

Integrated Studies of the Azraq Basin in Jordan

M. Shahbaz¹ and B. Sunna²

Abstract.—Many historical indications of the eastern Mediterranean Basin exhibit climatic changes or alterations effecting the status of water resources, hence, effecting human-kind and the quality of life. It is essential to deeply understand the nature of climates and geological structures employing state of the art techniques to assess rainfall, runoff, and floods that replenish groundwater in arid regions of the Middle East. The integrated watershed management approach being implemented in the Azraq Basin of eastern Jordan presents a unique opportunity to study the effectiveness of this approach to land and water management. Development and sustainable use of the available resources in this basin is essential for the future.

Introduction

Water scarcity has traditionally restricted development in the Middle East, and could be one of the limiting factors in the future if it is not fully and rationally evaluated. Watershed management, evaluation of water resources, defining target areas for exploring the groundwater, and development of appropriate supplies have been important goals of the current work in the Badia of eastern Jordan. It is worth mentioning that almost all previous work has concentrated on the surface water and groundwater resources in the upper aquifer of the Azraq Basin.

An integrated approach has to be applied to the development of surface and groundwater resources, in which management has to meet growing water demands. The integrated watershed management approach should take into consideration great variety of other development activities, which has an effect on the water resources. Mining, road construction, building of various types, agricultural activities, and exploitation of oil fields can influence water resources. Most water resources management activities are primarily aiming at the increased efficiency of water use and land resources. However, in a number of cases, these activities have had negative effects on the geologic-hydrologic environment including a decrease in

the productivity of water resources, pollution of groundwater, and intensification of superficial geological processes.

Scope of Paper

This paper describes the activities of a project of integrated studies implemented under the umbrella of the Higher Council for Science and Technology entitled "Integrated Studies of Azraq Basin for Optimum Utilization of the Natural Resources." Specifically, the paper describes methodology applied to better assess and evaluate natural resources with particular emphasis on water resources management. Results of these studies will target new areas for groundwater, minerals, and energy exploration, defining areas for agricultural applications, and for development of exploration strategies regarding natural resources in the basin as a pilot area for other basins in Jordan. The aim is also to show the value of the integration of geology and geophysics for land survey and land resources appraisal. The studies consist of:

- Photogeologic mapping and interpretation using aerial photographs, and high quality satellite photography and imagery.
- Subsurface studies integrating the information obtained from geological and geophysical data. Principal means of investigating the subsurface geology and structure of the basin are gravity and magnetic data, and an extensive network of seismic reflection data gathered in the course of exploration for oil and gas. Seismic lines were interpreted, augmented by information from deep boreholes and surface geological maps.

Azraq Basin

The Azraq Basin, about 12,750 km² in size, is located in the northeastern Badia region; the Badia forms 85% of Jordan's land surface. The drainage pattern of the main basin has been delineated as shown in figure 1. Few

¹ Director of Jordan Badia Research and Development Programme

² Project Coordinator, Integrated Studies of Azraq Basin for Optimum Utilization of the Natural Resources, Higher Council for Science and Technology, Amman, Jordan

climatic changes have occurred in the region since the Neolithic age (8,500-3,750 BC); the climate is hot and dry. Evidence exists that a large lake totaling 4,500 km² covered the Azraq depression in the Pleistocene age.

Geology

The basin incorporates exposures of sedimentary rocks and basalt, ranging in age from Cretaceous to Quaternary. In the southern part of the basin and on the surface, the Quaternary deposits and recent sediments cover the underlying Tertiary deposits. The latter are intermittently exposed at the surface in the south, southwest, and southeast. Eocene and top Tertiary sediments lie on the top of the sequence beyond the "Fuluk" fault to the south and southeast at Wadi Hazim and the Jebel El-Fuluk. The sedimentary sequence includes limestone, chert, marl, chalk, sandstone, clay, and evaporites. These rocks are frequently covered with a variably thick sequence of superficial deposits including alluvium, mud-silt flats, chert pavement, Pleistocene gravels, and sand and evaporite incrustations.

