	4.0	-20.6	5.1
4	**Bani-Haushaish**	6926	14529	133.4	24.3	12378	24.3	6.8	4.8	-98.6	24.3
5	**Sanhan**	8425	4082	37.5	6.8	3478	6.8	8.3	5.8	-27.7	6.8
6	**Bani-Bahlawll**	2622	1437	13.2	2.4	1224	2.4	2.6	1.8	-9.8	2.4
7	**khawlan**	31580	11051	101.5	18.5	9415	18.5	31.2	21.8	-75.0	18.5
8	**Belad-Arraws**	6857	2093	19.2	3.5	1783	3.5	6.8	4.7	-14.2	3.5
9	**Bani-Mattar**	24298	4633	42.5	7.8	3947	7.8	24.0	16.8	-31.4	7.8
10	**Alhaymah-Addkhiliah**	13104	627	5.8	1.1	534	1.1	12.9	9.0	-4.3	1.1
11	**Alhaymah-Alkharigaiah**	5484	1239	11.4	2.1	1056	2.1	5.4	3.8	-8.4	2.1
12	**Manakhah**	10664	0	-	-	0	-	10.5	7.4	0.0	0.0
13	**Sa'afan**	409	0	-	-	0	-	0.4	0.3	0.0	0.0

Note: Estimate of Pumped Wells Discharge =(av. amount of pumped water/hr *no. hours*no. wells).

Variation is attributed to the number of wells while pumping capacity of wells is constant and irrigated cropping area is proportionate to no. of wells.

Source: Ministry of Agriculture and Irrigation, Groundwater and Soil Conservation Projects, compiled from "Farmer Guideline -Alhodaiedah January,2008"

Ministry of Agriculture and Irrigation, Agricultural Statistics Year Book,Mar.,2009.

Ministry of Agriculture and Irrigation, 2002 Agricultural Census,Augest,2004.

The purpose of designing the previous table in such a way is to provide practical instrument for central as well as local authority for more accurate control, evolution and monitoring practices in groundwater management in order to ensure the long term sustainability of groundwater resources.

Based on the Agricultural Census of 2002, there were about **59,693**1 pumping wells in Sana'a governorate excluding number of wells not equipped with mechanical pumps. Wells pumping capacity estimated at 548 MCM in 2008 as noted earlier, but the surface wells with no pumping equipment is excluded from this analysis since large amount of water abstraction is associated with mechanical pumps installed in the wells, despite this exclusion, the number of wells is still large, by definition, for semi-arid areas as Sana'a governorate.

The growing groundwater deficit is proportionally associated with the number of wells presented in a district. For example, threatening groundwater situation exists in all Sana'a districts, except for Manakha and Sa'fan Districts. Water deficit ranged from -4 MCM/year in Alhymah to –about 99 MCM/ in Bani-Hoshish District in 2008. Sanhan, Hamdan and Blad Arraws represent the most serious districts as over-abstraction rate of groundwater is many times of recharge rate. None of the 13 districts of the governorate is showing a balanced situation of groundwater, except for two districts, namely, Manakha and Sa'fan which are believed to be more a result of doubtable data records.

The overall groundwater balance in Sana'a is negatively 405 MCM/year or misbalanced with recharge rate as table 2.11 and figure 2.12-2.14 indicate.

