

## **Autopsy of an aquifer: a case study of Al Hayma, Yemen**

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**Abstract** Despite the absence of an unique solution, a combination of the following methods permits an assessment of “who stole the water?” from the main aquifer on which a city of 400 000 people depends: (a) the Penman-Monteith method for deriving crop and soil evaporation, (b) the US Soil Conservation Service curve number method for calculating runoff, and (c) groundwater flow modelling to match historical water level trends

### **INTRODUCTION**

The Al Hayma valley constitutes the largest underground storage facility for water in proximity to the demand centre of Ta'iz, 12 km to the south. The demise of the city water supply has centred on the declining water levels in the Al Hayma aquifer. The cause of the decline is investigated so as to:

- (a) give a better understanding of the natural water movement processes;
- (b) assess the relative significance of different human water use activities;
- (c) determine the physical causes of the crisis;
- (d) define the sustainable yield of the aquifer;
- (e) predict how long it would take the aquifer to return to its sustainable condition.

In order to address points (a)–(e), a number of models (Table 1) have been developed to simulate the terms in the water-balance equation:

$$\text{Rainfall} + \text{Runoff} = \text{Outflow} + \text{Evaporation} + \text{City Abstraction} \pm \text{Change in Storage}$$

This was done to reproduce the observed decline in water levels (i.e. change in storage in the Al Hayma valley), over the period that abstraction for the city has been taking place. This constitutes the period 1983–1995. Because each of the terms has varying margins of error, the rationale behind the modelling has been to eliminate scenarios and assumptions that cannot reproduce the historical trend. Although it is not possible to arrive at a unique solution, the error margins of individual variables when considered together still permit an evaluation that addresses the five points.

### **RUNOFF TO AL HAYMA**

The analysis of evaporation and runoff based on ten-day, monthly, or longer averages must be questioned when 85% of the year's rainfall occurs in only twelve hours, if the periods of most intense rainfall are summed. The approach here has been to use daily data from the nearest meteorological station.

**Table 1** Function, inputs and outputs of each model used.

Function	Inputs	Outputs
<b>Run-on Model – Daily data from 1983 to 1995</b>		
To generate run-on volumes to Al Hayma.	Airport daily rainfall, SCS Land Use Types	Daily flows from tributaries and flanks to be applied to central wadi course and edge areas of Al Hayma (as mm)
<b>Evaporation Model – Daily data from 1983 to 1995</b>		
To estimate the amount of water required by each crop from abstraction above and beyond that provided by rainfall and runoff and, where water input from the latter two exceeds demand, to estimate the infiltration.	Airport daily mean dry and wet bulb temperatures, sunshine hours, Airport and Usayfra wind run. z-d and crop heights. Output from Run-on.	Net infiltration and abstraction for locations receiving central spates, flank spates and just rainfall for the appropriate cropping pattern (m <sup>3</sup> per 100m x 100m grid square per season. Dry season Oct-Feb, wet Mar-Sept)
<b>Steady State Groundwater Flow Model – 1976 pre-development calibration</b>		
To match groundwater heads in 1976 as an essentially pre-development steady-state condition and compare run-on indicated by the groundwater model with that by the run-on model.	Aquifer geometry, hydraulic conductivity, subsurface tributary and outlet constant heads, net recharge derived from evaporation model.	Calibration of flows and heads
<b>Transient Water Balance Model (a)</b>		
To run a mean rainfall year (1987) five times, incrementing drawdowns to examine whether the scenario being considered could approach matching the observed hydrographs.	Satellite image determined irrigation areas for 1986. Output from evaporation model for 1987.	Calibration of hydrographs. Assessment of flows.
<b>Transient Water Balance Model (b)</b>		
To match the complete observed hydrograph record from 1983 to 1995	Satellite image determined irrigation areas for 1986 and 1995. Output from evaporation model for 1983 to 1995.	Calibration of hydrographs. Assessment of flows.
<b>Recovery Model</b>		
To predict how long it would take the aquifer to recover to approximately pre-development levels if the city continued to abstract as in 1996 and there was no irrigation	Satellite image determined irrigation areas for 1995. Output from evaporation model for 1987.	Predictive hydrograph

Where there is no stream gauging, the SCS (Soil Conservation Service, US Department of Agriculture) runoff assessment method (Mockus, 1972; Noman, 1982) is recommended for use in Yemen in a modified form developed by the Technical Secretariat of the High Water Council (TS-HWC) and documented in DHV (1993). In order to test the relevance of the original and modified methods, thirteen wadi flows from ten rainfall events during storms in the Ta'iz area in the rainy seasons of 1995 and 1996 were monitored.

