# Groundwater development in the Tihama coastal plain

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## 1. Introduction

The Tihama Coastal Plain, with an estimated 5 000 km² of cultivable land, has become a prime target for agricultural development in the Yemen Arab Republic. About 30 percent (140000 ha) of this fertile land is located within the alluvial fans formed by the seven major wadis in the area.

Since 1973, the Tihama Development Authority (TDA), in collaboration with international aid agencies and foreign consultants, has carried out several multidisciplinary development projects in the area. Because of the large area of the Tihama (17 350 km²), the Ministry of Agriculture and Fisheries adopted a systematic 'single wadi development' approach in the Plain, starting with the two largest wadis, Zabid (1969-72) and Mawr (1972). Subsequently, individual development studies for the wadis Rima, Rasyan, Surdud and Siham were executed. Improved surface water irrigation systems have been developed for Wadi Zabid (1979), Wadi Rima (1984), Wadi Mawr (under construction, 1987) and Wadi Siham (design under tender). In 1983 all hydrometeorological data was compiled and a preliminary assessment of water resources undertaken. The assessment highlighted the deficiency in data, both in space and time, and gave cause for concern with regard over-exploitation of groundwater resources. A follow-up project was formulated with, for the first time, an all-Tihama perspective-the Tihama Basin Water Resources Study (TBWRS).

Preliminary results from this study, which is still in progress, supplement the data collected during previous studies and by the TDA since its inception. A summary description of the Tihama environment, incorporating physiography, climate, hydrogeology and groundwater use for agriculture, is given in Section 2 and is followed by a case study, the Zabid geohydrological province, giving detailed findings relating to groundwater development.

## 2. The Tihama Coastal Plain

### *2.1 Physiography and climate*

The country's main water divide lies at a distance of about 120 km from the Red Sea coast, running north-south for over 400 km before it bifurcates just south of the city of Dhamar. Areas west, east and south of this divide are called the western, eastern and southern escarpments respectively. The western escarpment comprises the Tihama Basin-plain and catchment areas. The boundary between the plain and the catchment areas is commonly drawn at approximately the 200 m contour line limit; the catchments are subdivided into lower (plain), middle (foothills) and upper (mountains).

The Tihama stretches some 400 km along the Red Sea, from the Asir region in the north to Bab al-Mandeb near the southern border. It ranges in width from 20 to 50 km, with its widest part stretching between the two largest wadis (Mawr and Zabid). The plain is characterised by flat to slightly undulating topography with a very gentle slope towards the sea; the only significant land forms on the plain are associated with the seven major and several minor wadis the courses of which generally disappear beneath the high sand dunes near the coast.

Mean monthly temperatures range from 26°C in December to 34°C in June, and a low annual rainfall (25-300 mm) concentrated in the period between May and September (figure 1). The Tihama is therefore best described as a tropical arid land. Inland, rainfall increases considerably due to the convergent air masses which are lifted and carried eastwards, leading to convective rainfalls of fairly high intensity, but short duration, along the western escarpment.

Runoff generated within the middle and upper catchment areas supplies the Tihama wadis. Two flood seasons occur, in spring and summer, which occasionally extend to a single prolonged season from April to September; mean annual discharges for the individual major wadis are in the range 10-230 million m³ with only exceptional flows reaching the coast.

### *2.2 Hydrogeology*

Hydro(geo)logical studies and geophysical investigations in the Tihama have, until recently, been confined to specific wadi areas. As a consequence, large areas (70 percent) of the plain were 'hydrogeologically' unexplored which, in turn, has prevented the formulation of models with a regional Tihama perspective. Compilation of data and integration at Tihama scale is currently being carried out, supervised by the TBWRS.

#### 2.2.1 *Geology*

The Tihama coastal plain constitutes the eastern part of the Red Sea rift valley which has been filled with erosion