Figure 2.12: Groundwater Balance Distribution by Districts of Sana'a, 2008

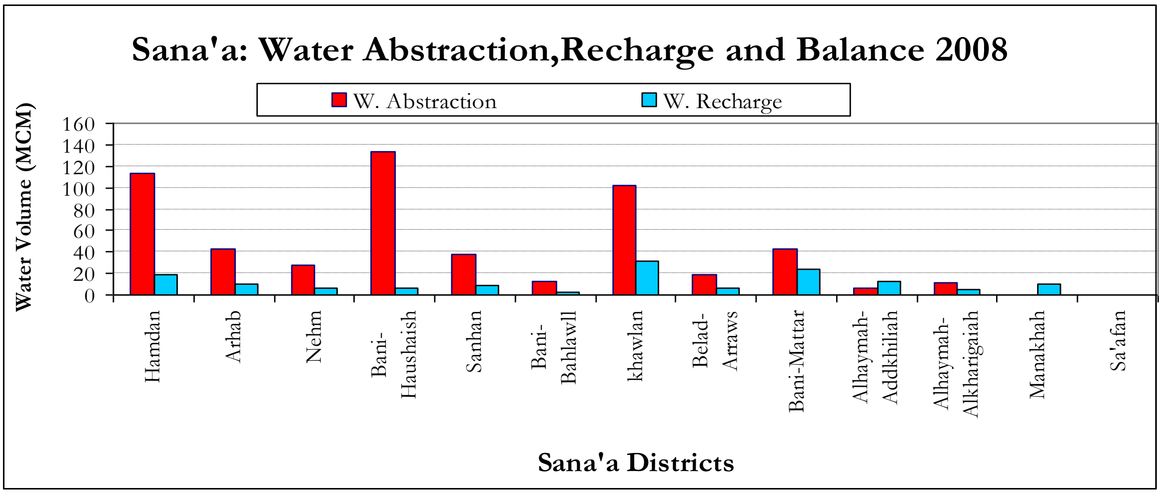
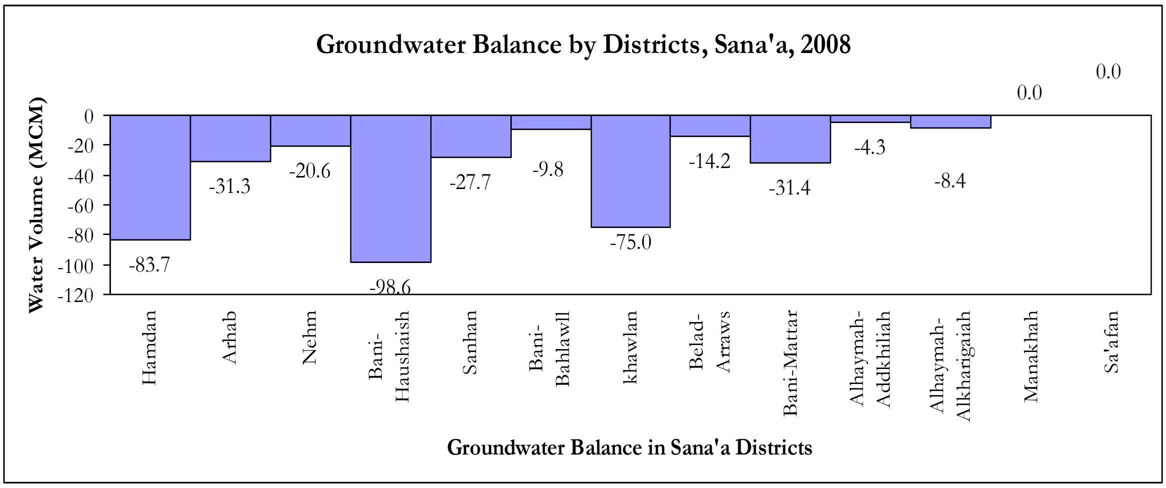


Figure 2.13: Water Balance Distribution by Districts, Sana'a 2008



Source: Table 2.11 Note: minus signs are indicating the water deficit in MCM for each district

7.2 Water Levels

Nearly all groundwater basins in Yemen experience a serious dropdown water levels. For example, one of recent study *"Water Conservation and sensible use of Water, 2008)* indicates that 8 wells have been constructed between 2001 and 2008 in Qaa' Gahran with average depth of more than 150 m from the ground surface. Another indicator of water level depletion is that a will constructed in 1978 has been deepened to 165 m during 1991-2001, which means a drop in water table more than 13m per year. Furthermore, the depth of wells in Gahran reaches 420 m in 2007 and to 800m in Sana'a Basin.

