Principles of water management in wadis

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1. Introduction

In arid areas, the ground water is the only permanent source of water. Aquifers—the ground water reservoirs that can be depleted and recharged, and store excess water in floods—play an important role in analysing the wadi hydrology. Development of wadi water resources therefore relies on coordination and management of spate and ground water, and control of water balance for optimal use in dry and wet periods. The objectives of assessing groundwater resources and spate hydrology are:

(i) to determine the parameters and characteristics of a geological ground water reservoir; and
(ii) to determine rainfall distribution and the probabilities of floods.

The evaluation of these probabilities for controlled use of spate water and ground water is based on these parameters. The purpose is to provide information on the aquifer and spate occurrence. Groundwater reservoirs should be used for control, planning and management of water resources in a form directly useful to planners and project leaders.

The result of the surveys depends on several factors: the methods used in the ground water survey; the measurement of spate characteristics; schematization of geological and hydrogeological properties of wadi catchment area; and methods of interpreting data. Qualified specialists are essential to an accurate assessment.

2. The main relations of water balance in wadis

2.1 Spate characteristics

Arid areas are noted for irregular, occasionally intensive but brief rainfall attaining accumulated annual precipitation ranging from several mm to several cm, in places exceeding 10 cm. Precipitation itself is insufficient to supply ground water or create floods, since the rain falls mostly on sandy rocks where it evaporates gradually and does not infiltrate the surface. A more favourable situation is in areas surrounded by extensive massifs of hard rock. In mountainous areas, the rainfall is higher, often exceeding 10 cm per annum. Nevertheless, this rain falls on hard rocks which form the surface runoff to streams feeding boulder-type wadis in lower areas. Concentrated surface water then flows as a flood wave for several hours—even days down wadi courses, where it can intensively infiltrate into sandy alluvial-type sediments and recharge the ground water. It can be used for spate irrigation or can flow into the sea or desert and evaporate. The spate is divided into two categories:

a) floods originating in the upper part of the area where the rain water is collected from runoff in streams forming boulder-type wadis. Precipitation mostly evaporates or infiltrates into the surface. Usually flood water is not directly useful for irrigation, and only a little infiltration takes place in crevices in hard rocks; and

b) floods extending in areas where water collects in alluvial types of wadis. This water is used for infiltration or spate irrigation, or it evaporates or outflows into the sea or desert.

Infiltration of flood water is substantion in alluvial-type wadis. It recharges the aquifer and is used for spate irrigation. Infiltration dissipates a large amount of flood water, and much of it is diverted for irrigation. For example, reported stabilized infiltration velocity in Wadi Markhah reaches 0.6 m per day. Using 4-hour infiltration tests in the Abyan Delta the infiltration velocity ranges from 0.13 to 1.13 m per hour.

2.2 Spate and ground water budget

An aquifer is a reservoir of ground water where flood water is stored for later use. The rate of water stored in an aquifer is given by the storage coefficient and increase in water level or The rate of ground water extraction can be determined from the storage coefficient and the decrease in water level, or interpreted from ground water level differences over a given period. The volume of water extracted by wells within the given area can be estimated. Following floods, the ground water level increases. Modelling the water level increase enables the reconstruction of the infiltrated rates for 1 m of wadi length. In the area of Hagar in the Markhah region, approximately 2 709 884 m^3 of water infiltrated along the wadi length of 4 km. This means that for the whole area of approximately 10 km^2, 27 cm of regularly spread water infiltrated. Fifty per cent of land in this area is cultivated. This means that ground water reserves from the flood in April and May 1983 correspond to irrigation of approximately 0.5 m of water. In these calculations, the storage coefficient estimation is important, because it is used to assess the amount of water the aquifer takes into or releases from storage. Together with the coefficient of wadi bed leakage, the storage coefficient gives an indication of infiltration of spate water and expiration of floods.

In dry areas, the estimation of aquifer storage parameters is more important than transmissivity, but until now, little attention has been given to preparing an estimate for arid lands. Examples show that in the same region various firms use water table storage parameters for ground water resources computation, e.g. in sandstone, from 0.02 to 0.19. These parameters are rough estimates, not based on actual measurements.