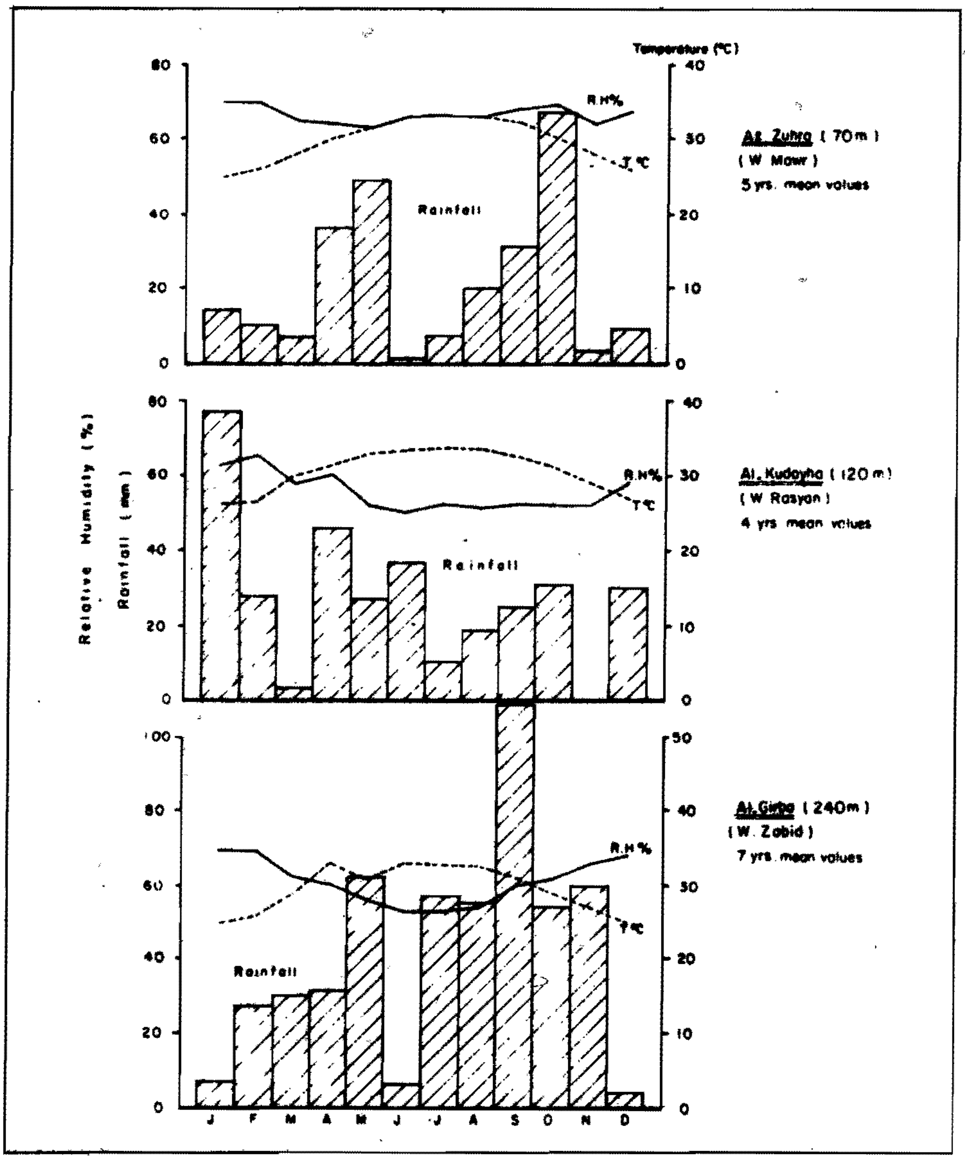



*Figure 1 Selected climatic data in Tihama meteorological stations*

products derived from the steep mountains of the western escarpment to the east (Geukens, 1963). As such, the geology of the Tihama is controlled by the tectonic and environmental history of this rift system. The rift movements and intensive block faulting which took place throughout the Tertiary, result in a series of NNW-SSE faults, subparallel to the Red Sea. This caused the Precambrian Basement rocks to be step-faulted downwards beneath the coastal plain where they now lie in blocks, at great depths, overlain by sedimentary deposits (figure 2).

Outcrops of the Basement and overlying Palaeozoic/Mesozoic sedimentary rocks are concentrated mainly in the middle and upper catchment areas to the north; intrusive rocks and volcanics of Tertiary/Cretaceous age predominate elsewhere (Grollier and Overstreet, 1978). The latter rocks constitute good aquifers in some locations because of both their primary (porous zones of basalt flows) and secondary (faults and fractures) permeabilities.

The alluvial deposits constitute the best aquifers in the whole country. These deposits, which cover the entire Tihama, can be subdivided into a Quaternary upper part (50-200 m thick) and a lower sequence of Tertiary (Miocene) age. The Quaternary deposits consist generally of poorly sorted sediments near the mountain front (sand, gravel, boulders) with increasing portions of intercalated silts and clays towards the coast.

The Tertiary sequence, consisting mainly of shallow marine deposits, evaporites and sediments of coastal origin, crops out in a few locations in the northern Tihama (Wadi Mawr and Wadi Surdud) and seems to coincide with the Baid Formations of coastal Saudi Arabia. Deep drillings for oil in both coastal Saudi Arabia and Yemen indicate that these evaporite-clastic series may reach thicknesses of over 3500 m, lying uncomfortably over Triassic-Jurassic sandstones (Kohlan series).

2.2.2 *Geo-electric model*

In the Tihama Basin Water Resources Study in 1985, 425 vertical electrical soundings were made throughout the Tihama to calculate the geometry of its aquifer system. Emphasis was given to determining:

1) the location, thickness and areal extent of fresh groundwater zones, and
2) the location/depth of aquifer boundaries.

Through an interactive process of computer modelling of the geo-electrical data, and calibration with existing geophysical, borehole logs and groundwater data, different layers occurring in the Tihama sub-surface were identified and compiled into a regional geo-electrical model.

The model identifies six different layers beneath the Tihama plain, each characterised by a specific resistivity, depth and location. The Tihama 'effective' aquifer is found to consist of two lithologically distinct units of Quaternary age (Layers IV and V) underlain by two older formations saturated with saline groundwaters (Layers II and III) and bedrock (Layer 1), which forms the impermeable base of the groundwater flow system in the eastern portion of the basin. In the western part, the bedrock is downthrown to great depths by several N-S to NW-SE step faults.

Layer V represents coarse wadi sediments containing fresh groundwater with electrical conductance (EC) in the range of 200 S.cm-1, and its occurrence is related to the major wadi areas. Layer IV is of slightly finer composition and saturated with groundwater of EC values varying between 1500-3000 S.cm-1, increasing generally towards the coastal zone and inter-wadi areas. The combined thickness of the two layers varies from tens of metres near the mountains to about 400 m in the centre of the basin. The regional geo-electrical investigations in the Tihama indicate the presence of extensive, thick Quaternary deposits which form the 'effective' aquifer for groundwater development in the area.

### 2.2.3 *Hydrogeologic model*

The major source of recharge to the Tihama alluvial aquifer is percolation of surface wadi flow from variously, wadi beds, off-take canals and irrigated fields. Natural discharge is effected by coastal submarine outflow and/or evapo(transpi)ration. Recharge, and historic natural discharge, of the Tihama alluvial aquifer is estimated to be 650 million $m^3$/year. Water level observations and pump test data indicate that on a regional scale the alluvial sediments comprise a single unconfined aquifer system.