8. HYDROLOGICAL EVALUATION AND MONITORING

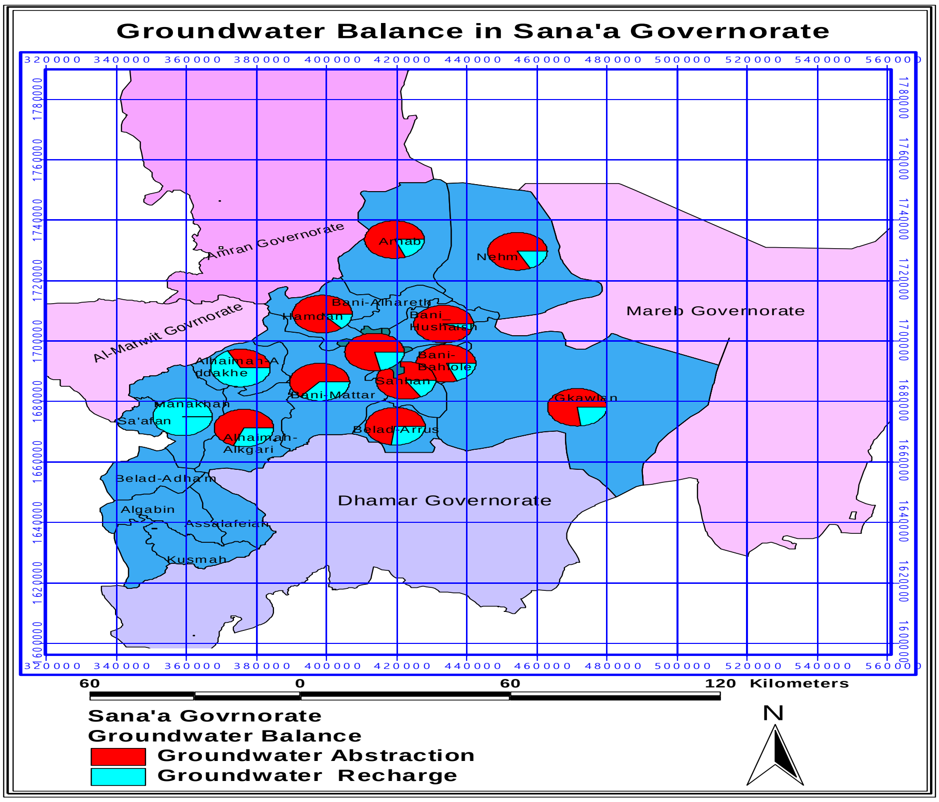
Hydrological study analysis has shown the advantage and gained benefits of MIP particularly, about 1.5 MCM/year is relatively an enormous amount of water will be saved as result of installing a small network acreage not exceeding 330 ha. by adopting Modern Irrigation Technologies of current project. This figure is based on analyses of valid data collected from field units' measurement. The project also preserves the nation's water recourses and make them sustainable apart from the gains comes from the cutoff cost of water, energy consumed, and from the decrease in labor work in form of wages. Furthermore, invisible benefits are associated with community such as regulation, awareness, and technical experience at various levels.

The result of hydrological data analyses monitored and performed according to three levels: Wadi and basin level, governorate level and district level in a way to facilitates clear monitoring and show indicators at all these levels in order to provide central and local authorities with solid base for decision-making process.

The current study of hydrological analysis has relied on several results of previous reports and on the demonstration farms established by Groundwater and Soil Conservation Project (GWSCP).

Data samples parameters of on-farm Field Units and on pumping capacity of wells obtained from GWSCP has all been taken variably in order to accurately assess groundwater discharge in relation to groundwater recharge, in addition to further check out validity of data regarding recharge estimation. Variables of these parameters are all used in association and compared with groundwater abstraction and recharge rates and further subdivided from governorate level to district level in purpose to define and establish controlling systems of water consumption in both ground and surface or spate irrigation for each district.

Figure 2.14: Groundwater Balance Spatial Distribution of Sana'a Governorate



9. Quantity and Cost of the Monitoring equipment and devices (Cost US$ 3.098 million)

In summary, the cost of equipment and devices required for Sana’a project for water measurement and groundwater monitoring activities. Details about number of available need equipment units, and their specifications.