To the north and northeast, basalt eruptions of different age appear on the surface and extend northwards to cover a wide area known as the "Basalt Plateau." This basalt area is related to the North Arabian Volcanic Province, which extends from Syria across Jordan into Saudi Arabia, covering in Jordan an area of 1,100 km².

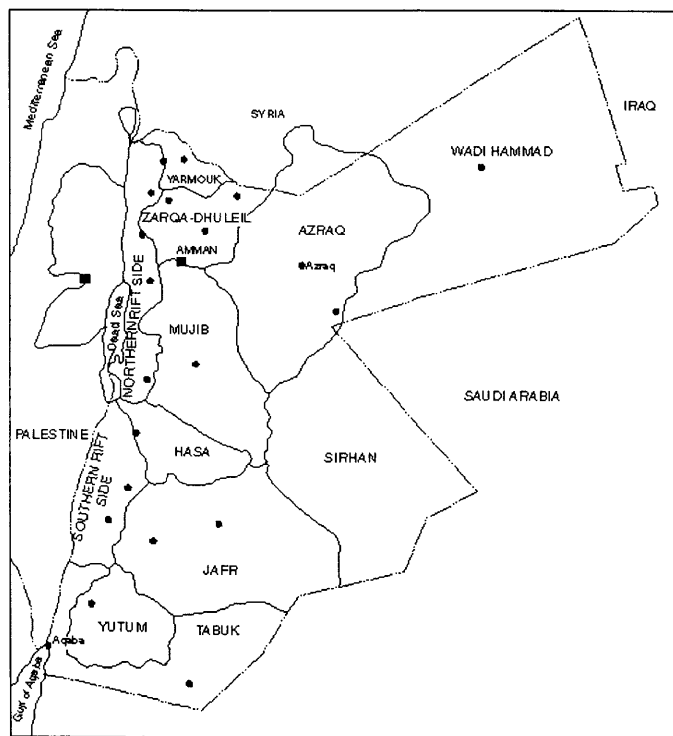


Figure 1. Map of the Azraq Basin.

The Azraq Basin represents a thick stratigraphic section. The area has been subject to extensive oil exploration activities, which added a lot of information regarding the stratigraphic sequence and sedimentary section. In the subsurface, a thick sedimentary section that is changing in thickness and varying in the lithostratigraphic and formation units represents the basin. These sediments range in age from early Paleozoic to Pleistocene, and are primarily composed of carbonates, sandstones and shales. The major thickness reduction in the sequence appears towards the south and southwest directions, while a remarkable increase in thickness is observed east of Azraq town towards the Fuluq fault.

The Cretaceous-Tertiary deposits in the basin comprise a thick sedimentary section measuring more than 3,500 m of mostly marine deposits. The lower Cretaceous boundary, identified by a recognizable sandstone unit of the Nubian type known as the "Kurnub Sandstone," is identified in several wells, as the sandstone formation underlying the carbonate facies of the Cenomanian age. This sandstone unit varies in thickness and depth, and marks the transition zone on the major unconformity between the Jurassic and the early Cretaceous.

The basin is characterized by the presence of distinctive structures including the Sirhan-Fuluq Siwaqa, Zarqa Main, and Baqa'- Wisad fault systems. Structurally, the area is tectonically active and dominated with NW-SE, E-W, NE-SW and N-S faults and lineaments; the NW-SE and the E-W fault systems are the main ones believed to have controlled the development of the Azraq depression and Azraq Lake. The regional dip is towards northeast. Folds are relatively small with gentle dip and mainly associated with some NE faults and lineaments.

Hydrology and Hydrogeology

The town of Azraq in the center of the basin was built around an oasis formed by the emergence of groundwater spring. The oasis is the base-level of groundwater and surface water of a large part of eastern Jordan. Over recent decades, expansion of irrigated agriculture; increases in populations and, consequently, the need for water in nearby major cities such as Irbid and Amman; and raised standards of living have forced greater groundwater abstraction from the basin. This has resulted in depression of the regional groundwater table and the consequent degradation of most of the oasis.