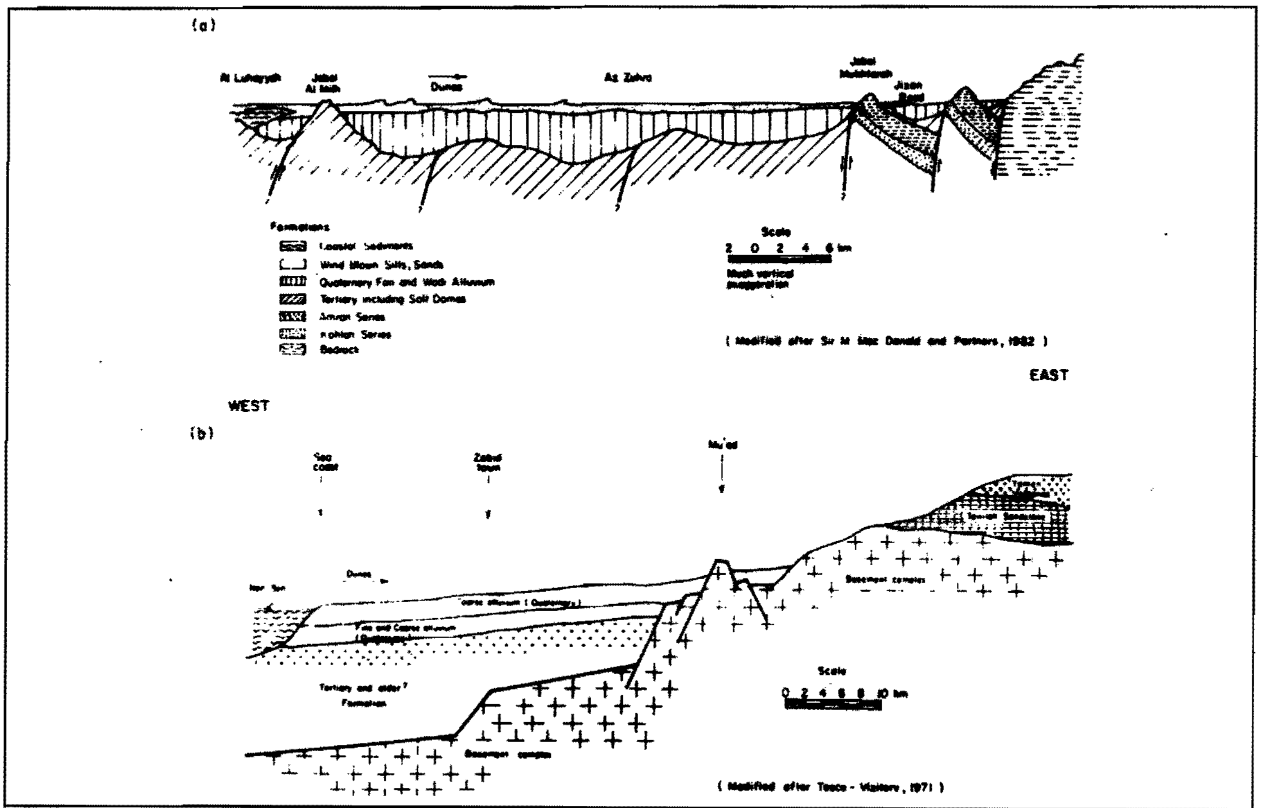
Recharge/discharge phenomena are witnessed by the general piezometry of the Tihama which indicate:

- groundwater flow is from east to west,
- hydraulic gradients are greatest near the mountain front and along wadi courses, and
- there is a marked decrease in gradients toward the coastal areas.

The decrease in hydraulic gradient in the coastal areas, however, is not considered to be entirely the result of groundwater discharge; in many areas, increased transmissivity, through a marked increase in aquifer thickness (figure 3) and inclusion of aeolian/marine sediments, is considered to be the dominant control. Aquifer permeability has been found to be extremely variable at the local scale, preventing establishment of detailed trends, although it is observed that significantly higher values are associated with wadi courses; a permeability decrease with depth is also apparent. Anisotropy is marked in the recharge areas of the alluvial fans as may be expected considering the mode of deposition; horizontal permeability is greatest east-west.

On a regional scale transmissivity is seen to increase from <1000 $m^2$/d within the alluvial fans (<500 $m^2$/d in inter-wadi, mountain front areas), 1000-2000 $m^2$/d in the central plains to around 3 000 $m^2$/d at the coast. Delineation of the groundwater flow systems of individual wadis

*Figure 2 Geological cross-sections of (a) Wadi Mawr and (b) Wadi Zabid*



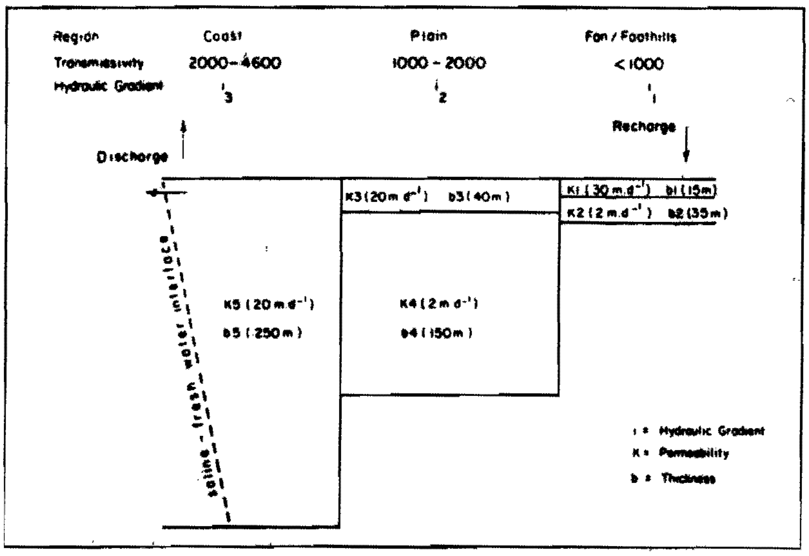



*Figure 3A Hydrogeological model*

has, together with an appreciation of sub-surface structure as indicated by the geo-electric survey, enabled differentiation of the Tihama into 11 geohydrological provinces. The geohydrological province is considered the coarsest unit for detailed studies in the Tihama.

On the basis of data from current and previous studies, a simple model has been formulated for the Tihama which incorporates the main hydrogeological features. Although a gross over-simplification of the heterogenous aquifer system, the model provides a basis for further study and investigations with a Tihama, rather than local, perspective.