Total project equipment cost for Sana’a project is estimated at **2,681,988 US$** plus the cost of sensitivity estimated at **415, 708 US$** (20%) for physical, engineering and financial Contingency cost resulting in grand total of **3,097,696 US$**.

Table 2.13 shows the cost of equipment as is distributed over the first five years of the project life on line with the distribution of irrigation network systems, that is 30% of the cost (929,309 US$) will be spend in the first year, 50% of equipment cost (1,548,848 US$) will be allocated in the second year and the remaining 20 % of the cost (619,539 US$) will be assigned for the third year of the project life in order to speed up the gaining and benefits of the project investment.

10. CONCLUSION

There is a current and evolving deficit between the availability of groundwater resources and their use in all districts of Sana'a, particularly in Sanhan, Hamdan, and Blad Arraws districts. None of the 13 districts in Sana'a do present a balanced situation between groundwater abstraction and recharge in the governorate. Water abstraction volume is accounted for many times of recharge rate with some variation where abstraction too large or a little less than recharge rates across the governorate districts. Exception is recorded for Mankha and Sa'fan districts for not having data assigned to wells, but this exceptional situation is not far from crucial deficit. Areas harvesting more recharge volume than total abstraction are not present with case of Sana'a. The water balance is properly quantify the magnitude of the deficit; several important parameters are measured on either supply side and/or demand side. The total stock of annual rainfall, runoff and recharge were assessed and quantified for each basin and wadis of concerned project along with groundwater abstraction on the demand side using wells inventory, pumping capacity and irrigated crop requirement measured on field units.

Based on data it is found that many groundwater basins are experiencing a water deficit where recharge rate is too far less from balancing situation to compensate for growing groundwater abstraction. It is anticipated that groundwater abstraction increase steadily over time due to the rapid increase in population growth as well as the increasing area of irrigated crops unless immediate mediation is to be taken by concerned authorities and communities to regulate and manage in sustainable manner the groundwater resource in Yemen. Controlling indicators is set forth to help managing to sustain this most important source of water.

Hydrological analysis assessment revealed that the total annual groundwater recharge into the valleys and basins of Sana'a governorate where the main basins and four sub-basins reach a total recharge amount of 143 MCM /year in 2008 and 162 MCM in 2020 as the recharge aggregated for the 4 main basins and 14 sub-basins in the governorate. The total Irrigated Area from groundwater in Sana'a Governorate was approximately 70,000 hectare in the year 2007, and about 51.000 in 2008. Results of data analysis are exposed and show that water balance in Sana'a basin reach a very critical situation where the difference in the amount of water between charged and discharged in the basins of Sana'a record an alarming indicator, they are accounted for a negative value amounting - 405 MCM, over four hundred millions cubic meter being lost annually (143- 548= -405)

Hydrological analysis results show that the area of irrigated crop from underground water in Sana'a governorate was 50,856 hectares in 2008, representing about 62 % of the total irrigated area in the governorate, which consumes 548 MCM/year of underground water, this tremendous amount corresponds to the total abstraction of water used for irrigation could be minimized. It is a huge volume of water use, particularly with respect to 42 % average in water saving, which equals to 330 MCM/year for total irrigated area, which could be saved, contributing to the augmentation of groundwater recharge. An amount of water equal to 548 MCM/year is consumed for irrigation based traditional use vs. 318 MCM/year using improved irrigation method, which means a deference of 330 MCM/year is accounted for water savaging, assuming that all irrigated land be covered with modern irrigation techniques in Sana'a Governorate.

Therefore, to mitigate such a problem, Yemeni Government realized that water resources issue in the country is a critical issue and started to take some very important steps to address this problem. One of these remedies is the current project objectives of MIPs to reduce the current rates of abstraction in many aquifers specially those of critical and serious situations in order to improve the demand management of this scarce resource and serve for Lang-term sustainability.

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