Although there are regular, short-duration floods during winter in the wadis flowing south from Jabal al-Arab, these flows have not been measured. However, total flows have been estimated from rainfall data to average 27 million m³/year. Although some surface water flows through the Marabs and supports natural vegetation, most of the water runs onto the mudflats of the Qa'as and is lost

through evaporation. Flood frequencies and magnitudes have declined in recent years, due largely to the construction of dams on the upper reaches of the wadis in Syria. A Jordanian dam was constructed on the lower reach of Wadi Rajil in the 1980s, but the reservoir has only filled once, in the winter of 1994-95.

Groundwater Resources

Three main aquifers in the basin are the shallow aquifer, which consists of Basalt and Rijam Formations separated in places by the marls and chalk of the Shallala formation; the middle aquifer system which consists of Amman and Wadi Sir formations; and the lower (deep aquifer) which consists of the Kurnub Sandstone formation. Groundwater that discharges at Azraq is one of the major sources of water in northern and eastern Jordan.

Extraction of Groundwater

The upper aquifer contains substantial volumes of high quality, easily exploited water. In the last 20 years, there has been a significant increase in the number of irrigation wells constructed by the private sector abstracting water. On a basin scale, current extraction exceeds recharge and, therefore, groundwater is being "mined" from storage. The total volume of groundwater removed from storage is between 40 and 45 MCM/year (about 15-25 MCM/year is being pumped to the Amman area), while the calculated recharge ranges between 10 and 35 MCM/year.

The upper aquifer is being exploited beyond its safe yield, and storage depletion and water quality deterioration will continue to occur (Noble 1998). Consequently, current extraction of groundwater are already unsustainable, with a detrimental impact on the unique environment of the Azraq oasis. The piezometric groundwater level in the well field has lowered by as much as 5 m. Wells are concentrated in the three demand centers of Azraq, Umm al-Quttain, and southern Syria. Unfortunately, it was not possible to obtain an estimate of water demand from the Syrian part of the Azraq Basin.

The Amman Water and Sewage Authority drilled a well field north of Azraq Druz to avoid unwanted ecological consequences for the basin's nature reserve area and neighboring farms. Restrictions have been placed on further drilling due to the Government's uncertainty of what effects withdrawals in this area will have on the long-term quantity and quality of the spring discharge.

The Umm al-Quttain well field is located in the north-western part of the basin, where early settlements obtained water by storing flash-flood runoff in reservoirs. This method of obtaining water has been replaced by groundwater extractions from deep boreholes. The Umm al-Quttain region is different from Azraq in that it covers

a larger area of 34 villages, has an older and less sophisticated distribution system, and the water is abstracted by a widely spaced network of 11 municipal wells. Umm al-Quttain and surrounding villages have seen a dramatic increase in groundwater abstraction over the last decade. Total abstraction was 6.7 MCM in 1993, 81% of which was exported from the region.

Groundwater Chemistry

Another problem is the salinity of groundwater in both the basin and in the mud pan of Qa' Azraq (Azraq lake). Because water leaves this closed basin only by evaporation, always leaving the dissolved matter behind, salt concentrations are highly elevated in the center of the basin. Consequently, an interface between fresh and saline groundwater has developed. It is necessary to know the location and gradient of this interface to assess this danger. The geological model being developed will help re-evaluate such relations. Several wells located north of Azraq were sampled in 1993 for chemical analysis. The results indicate that the water is either sodium chloride type or calcium carbonate type. Evolution of the ion chemistry can be explained by the relatively high volume of recharge of rainwater in the north, and saline conditions further south due to infiltration of smaller volumes of water that are charged with salts derived by dissolution of evaporitic crust (Drury 1998).

Phases of the Integrated Studies

Effective watershed management cannot be carried out successfully without integrating surface with the subsurface information. With respect to the long-term, there is a need to attain sufficient knowledge of the hydrological cycle to achieve effective watershed management and conservation of the critical fresh water resources. The approach adopted as the basis of the Badia Programme to bring together a set of technologies and methodologies to focus upon a wide range of problems. This approach in watershed management consists of carrying out studies in a Manual Integration Phase, a Monitoring Phase, Development of a Geographic Information System, and a Watershed Management Phase.