### *2.3 Groundwater quality*

Groundwater quality in the Tihama is variable but generally follows the flow pattern with groundwater near the alluvial fans reflecting recharging wadi waters (EC typically <1 000 S/cm) and groundwater near the coast commonly having EC values >3000 S/cm. Local anomalies occur resulting, variously, from inflow of mineralized water from adjacent bedrock sources (often of hydrothermal origin), dissolution of evaporitic deposits/inclusions; it is possible that the high salinities of some coastal areas reflect geologically recent marine transgressions. The compilation of available hydrochemical data and EC data derived from well inventories indicates that about 50 percent of the Tihama is underlain by fresh to brackish water (<2000 S/cm) whilst almost 20 percent overlies brackish to saline groundwater (>4000 S/cm).

### *2.3 Groundwater use for irrigation*

Information relating to groundwater use for agriculture has been derived from thirteen well inventories, each confined to a specific wadi area, that have been conducted in the Tihama through the period 1971-1983. The TBWRS inventory, currently in progress, will cover all previously uncharted areas and successively update previous work. Pump or groundwater irrigation is seen as a relatively recent phenomenon in the Tihama. Although the first pumps were introduced in the late Imamic period, significant areas of groundwater irrigated lands were not developed until the early 1970s. An increasing rate of development, commencing 1975-1978, is an indication of a new impetus in the central and northern areas where increased growth rates are observed from 1984-1985.

There are an estimated 10 000 pumping wells in the Tihama with a cumulative gross abstraction of the order 800 million m$^3$/year. Hand-dug wells predominate although drilling equipment is becoming more common. Individual farm sizes are variable but tend to range from 5 to 10 ha whilst groundwater application ranges from 10 000 to 25 000 million m$^3$/ha/year. Irrigation returns from unlined canals and irrigated fields are estimated to be of the order of 30 percent.

Well distribution and density are, to a large extent, controlled by depth to water and water quality; abstraction has tended to be concentrated along wadi courses and in those coastal areas where dune cover minimises evaporative losses/groundwater salinisation, and where hydraulic gradients maintain submarine discharge. Whilst sand dunes form a natural barrier to further development in many parts of the Tihama, there is still room for significant expansion of the groundwater irrigation sector. The draft on the alluvial aquifer system, however, already exceeds recharge. With coastal hydraulic gradients maintaining appreciable natural discharge, particularly in the central Tihama, a groundwater storage deficit is accumulating at a rate of the order 550 million m$^3$/year.

The accumulating groundwater storage deficit is reflected by the widespread occurence of declining water levels.

## 3. Case study: Wadi Rima/Zabid environs

### *3.1 Introduction*

Wadis Rima and Zabid enter the Tihama coastal Plain between 75 and 90 km SE of Hodeidah and, in common with the majority of Tihama wadis, both flow westwards, towards the Red Sea.

Wadi Zabid received early attention with regard to development of improved surface irrigation works and consequently became the subject of detailed study during

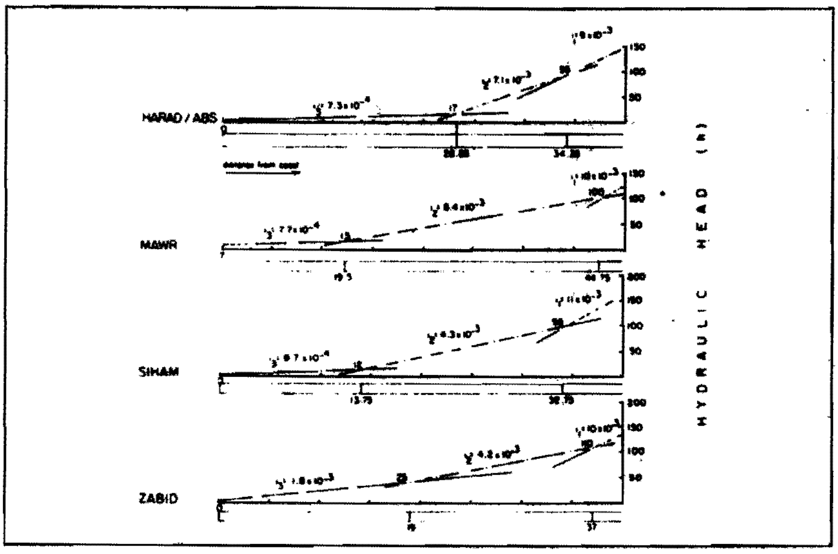



*Figure 3B Regional piezometry: hydraulic gradients*

1969-1976. Improvements to the traditional irrigation system, comprising five diversion structures with associated canal off-takes, were completed in 1979.

The groundwater and, to a certain extent, surface water systems of wadis Rima and Zabid collectively constitute the Zabid geohydrological province which covers an area of 2 250 km². The population of the province is estimated currently to be 200 000, the majority of which inhabits agricultural lands as shown in Table 1.

The initial studies in both wadi areas involved the establishment of hydrologic and meteorologic networks such that by the end of 1981 the combined areas possessed 92 well monitoring points, 2 streamflow recorders, 1 agro-meteorological station and 26 catchment raingauge stations.

Routine monitoring activities in the Rima/Zabid environs include;

- ❑ monthly monitoring of groundwater levels;
- ❑ bi-weekly streamflow measurements;
- ❑ maintenance of automatic streamflow recorders on both wadis;
- ❑ maintenance of lower, middle and upper catchment rainfall stations; and
- ❑ maintenance of one agro-meteorological station.

*3.2 Surface water resources*

Mean annual rainfall in the province increases from 100 mm near the coast to 300-600 mm at the foothills. Significant rainfed agriculture appears limited to those areas that receive >250 mm rainfall per year. With surface evaporation about 7 mm/day, recharge from rainfall is considered to be limited to intense rainfall on irrigated lands; cumulative annual recharge from rainfall (PR) is estimated at 30 million m³. Summary data relating to the catchments (middle and upper) and mean annual flows (MAF) of wadis Rima and Zabid are given below in Table 2.

Base flows of the order 1-2 million m³/s are virtually perennial in both wadis and support double and sometimes triple cropping in the upper parts of the irrigation systems; elsewhere cropping frequency is largely determined by availability of flood waters which naturally diminishes

**Table 1 Land use and population, Zabid Geohydrological Province**

| Land use category | Area (ha) | Population (1985)* |
|---|---|---|
| Rain-fed | 61 000 | 81 000 |
| Wadi irrigated | 19 600 | 56 000 |
| Groundwater irrigated | 26 700 | 38 500 |

* projection of 1975 census data.