3. Assessment of surface water resources

In a wadi, a flood only creates direct runoff, with surface runoff as the greatest source of water, plus wadi bed precipitation and rapid interflow of shallow origin. The surface runoff usually contributes most water to floods. The main basic factors are:

- basin precipitation (distribution in spate and time);
- basin extent and shape (catchment factors);
- basin evaporation and climatological factors;
- geomorphological conditions;
- geological factors;
- hydrogeological conditions;
- wadi bed characteristics; and
- man made barrages, barriers, akmas, stone sills, and weirs.

All factors mentioned can be illustrated in a hydrograph. The hydrograph of a wadi shows the distribution of stream discharge in a flood. A hydrograph can be measured and statistically evaluated. Hydrograph measurement forms the basis of assessing surface water resources in a wadi; and of all water balances and computations of water use. It is easier to provide a hydrograph than to compute and collect data for computation of a hydrograph from all the above factors. We recommend construction of wadi gauging stations distributed throughout the whole length of the wadi, using artificially hardened and adapted wadi profiles, which are useful for measurement, and for flood warning systems, as well as for spate irrigation management.

4. Assessment of ground water resources

Aquifers are not universally regarded as real ground water resource reservoirs. The latter have two physical properties; to conduct and store ground water. In arid areas the storage properties of aquifers are more important than conductivity.

The storage coefficient of a water table results from its gravity drainage, directly dependent on the geological location of the water table. In gravel, the coefficient of storage is approximately 0.2; in sand 0.15; in loess 0.08; in fissured rocks 0.02; in sound rocks or clay less than 0.01. Cementation and consolidation of sediments lowers storage properties considerably. This means, for example, that 1 m^3 of gravel absorbs approximately 0.2 m^3 of water. The typical geological profile of Wadi Markhah (Mucha, Paulikova 1984) can be described as follows.

0.0 - 11.4 m	sand, aeolian sand, loess, gravel of wadi bed
11.4 - 13.6 m	conglomerates with calc-clay cement
13.6 - 14.7 m	gravel
14.7 - 16.3 m	conglomerates
16.3 - 21.4 m	conglomerates with gravel positions
21.4 - 51.0 m	conglomerates, within the intervals 25-35.6 m and 38.9-42.5 m, strongly disintegrated
51.0 - 52.6 m	debris, disintegrated bedrocks
52.6 - more m	bedrock

The interpretation of pumping tests in such aquifers—using conventional methods derived from schematizing homogenous aquifers—leads to incorrect estimates of transmissivity and storage coefficient. According to the pumping test, transmissivity is a characteristic of the whole wadi, but storage parameters are only characteristic of the part of the aquifer where ground water levels fluctuate. The water table storage coefficient relies on the rapidity of the decrease in water level, caused by (for example) use in irrigation.

When considering the vertical profile of a wadi (Fig.1), with estimated corresponding values of storage coefficients, the velocity of ground water table will decrease by 10 l/s of water over an area of 1 km^2 with no storage replenishment, as shown in Fig.1. It is clear that calculating the proper storage coefficient is essential for determining the volume of ground water in an aquifer, its decrease, depletion and replenishment and its optimum use.

Ground water reserves are defined by balancing out the volume of usable groundwater with irregular rain and surface water in wadi floods. Reserves can be recharged by natural or artificial infiltration, which can be encouraged by flood control in the upper part of the wadi, or by ploughing the wadi bed, building barrages (stone sils) and barriers (ogmas) across the wadi. Other methods include lengthening the wadi bed, digging dykes, and higher flooding of fields etc. Flooding the soil by spate irrigation not only increases infiltration, but reduces the need for pumping ground water for irrigation and leaches the soil of hazardous self-accumulations.