Manual Integration Phase

The integrated approach brings together a set of disciplines (geology, geophysics, mineral, energy, and water resources, agriculture, and environment) and a set of technologies and methodologies to focus upon a wide

range of problems. Integration of the geological and geophysical data is considered in this paper. The methodology includes the following studies and activities.

Collection of Data and Reconnaissance Studies

Collection of data involves a review of relevant literature to develop a geological data-base consisting of geomorphological, geological, geophysical, and soil data; it also includes gathering of detailed information on the previous studies and data from wells drilled for various oil, water, and mineral exploration targets. This phase includes preparing and collection the base maps, satellite images, aerial photographs, and geological maps covering the basin; gravity and magnetic maps; geoelectric maps and sections; seismic lines which include index maps for the seismic lines and paper print of the following lines: geological maps scales of 1:250,000, 1:100,000, and 1:50,000; and data concerning all the drilled boreholes for various purposes.

Photogeologic-Geomorphic Analysis and Remote Sensing Studies

The objective here is to map the basin by remote sensing and identify distinctive geomorphic, morphotectonic and geologic units, while focusing on areas of high economic potential and those suitable for agricultural purposes. Remote sensing studies using high-quality satellite photography and imagery, and manual interpretation and digital image processing of Landsat TM and MSS satellite imagery, are carried out.

The photogeologic-geomorphic analysis using aerial photographs (at a scale 1:100,000) represents one of the most comprehensive and detailed analyses of the geology of Azraq Basin. The uniqueness and value of this study stem from the set of high-quality satellite imagery used and the methodology utilized for its interpretation. The photogeologic-geomorphic study is concerned with determining the degree of influence that structure and lithology had on the morphological development of the area.

The most extensive information on the basin is presented on geomorphological and geological maps whose analysis reveals features such as surface runoff patterns, the recharge, transit, and discharge areas of groundwater, and the relationship between surface and groundwater resources. Based on 1:100,000 scale imagery, remote sensing allows geomorphic subdivisions of the area to be identified, and the boundary of the soil and rock formations to be delineated. The imagery and methodology have facilitated mapping of local and regional structures in a comprehensive fashion unique to geologic mapping from space. This mapping provides useful information for distinguishing areas or structures with the greatest exploration potential.

A study of Landsat imagery provides valuable information on the geology and hydrology of the area. Such an analysis contributes to the general knowledge of the basin's geology, the location and distribution of aquifers, and presence of geologic anomalies that can denote the presence of groundwater, mineralization, or hydrocarbons. The satellite data contributes to the accuracy of the final products, and to the speed with which geologic mapping is accomplished. Geological remote sensing techniques are being employed to minimize costs and maximize results of ground-based geologic investigation.

Land Form Analysis

In desert areas such as the Azraq Basin, outcropping rocks are often directly observable, and their characters of bedding, hardness, tone, color, setting, fracturation, and mutual relationships among different geological information can be recognized. However, thickness of superficial deposits prevent direct observation; in this case, recognition of geological features on image is based on the interpretation of the surface effects of the geological substratum. The Azraq Basin comprises two dominant landform components, volcanic basalt and sedimentary rocks shown in figure 2.

The volcanic basalt component, located in the northern part of the basin, is occupied by a terrain composed of basalt flow, volcanic centers, isolated volcanic rocks, and