**Table 2 Summary data, Wadis Rima and Zabid**

| Wadi | Catchment Area (km²) | Catchment Rainfall (mm) | MAF (million m³/a) | Irrigable area (ha) | Percolation (recharge)* (million m³/a) |
|---|---|---|---|---|---|
| Zabid | 4 560 | 400-800 | 140 | 11 500 (1) | 92 |
| Rima | 2 760 | 500-700 | 80 | 8 000 (2) | 46 |

* sum of percolation from wadi, canals and fields
(1) Wadi Zabid Appraisal Report, 1973
(2) Wadi Rima Appraisal Report, 1979

with distance from the wadi outlet. Water distribution in both irrigation systems is subject to TDA management control on the basis of traditional water rights.

Interception and use of base flows in the upstream areas of the middle catchment has increased in recent years to meet the demands of expanding wadi bed banana plantations, stimulated by national controls on fruit imports; the resultant reduction in flow to the Tihama has not yet been quantified, but is considered to be of the order of 5 million $m^3$/year.

With percolation losses through, variously, wadi bed, canals and fields the surface water irrigation areas constitute the primary groundwater recharge areas of the province; cumulative recharge (PERCw + PERCc + PERCf) from wadi flow is estimated at 138 million $m^3$/year.

Runoff from the Tihama-facing foothills slopes contributes a third surface water influx. Whilst of minor importance at province scale, runoff supports an established farming community at the base of the foothills where contour-orientated fields are prevalent. Recharge from direct runoff (ROR) is estimated at 3 million $m^3$/year.

*3.3 Groundwater resources*

Information on the hydrogeological environment of the province has come from borehole drilling/logging (28 sites), geo-electric surveying and limited seismic refraction profiling. The alluvial aquifer (Layers IV and V in the geo-electric section) is well developed throughout the province, ranging in thickness from 25 m in the east, near the foothills, to 150 m in the plain and 300 m at the coast. Aquifer tests yielding meaningful transmissivity and specific yield values are limited; in general, transmissivities increase from 100-500 $m^2$/d in the east to 2000-3000 $m^2$/d in the west. Specific yield values ranging, variously, from 0.07 to 0.27 have been derived through field tests and/or assessment of recharge mound development; recent studies of groundwater depletion have led to the adoption of a mean value of 0.13.

The aquifer rests on pre-Tertiary bedrock in the east, whereas to the west the underlying strata are interpreted to be low permeability/saline Tertiary sediments of the Baid Formation. Bedrock topography is markedly affected by faulting which tends to be of graben type with individual faults trending N-S parallel to both the Red Sea axis and foothills exposure. A significant increase in aquifer thickness, attributed to structural control, occurs about 20 km from the coast.

Groundwater monitoring in the province commenced in 1969 (Zabid area) and was extended in 1981 (Rima area). Groundwater flow is typically east to west although radially divergent flow is evident about the principal recharge areas of wadi inflow. A significant number of well monitoring points have been lost over the years, mainly because of declining water levels. Despite attempts to locate and re-initiate monitoring in replacement wells, the monitoring network has declined dramatically over the years. Water balance studies in the province have been hampered by the absence of long-term data series; aquifer recharge is estimated currently as:

$$\begin{aligned}\text{Recharge} &= PR + ROR + (PERCw + PERCc + PERCf) + WU + BI \\ &= 30 + 3 + 138 + 8 + 1 \\ &= 180 \text{ million m}^3\text{/year}\end{aligned}$$

where: PR = recharge from rainfall
ROR = recharge from run-off
PERC = recharge from wadi inflow (wadi, canal, field)
WU = wadi underflow
BI = bedrock inflow

With inefficient water distribution and use, it is envisaged that recharge, before improvements to the surface water irrigation systems of wadis Zabid and Rima, would have been 10-20 percent higher than present (ie 200-220 million $m^3$/year). Aquifer discharge, prior to significant abstraction, would have been equivalent to the historic recharge. Natural aquifer discharge at the coast, however, has decreased with the falling hydraulic gradients resulting from abstraction. Current estimates, derived from measured coastal gradients and assumed transmissivities, indicate a reduction of the same magnitude as the reduction in aquifer recharge; thus currently:

$$\begin{aligned}\text{Discharge} &= CD + (E + ET) + IPF \\ &= 146 + 14 + 20 \\ &= 180 \text{ million m}^3\text{/year}\end{aligned}$$

where CD is coastal discharge, (E+ET) is coastal evaporation and evapotranspiration, and IPF is inter-province flow.

Although the error potential in the balances given remains large, it is evident from the foregoing that abstraction in the province results in groundwater mining with creation of a groundwater storage deficit.

*3.4 Groundwater irrigation*

Several well inventories have been undertaken in the province as part of the investigations of previous studies. Groundwater abstraction for agriculture reached significant proportions around 1970, after which development continued at a steady and substantial rate (200 wells/year) for 5-6 years. It is estimated that the province currently hosts 2200 pumped wells with a growth rate of the order 80 wells/year. Well distribution and growth are shown in figure 4. Abstraction (groundwater irrigated) areas have expanded eastward into previously mapped wadi irrigated lands. The demand for a secure water supply and deficiencies in wadi flows in recent years are doubtless contributing factors. The predominant abstraction areas are in the central plains areas of the two wadis where fresh water (EC<1500 S/cm), moderate groundwater depth (20-40 m) together with the occurence of fertile fluvial soils, augments development. The remaining areas are located along the coastal fringe where shallow, sometimes brackish waters are tapped by numerous centrifugal pumps to service a well established date palm culture.