5. Optimal water balance between surface and ground water

It is necessary to define the objective of optimization. It may relate to the water supply for irrigation, to ground water levels (eg in a high root zone of palm trees or crops), or to the leaching of soils. There is often more than one aim involved in the optimization. The data necessary for optimization of fthe surface and ground water balance include:

- ❑ a deterministic description of the surface-soil-ground water system as shown in section 2 above;
- ❑ a stochastic description of data on the hydrological probability of water inflow into the area of interest; and

SIGN	TYPE OF ROCKS	STORAGE COEFFICIENT	VELOCITY OF GROUNDWATER LEVEL M PER YEAR
	LOESS SILT FINE SAND	0.1	3.15
	GRAVEL	0.2	1.58
	SANDSTONE CONGLOMERATE	0.02	15.8
	GRAVEL	0.18	1.75
	SANDSTONE CONGLOMERATE	0.01	3.15
	GRANITE	0.001	3.15

Figure 1 Geological profile and storage parameters

- a description of the objectives in order of priority.

All these data create a complex system; the first two are stable elements given by nature, and the third is changeable according to demand and criteria set.

From the mathematical point of view it is an open, non-linear system, to be optimized by interactive cooperation between man and the model of natural structures. Man is the most important factor. Education of specialists is therefore strongly recommended.

In arid areas and wadis, this system is very variable due to climatic changes (monsoon periods, long term changes in precipitation and climate, dry and wet periods) and optimization of water balance should allow for water reserves for long dry periods and with storage capabilities (in aquifers) for short extremely high floods.

In arid areas an optimal water balance is determined by a limited amount of ground water and flood water. In these areas more than anywhere else it is true that the amount of groundwater used must not exceed the amount replenished during the rainfall period. For example, in Wadi Markhah the ground water in storage is approximately 1 x 10.8 m^3. The numerical amount seems high, yet considering the increase of the pumping rate by 400 l/s in the area under consideration, the storage of water will be exhausted within 10 years (Mucha, Paulikova, 1984). For optimal water balance control it is necessary to know:

- the immediate volume of ground water stored in aquifer (computed from equipotential lines of water table, bed rock surface and water table storage coefficient distribution in aquifer);
- the immediate free volume of aquifer to take infiltration water into storage (computed from equipotential lines of water table; terrain surface and water table storage coefficient distribution between the surface and water table);
- the probability of flood occurrence and the possibility of ground water recharge;
- the amount of water in the soil from the last irrigation and water demand; and
- the priority of crops and fields to be irrigated and priority of demand for water supply.

These will require a monitoring network for ground water, spate water and soil moisture. It is necessary to have a management model of water balance which will show how the water balance changes if spate or ground water is used for irrigation or water supply. The surface and ground water survey must be carried out continuously with the aim of adjusting the model with new data.

6. Conclusions and recommendations

In wadis in arid areas there is a limited amount of spate and ground water. Development of the water resources in wadis means, therefore, maintaining a proper balance between spate and ground water.

Hydrographs provide the basis of an assessment of surface water resources and of all water balances and ground water recharge computations. Construction of wadi gauging stations along the wadi is, therefore, a first priority.

Aquifers have not been regarded yet as real groundwater reservoir which can be replenished and depleted. Parameters are often calculated using confined aquifer equations not suited to wadi conditions (water table, layered aquifer, partial, often large diameter wells, etc.) and most parameters (storage, vertical conductivity, leakage etc.) are rough estimates, making accurate surveys of ground water and aquifers impossible. A first step in improving this was made by introducing a modelling method by pumping test interpretation, adopted for wadi conditions. This was reported by Mucha, Paulikova and Fara 1984. On the basis of field work in the PDR of Yemen, Mucha and Paulikova (1986) prepared a user manual of the methodology of pumping test interpretation especially suited for arid lands and wadi conditions. Special attention was given to interpretation of tests on large diameter dug wells, to storage parameter interpretation and to type curve construction for any individual pumping test.

The main aims of developing available wadi resources are the improvement of the aquifer survey, the provision of a survey of infiltration and recharge from floods, and estimation of the rechargeable/depletable volume of aquifer storage.

Theoretically, a connected model of flood and aquifer for wadi condition should be constructed. The model should be programmed to enable modeller and manager to use computers, and to load and change the data, using different data bases created especially for every wadi.

Local well-trained specialists are an essential element in wadi development. Models, computers, and reports of the most renowned firms are of little use without local specialists who can use these achievements of science. Education should, therefore, be an important aspect in wadi development. Local postgraduate courses should be organized in PDRY and other arid countries.

A comprehensive understanding of the conditions and goals of wadi water resources determination is the first step to wadi development.

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