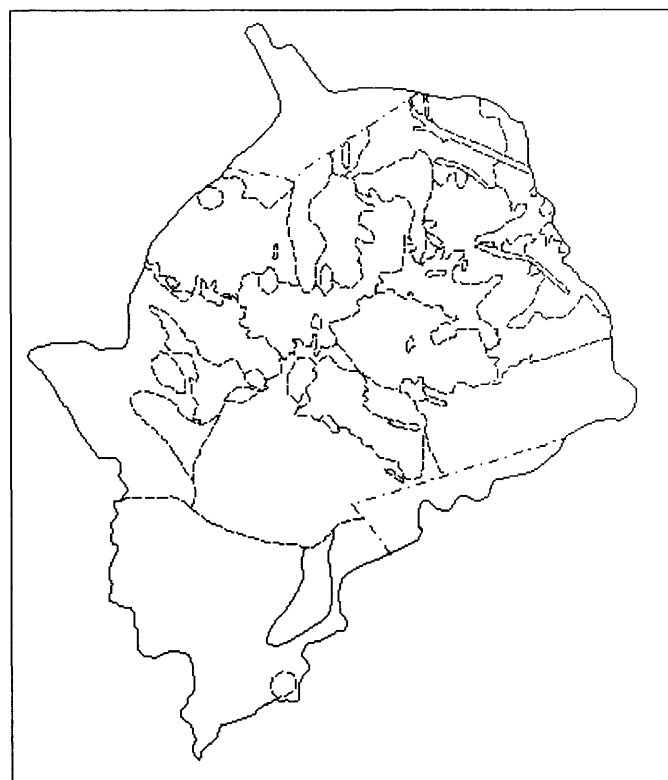


Figure 2. Physiographic Provinces of the Azraq Basin.

basaltic ridges (fissure effusion). Basalt boulders cover most of the ground surface. The size and spacing of clasts varies, with associations between lava flow type and stone cover. The component has a high density of wadis and numerous small Qa' deposits. Most wadis drain south, southwest, and southeast. In most places, continuity of cover forms a desert pavement protecting the underlying fine-grained, orange-brown sediment; in other places, boulders are much larger, approaching 50 cm in diameter, with spaces between individual clasts revealing the underlying sediment. Elevation of the basalt gradually decreases from about 1,500 m at Jebel Drouz in Syria to 1,100 m at Syrian-Jordan border to about 550 m near north of Azraq. This Basaltic Plateau has a gentle undulating surface of low relief.

The sedimentary rock component consists of an extensive flat or gently sloping flint- or chert-covered surfaces with a distinctive fern-like dendritic and drainage pattern. It is further characterized by horizontal or gently dipping limestone, marls, and chert beds which form table scarps of outliners, partially covered by unconsolidated Quaternary deposits.

These two landform components can be subdivided into zones delineated according to stratigraphy, structural evolution, types of deformation, drainage pattern, landform, fracture patterns, and image tonal characteristics. These zones represent the main landscape units as defined by data from Landsat images hard copy. The volcanic basalt has been subdivided into 14 zones and the sedimentary rocks into 6 zones as shown in figure 2.

Drainage Analysis

The drainage network map of the Azraq Basin shows several main wadis draining from all sides towards the central portion of the basin in a centripetal form. Analysis of the six basic drainage patterns (dendritic, trellis, parallel, radial, annular, and centripetal) revealed significant relationships between their pattern and the soils and bedrock of the basin and the structural setup. Fine, medium, and coarse drainage textures have been identified.

Structure and Fracture Patterns

The basin is a northwest topographic and structural depression positioned between the Jordan Arch-Central plateau region on the west and the northeastern plateau-Risha area on the east. Its shape and configuration is outlined by Tertiary and Quaternary deposits in its central axial part. Numerous faults and strong surface alignments indicate the presence of complex structural conditions beneath the young surface sediments. Several of these faults are known from seismic data to represent major structural zones of weakness in the deeper beds. Mapping of individual faults, fractures, and alignment, and their resultant areal pattern gives clues to geologic features of

significance. Photogeologic-geomorphic evaluations have revealed the presence of numerous distinctive surface alignments and lineaments of varying length and trend.

Important Results of this Study Phase

One result of this phase of the study has been the preparation of updated geological maps, establishing a new classification for the basalt, and defining the exact locations of some of the most important major fault, which has a direct influence on the groundwater movement. Development of a three-dimensional geological model, shown in figure 3, is another noteworthy results. This model is an essential complement to the other hydrological data. To develop a proper structural model, it was necessary to integrate information derived from the previous mentioned studies with data derived from the subsurface (geophysical and well) data.