Hand-dug wells of 1 m diameter are predominant;

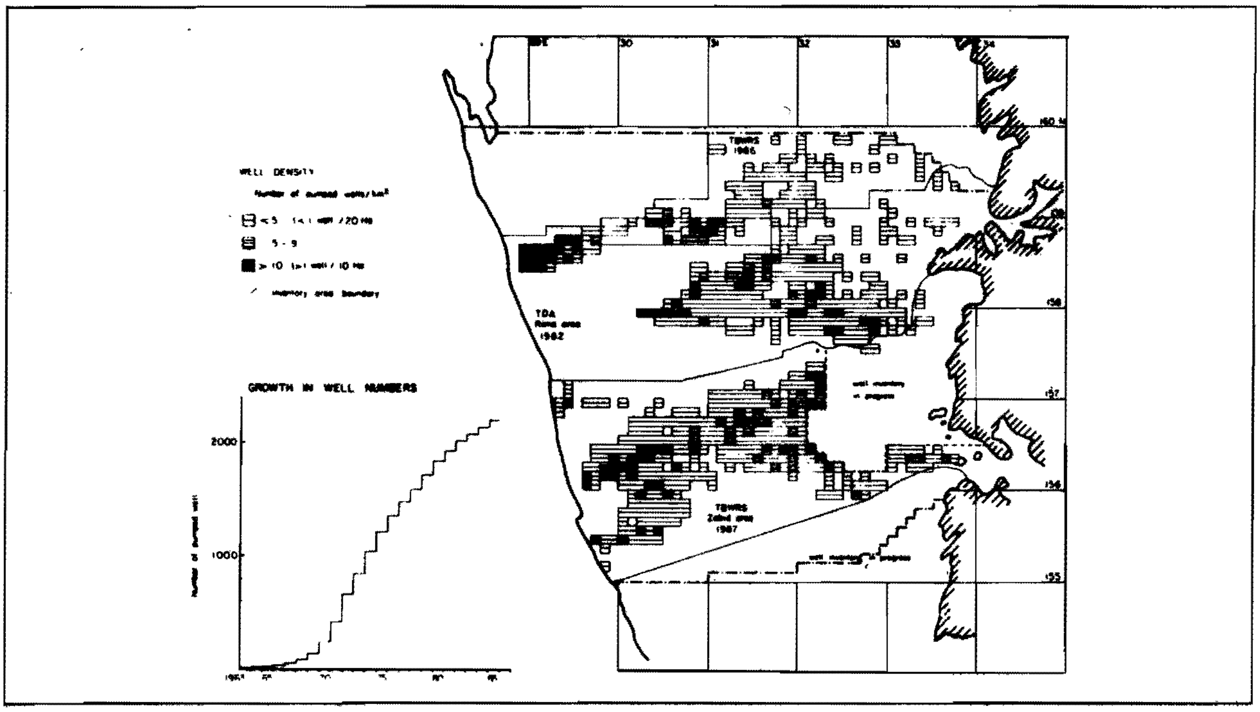



*Figure 4 Well distribution and growth*

drilled wells, typically of 200 mm diameter, represent less than 5 percent of the total. Aquifer penetration is generally limited to about 3 m, thus all wells draw water from the uppermost aquifer horizons. Individual well yields range from 4-25 l/s with a mean of 10 l/s, with each well servicing an area of the order of 10 ha.

Pumping equipment has been found to exhibit a high degree of standardization with common use of 150 mm diameter, 4-6 stage line-shaft pumps powered by 23 HP diesel engines. Irrigation is normally carried out by small-scale basin flooding with transmission via unlined earthen canals; furrow irrigation is employed for some crops, eg. melons, but is not common. For the small farmer, farm and irrigation system design is not subject to water conservation criteria; individual plots may be located some distance from the well-head resulting in water conveyance systems, which typically follow the main field boundaries.

The availability of water throughout the year, and the degree of water control possible, results in a diverse range of crops in the groundwater irrigated areas. Cereal grains, particularly sorghum, remain the dominant crop due to their low risk and high subsistence value, although there is a tendency, particularly evident in the Rima area, for increased production of vegetables and fruits for income generation. Significant differences in cropping patterns can be observed between the Rima and Zabid groundwater irrigation areas *(see Table 3)*.

Water application volumes and schedules are variable, reflecting not only the diversity of crops and cropping patterns but also farm practice, soil and climatic condi-

**Table 3 Groundwater irrigation, crop areas, preferred crop types and percentage distribution**

| | **Rima** | **Zabid** |
|---|---|---|
| **Cropped area (ha)** | **6 900**[(1)] | **17 700**[(2)] |
| **Crop type** | **Crop distribution*** **(%)** | |
| cereal grains (sorghum, millet, maize) | 38.8 (90) | 70.2 (97) |
| vegetables (tomatoes, onion, cucumber, peppers) | 26.9 | 13.8 |
| fruits (papaya, melon, dates, banana) | 22.8 (9) | 9.1 (1) |
| other cash crops (cotton, tobacco, sesame) | 11.5 (1) | 6.9 (2) |

*TDA Extension Service data, 1985-86
(1) Wadi Rima, Project Completion Report (2) TDA Extension Service data, 1985-86

tions; the mean application extends over 10 hours/day for some 275 days of the year. Total annual abstraction of groundwater for agricultural purposes in the province is estimated to be of the order of 200 million m³/year.

Field experience indicates that local farmers have little definitive knowledge of crop water requirements and optimum water application schedules. Previous studies in the Tihama have provided conflicting evidence about the ratio of crop water demand to actual water supply. Indications in the Zabid province suggest 'over-watering' with more than adequate leaching.

Irrigation losses, or groundwater returns, are currently estimated to be of the order of 30 percent of the gross volume abstracted resulting in a net groundwater abstraction of the order of 140 million m³/year.

This shows that groundwater of suitable quality for irrigation is found throughout the province. A localised deterioration in groundwater quality has been identified in the Rima pumping area which has been attributed to cyclical leaching of saline surface horizons initiated by the introduction of regular pump irrigation. This phenomenon is believed to result from the occurence of cemented layers near the water table which inhibit mixing and encourage water stratification (Morris, 1979).

Crop yields, whilst typically higher than in other local farming systems due to the assured and adequate water supply, remain low due to the maintenance of traditional farming practice and general absence of fertilisers, pesticides and cultivars.