A key feature of the model is the Azraq depression, a prominent structural basin since the Paleozoic time. This feature, located within the Azraq Outer Basin, was formed as a result of four majors grabens and fault systems crossing the outer Azraq Basin; these are the Ghadaf-Makhruq Graben from the south, the Fuluq fault from the east, the Sirhan fault system from the west, and the Baqa'- Wisad fault system from the north. The depression is a fault-

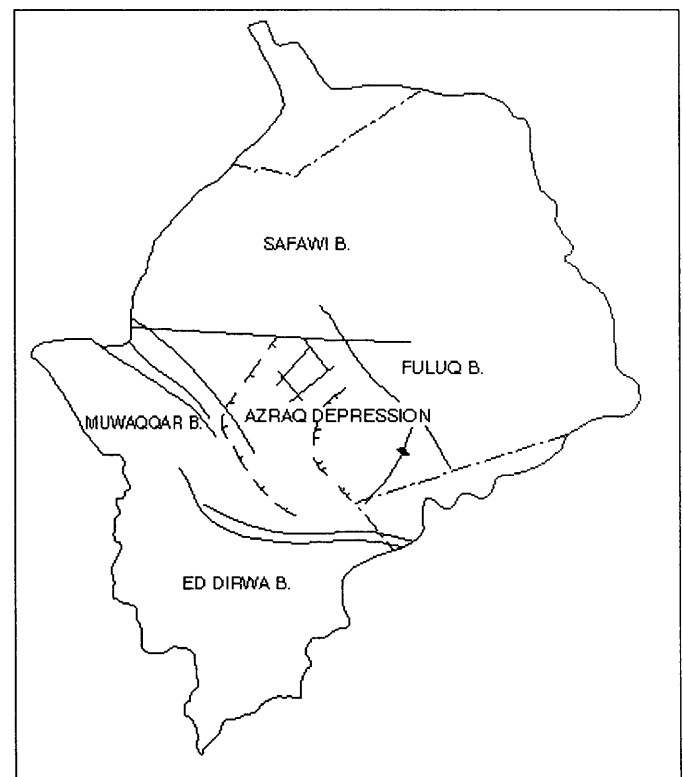


Figure 3. Geological Model of the Azraq Basin.

bounded major block with Mesozoic fill. Location of this depression within the outer basin, with the presence of the major fault systems, resulted in separating the Azraq outer basin into several blocks surrounding the central depression, including the eastern (Fuluq) block, the southern (Al Dhirwa) block, the northern (Safawi) block, and the western (Muwaqqar) block.

A comprehensive vision of water resources and structure in the Azraq Basin has also been obtained. A better definition of the geomorphic units of surface water resources has been obtained; there is an increased understanding of surface runoff processes; and the potential drainage system for surface flows has been delineated. A better geologic-hydrologic model of groundwater resources has also been obtained; a better understanding of recharge areas for the groundwater aquifers has been achieved; and, importantly, target areas for groundwater exploration have been identified.

Assumptions have been made in the development of a conceptual geologic-hydrologic model for targeting groundwater exploration in the Azraq Basin to compensate for the lack of factual information. These assumptions were that faults and joints in the bedrock influence the development of drainage patterns easily in the geomorphic evolution of the basin; that lineaments mark the location of faults and joints; that fine-grained silty clay materials transported by drainage systems are located within the central part of the basin; that a fine drainage texture indicates fine-grained sediments and areas where water infiltrate slowly; that areas close to crossing points of major faults are favorable sites for well drilling; that anomalies in vegetation, lithology, soils moisture, and that their pattern of distribution can be indicative of underlying groundwater conditions; that groundwater moves down the lower slopes, and down the alluvial valleys in the same direction as surface streams; and that the major structural features revealed by the photogeologic study are indicative of the probable control of movement and entrapment of groundwater.

Making use of existing and developing new water resources, important for the whole country, are the main aims of the integrated study. Results of the integrated studies showed that the geological succession in Azraq Basin could be hydrogeologically subdivided into lithostratigraphic units, which form systems of aquifers and aquicludes. These systems have been grouped by the Lower Deep Aquifer System, the Middle Aquifer System, and the Upper Shallow Aquifer System.

Isopach maps and structural contour maps for the top of these systems have been prepared to help identify the thickness of and depth to each system or group. Each of these systems comprises one or more aquifers. It is important to note that the subdivision into shallow, middle, and

deep systems is based mainly on the geological succession, and has nothing to do with depth. Some of the deep aquifers of the middle system which are deep in the center of the basin are shallow in other parts of Jordan, or even in some of the blocks of the Azraq Basin itself. Some of the deep aquifers of the lower system are shallow as in the Disi area.

Monitoring Phase

This study phase consists of monitoring the dynamics of water replenishment by detection of direct indicators such as outcrops of the water table or the water table in water wells; or by the analysis of indirect indicators based on the surface and subsurface geological conditions and the vegetative aspect. Establishing a monitoring network utilizing the existing wells, the monitoring should continue during the management phase; in addition new monitoring boreholes need to be established.

Principal features of the monitoring strategy are to support the surface and groundwater protection strategy on the regional (also municipal, district, basin, or provincial) and the national levels. The aim of this strategy is preserving natural properties of water especially for drinking purposes; provide representative data on the current state; supply correct and accurate data to help identify the existing and potential point and diffuse pollution sources; and study the time and spatial changes in the quality of water.

Monitoring Objectives

Monitoring objectives are to identify the physical, chemical, and biological properties of the surface and groundwater; define the water resources' quality and quantity; define the effects of natural processes and human impacts on hydrogeological system; forecast long-term trends in the groundwater quality and quantity; define measures to be adopted to prevent groundwater depletion and pollution, or to restore the aquifers which have already been affected; and determine priorities and conflicts among the users of water resources and other natural resources.

Monitoring Program

The form of the monitoring program is governed mainly by the monitoring objectives, extent of the territory to be monitored, duration of the monitoring effort, and effects

of the monitoring on the hydrogeological system. The monitoring program should be planned on national, regional (basins), and local (site-specific) networks.

The methods used for design and implementation of the networks depend on the objectives of the monitoring. A simplified scheme of a monitoring system in Azraq Basin is shown in figure 4. This scheme should satisfy the demand driven policies of the government.

Development of a Geographic Information System

Assembling, storing, manipulating, and displaying the collected geographically referenced information will be