The investment and operating costs of a groundwater irrigation system makes economics a principal factor in development. Well inventory data indicates that well construction, equipment and establishment, collectively, are in the range YR 0.1-0.2 million, whilst annual running costs may reach YR 50 000/well. Finance is often derived from the remittances of family members working abroad although credit facilities are available through the local branches of the Agricultural Credit Bank (ACB); informal credit arrangements are also common.

Pump-owners typically make arrangements to provide water to adjacent lands where farmers are unable to make the necessary investments to be wholly self-supporting; crop-sharing is the predominant method of payment. TDA Extension Service data indicate that, on average, five farmers are serviced by one irrigation well.

The investments in groundwater irrigation are not risk-free; pests and crop diseases, whilst the subject of current eradication programmes, are still common and often have devastating effects on crop yields. Market prices, particularly for the cash crops, are variable and often unpredictable resulting generally in crop diversification as the farmer seeks to maximize his returns by spreading his risks.

*3.5 Problems and constraints*

For the farmer, socio-economic factors such as marketing and stability, financing and share-cropping arrangements, may be paramount; controls through traditional practices and/or cultural influences, such as farm layout and crop selection, are apparent, although not static.

For the developing agency, water resource monitoring and assessment to ensure an optimal balance between water use and agricultural production, and the provision of adequate extension services, to improve farm practice and crop yields, become a commitment.

It is the intention of this presentation to expand on two critical problems in groundwater development both of which are well illustrated by the case study presented:

1) the effects of natural piezometry/flow system adjustment to accommodate abstraction, and
2) modifications to system recharge.

3.5.1 *Adjustment of flow system to accommodate abstraction.* A groundwater storage deficit, extending over several hundreds of square kilometres, has been created in the Zabid geohydrological province as the groundwater system moves toward a new balance state. Within this dynamic state there are modifications to natural piezometry and thus flow patterns. Currently estimated to be accumulating at the rate of 140 million m³/year, it is reflected by an extensive, general lowering of water levels. In the areas of high well density, water level declines of up to 15 m have been registered for the period 1969-1985.

Continuous water level declines in pumping wells has necessitated deepening wells in many areas, thereby placing additional financial burden on farmers. Wells, often only deepened by 2-3 m when the need arises (at a cost of the order YR 10 000), may need attention every three years in the high abstraction areas. The main abstraction areas are located between 5-25 km from the coast and local hydraulic gradients, of the order 0.002, still maintain significant coastal discharge. Whilst recent monitoring data in the abstraction areas is limited, available records show no deceleration in the rate of water level decline; the system remains in an unsteady state.

A future balance state, once acquired, can only be stable within the province if nett groundwater abstraction (Q) is less than aquifer recharge (q).

On attaining stability, flow to the coast will remain positive and equivalent to (q-Q), unless there is some impediment to flow between recharge and abstraction areas, for example if the declining water levels intersect zones of lower permeability.

If such boundary conditions are encountered, then the decline of water levels will accelerate, extend over a greater area and may, through reversal of coastal hydraulic gradients, induce influx of saline. Something similar will happen if, through continued groundwater development, abstraction exceeds recharge, or $Q>q$.

Although current water balance studies in the Zabid geohydrological province indicate that $Q<q$ the error potential in calculating both parameters remains significant and exceeds that necessary to have a high degree of confidence. That the apparent water surplus (q-Q) = 40 million m³/year is also within the range of annual recharge fluctuations augments concern about the uncertainty of the current and future situations.

3.3.2 *Modification to system recharge.* The introduction of improved surface water irrigation systems has, through improved distribution efficiency, led to a reduction in aquifer recharge and consequent increase in the groundwater deficit. More farming in the upper reaches of the flow system has placed greater demands on wadi flows that otherwise would benefit farmers of the downstream irrigation development. The decreased supply of water to the downstream areas has led to a further reduction in aquifer recharge and increase in groundwater storage deficit.

Thus, through a common objective of agricultural production, developments occur with conflicting interests in water use. The stress imposed on the hydro(geo)logic system naturally results in a greater sensitivity to climatic variation. The effect of long-term natural variations in climatic variables exacerbate the scenarios described above through reduction in aquifer recharge.

*3.6 Current situation*

In recognizing the problems outlined above TDA has, in addition to maintaining water resource monitoring activities, instigated action on three fronts:

1) limitations on further groundwater development;
2) instigation of water resources and water use studies; and
3) promotion of extension services.

3.6.1 *Limitation of further groundwater development.* Falling water levels in the province led to the 1982 inventory of abstraction wells in the Rima area. Study of the collected data was followed by the delineation of specific areas where further abstraction should be restricted. Abstraction control, however, could only be administered through the Agricultural Credit Bank who, in providing credit facilities for new wells, deepening of wells or pump purchase, could apply restriction criteria to the financing process. TDA approval of the proposed site/water use is typically sought prior to extension of any credit. No control currently exists, however, on groundwater abstraction resulting from private financing.

3.6.2 *Water resource and water use studies.* The Tihama Basin Water Resources Study was commissioned in 1984 and comprises a multi-disciplinary study of water resources, agronomy and socio-economics with a Tihama perspective. Water resource studies involve the establishment of a data base for all hydrometeorological elements, extension and upgrading of monitoring networks, analysis and assessment of all available surface and groundwater resources. Within the Zabid geohydrological province the following works are being executed in addition to routine monitoring activities:

- well inventory update;
- extension of well monitoring and raingauge networks;
- irrigation system monitoring;
- infiltration studies;
- pumping well discharge monitoring; and
- water use studies (agro-socio-economic research).

An exploratory drilling programme is being planned to facilitate calibration of the geophysical data and provide data on aquifer characteristics and parameters. Work has also recently started on the development of a mathematical groundwater flow model with which it is intended to raise the degree of confidence in water resource assessment, investigate the problems described above and consider future development options. A UNDP/FAO programme implementing methods for improved pump-irrigation efficiency was commissioned in 1985. With farmer participation, piped conveyance systems are being installed with the objective of reducing water losses by around 40 percent.

3.6.3 *Extension services.* TDA maintain extension services from their regional office at Zabid. Agricultural extension deals mainly with the introduction of fertilizers and pest control although advice on irrigation, farm and cropping practice is widely sought. Field and home visits to farmers are conducted; practical demonstrations are given on integrated extension farms or at demonstration farms maintained by TDA.