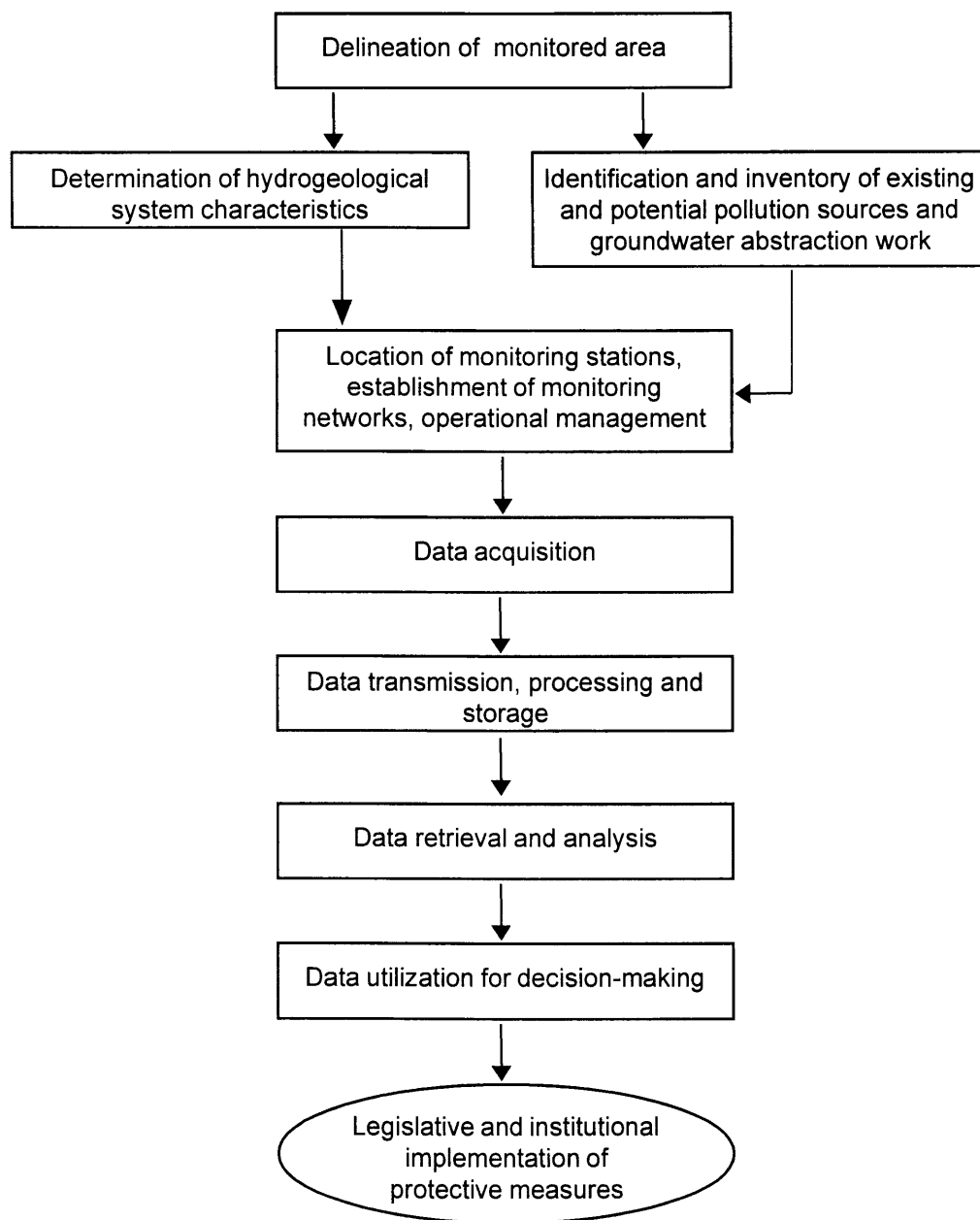


Figure 4. A simplified scheme of a monitoring system in the Azraq Basin.

the next step in the study, not only for the watershed management, but also for scientific investigations, resource management, and development planning. Development of the geographic information system (GIS) is still in progress; however, it is planned that the system will consist of relating information from different sources; capturing of data; integration of data; projection and registration; data structures and modeling; an information retrieval network; and data output. The use of GIS may encourage cooperation and communication among the agencies involved in resource management and environmental protection.

Watershed Management Phase

Watershed management efficiency can be measured by its performance. Sound management occurs when all water resources and their use in a basin is considered. Appropriate watershed management practices should be addressed within a comprehensive framework of the potential quantity and quality aspects of water and other natural resources. Since it is essential to consider the smallest development unit as a water basin for arid land development, the water resources available in the Azraq Basin should be able to support any developmental activity that takes place in the basin (table 1).

A long-term objective of this concept is to integrate such a model across the rest of the basins in Jordan. In this case, considering a National Water Carrier that is anticipated to be constructed, demands for water can be managed more efficiently. Needs can then be satisfied through a central operations unit. Another long-term objective can be achieved through sound future planning of water resources.

Table 1. A tentative water balance for the Azraq basin.

	Out (MCM/Yr)	In (MCM/Yr)	Balance (MCM/Yr)
Public Supply	28.84		
Agriculture	47.71	22.9	
Leakage	93.30	29.3	
Recharge		37	
Total (With leakage)	169.85	89.23	-80.6
Total (without leakage)	76.55	59.93	-16.62

Summary

Watershed management in the Azraq Basin incorporates all aspects of water and other natural resources (minerals, energy, and agriculture), developmental issues and various uses of both surface and groundwater resources, and other relevant environmental and economic issues. Satellite images have been useful in providing hydrological data for the analysis and evaluation of the surface water resources and major structural features revealed by the photogeologic study with respect to probable control of movement and entrapment of groundwater; maps of surface water bodies as small as several hectares to determine the extent of water reserves; a basis for surveying and monitoring of surface conditions in this large watershed as a guide to management; maps of the extent and duration of flooded areas as a basis for flood protection and land capability assessment; and a framework for the development of an operational geologic-hydrologic model. The geologic-hydrologic model should help describe the active constituents and respond to the following needs: short-term (days or weeks) to predict actual needs; medium-term (months); and long-term (years). Development of a circulation geologic-hydrologic model in connection with the other models for the rest of the basins in Jordan is also necessary.

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