Whilst studies and extension service progress, groundwater abstraction and upstream use of surface water continues to expand. The risks of water quality deterioration, particularly in the coastal areas, and well abandonment through declining water levels, are significant. Aquifer damage, from saline incursion, and will be long lasting and will result in abandonment of irrigated land, thus agricultural production, on a large scale.

## 4. The future

The case study presented, in summarily describing the hydrogeologic regime and the groundwater irrigation and farming environment, identifies a host of factors relevant to development of groundwater resources for agriculture. Although commonly interrelated, these factors can, as seen in the case study, be considered at three discrete levels-farm, regional and national-and collectively point to the need for:

1) continued technical development;
2) formulation of a national water policy; and
3) institutional development.

*4.1 Technical development*

At the farm level there is a need for improvements in water use efficiency both with regard to water conveyance and application. This may best be approached through existing extension services with practical use of demonstration farms and supporting education facilities. Technical development at regional level must continue through maintenance of monitoring practices and hydro(geo)logical study; the error potential of parameter measurement/estimation must be reduced and modelling techniques developed to improve the degree of confidence in resource assessment and enable evaluation of future scenarios.

In the Zabid geohydrological province, the total draft on groundwater resources exceeds natural recharge. Groundwater level declines are up to 1 m/year. The associated problems of irrigation, well deepening and monitoring well replacement, are exacerbated by reduced recharge, in recent years, due to natural causes and man-made interventions within the hydrologic system. The groundwater regime in the province is in an unsteady state and moving toward new balance levels.

The possibilty of saline incursions in the near future, however, is real; the livelihood of a large proportion of well irrigation farmers is threatened. There is an acute demand for answers to the following questions:

- ❑ can a new balance state be attained within the province without deterioration of water quality? and
- ❑ how susceptible are the current and future projected groundwater regimes to recharge fluctuations?

Technical development should not be confined to standard hydro(geo)logical practice but should continue to be supported by complementary work in agronomy, economics and sociology, all of which should be undertaken at farm, regional and national levels.
As shown by the case study, the local demands and practices of different groups within a single flow system can, despite the common objective of agricultural production, result in conflicting interests with regard water use. Questions that need to be answered are:

- ❑ what are the stimuli and existing controls on farm practice and water use and what is the potential for their modification?
- ❑ what are the future projected uses of surface and groundwater resources? and
- ❑ to what extent will declining water levels produce a reduction in groundwater abstraction as the economics of pump irrigation are adversely effected?

The accumulating groundwater storage deficit in the case study area, where uncontrolled use of surface and groundwater resources occurs, confirms the need for long-term planning.

*4.2 Formulation of a national water policy*

There a great need for better water management policies, and restrictions on further development of resources.

The case described illustrates the need for water management to be be executed at the hydrologic system, or drainage basin, level, incorporating both surface and groundwater resources. Policy, however, must be determined within a national perspective. Development for maximum agricultural production will result in conflicts with development through water use efficiency (conservation). National objectives for water use must be related, through water availability and control, to the needs of agriculture and other users (industrial, domestic). The maximum or optimal net gain for the entire community (nation) must be sought.

In the Tihama, as in many arid areas of the world, water resource problems are serviced by legal systems that are deeply rooted in the past with only minor modifications to accomodate current technical developments and circumstances (Towner, 1982). Investigation of existing water use codes, both in Yemen and elsewhere in the Middle East, where similar problems prevail, should be undertaken (Caponera, 1973 and Teclaff, 1977). This should lead to a new legal code with which the resource can be placed wholly within community ownership.

Future water management must also provide for the declaration of prohibited zones and tha any drilling or use of the resource, other than in minor amounts, should be subject to permit; with regard to groundwater use, the common law doctrine of absolute ownership must be challenged. Permit issues should be narrowly proscribed and subject to:

- ❑ consideration of the hydro(geo)logy of the region;
- ❑ the effect on existing permits;
- ❑ the degree of beneficial use; and
- ❑ the needs of the local community and the nation.

Permits should also be limited to use on a particular parcel of land being transferable only upon approval of the issuing authority.

*4.3 Institutional development*

Institutional development is necessary for long-term planning and the formulation of a national water policy, (Bradley, 1982). A national authority, responsible for all water resources, should be constituted with an executive branch comprising representatives of all major users. The authority should itself be represented at the highest government levels so as to be able to contribute to, and advise on, national planning and policy formulation.

Monitoring requirements are increasing as emphasis is directed to undeveloped areas of the Tihama. In addition to the technical requirement for water use monitoring there will, with a commitment to a policy of water management, be an increasing demand for the establishment of an allied, comprehensive monitoring and administration unit to enable regulation of resource use.

It is impracticable to consider 'over-night' solutions. A programme should, however, be initiated with a fixed-time (say, 5 years) objective of establishing an authority, formulating policies and legal codes so as to enable, on completion, implementation and administration of a national water management policy. The programme should publicise explanatory information related to the need for control, the methods being considered, and the consequences of inaction. Feedback from the society, which should be sought and valued, will assist in policy formulation and the determination of optimal management controls.

## 5. Conclusion

A large number of factors are relevant to the development of groundwater resources for agriculture, and not all are technically oriented. Commonly interrelated, development factors can be considered at three discrete levels—farm, regional and national—and collectively point to the need for:

- ❑ continued technical development and provision of extension services;
- ❑ formulation of a national water policy; and
- ❑ institutional development.

Uncontrolled use of surface and groundwater resources in parts of the Tihama has resulted in a significant groundwater storage deficit; there is a real risk of widespread well abandonment and water quality deterioration through saline incursion. This will lead to aquifer damage and loss of livelihood for large numbers of farmers.

If water resources and the benefits that accrue from their use are valued, then restrictions on further development of water resources must be imposed and legal codes established that cater for prevailing conditions. The long-term perspective can no longer be considered an unaffordable luxury. It is the responsibility of current planners to act now to secure prime national interests—water resources and the livelihood and well-being of future generations.

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