The observed and calculated wadi runoff/rainfall ratios are contrasted in Fig. 1. Although the ratio determined by calculation was greatly different from the observed data in some instances, these instances tended to be for the lower rainfall events where a greater margin of error might be expected due to the raingauge being distant from the

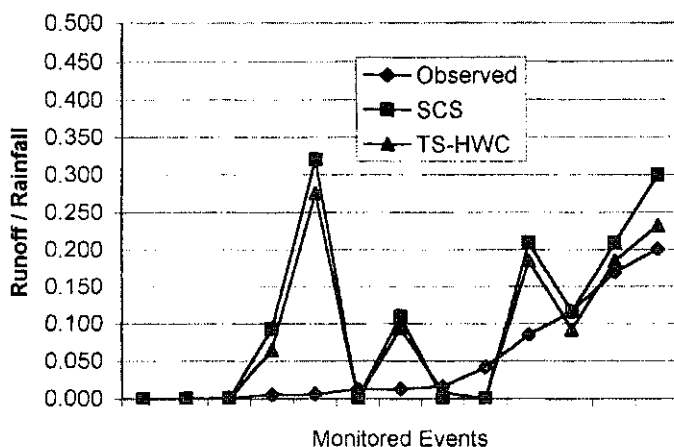


Fig. 1 Comparison of observed and calculated runoff/rainfall coefficients in Ta'iz catchments.

storm centre. For the purpose of adopting a method to simulate runoff, it is more important that calculated and observed runoff are closer for the higher rainfall events, as was the case. On the whole the TS-HWC values were closer to the observed than the SCS ones. This is thought to be because land type descriptions, and therefore land type areas, in the TS-HWC method more closely approximate the field condition. The TS-HWC CN and Ia values have been used in preference to the SCS ones in calculating run-on to Wadi Al Hayma.

The stream monitoring also suggests:

- Daily rainfall below 6 mm should not contribute to runoff (similar to DHV, 1993) and therefore should be excluded.
- For catchments of the order of tens of km<sup>2</sup>, such as those tributary to Al Hayma, that a maximum runoff/rainfall ratio of 10% occurs.

In order to assess the validity of the last point, as part of the model sensitivity analysis, three variants have been considered:

- runoff without a maximum cutoff,
- a runoff maximum of 10% of the rainfall, and
- a scaling down of all runoff quantities so that the maximum calculated runoff/rainfall ratio does not exceed 10%. This involves a scaling down to 20% of the initially calculated runoff values.

Three different types of runoff to Wadi Al Hayma are observed:

- inflow at specific points where there are known wadi flows (within the period of resource development/modelling viz. 1983–1995) and which form a linear source along the length of the wadi bed as spate flows;
- inflow at specific points where major subsurface inflows occur at the entry points of major tributaries to the valley;
- runoff from a large number of small wadis on either side of the main valley where the water harvesting system spreads the run-on over the fields along the main valley perimeter. This is said by locals to extend approximately 200–300 m into the main valley.

## EVAPORATION

Methods of measuring evaporation directly require equipment not generally available (or in some instances, poorly maintained). Empirical methods have very limited applicability, and physical methods require equipment which, although used in a research context, is not found in routine meteorological station monitoring. The best compromise of applicability, accuracy and data requirement is in the less complex physical-based formulae. Since the FAO recommendation of 1990, the Modified Penman method of Doorenbos & Pruitt (1977) has been superseded by the Penman-Monteith method (Monteith, 1965), as a basis for calculating crop water requirements.

The derivation of the Penman-Monteith equation for the estimation of evaporation is described in Monteith (1965, 1991) and in Monteith & Unsworth, (1990). Values used for the location-specific constants and the basis for their selection in the Ta'iz context are given in Table 2.

**Table 2** Values of location-specific parameters used in the Penman-Monteith equation and the basis for their selection.

	Description	Value	Basis
Alpha	Albedo	0.25	Doorenbos & Pruitt (1977)
<i>a</i>	Constants in equation for atmospheric emissivity	0.34	Al Derwish (1995)
<i>b</i>		0.044	
<i>a'</i>	Constant in equation for net long wave radiation	0.2	Al Derwish (1995)
<i>A</i>	Radiation constants	0.25	Doorenbos & Pruitt (1977)
<i>B</i>		0.5	
<i>C</i>	Surface soil heat flux = C (net radiation)	0.3	Al Derwish (1995)
<i>r<sub>s</sub></i>	Surface resistance	60 s m <sup>-1</sup>	Monteith (1991)
<i>d</i>	Rule of thumb crop height multipliers	0.65	Monteith & Unsworth (1990)
<i>z<sub>0</sub></i>		0.1	

Daily measurements of mean dry bulb temperature, mean wet bulb temperature, wind speed and sunshine hours were provided from the Ta'iz airport meteorological station. Saturation vapour pressures were calculated from the wet and dry bulb temperatures using the method described in Abbot & Tabony (1985). Crop heights have been derived from field observations for the different crops concerned for the initial, crop development, mid-season and late season growth stages as defined in Smith (1992)

The absence of data regarding soil moisture content with depth at different times since rainfall or irrigation precludes the use of a zero flux plane model. A simpler available moisture content model, more commensurate with the available data, is used here. For the summer crops, it is assumed that for the medium silty loam soils of the Al Hayma valley, Dar El Yemen (1997), the total available soil moisture content is 14%, (Doorenbos & Pruitt, 1977; Smith, 1992). Applying the effective rooting depth (Doorenbos & Pruitt, 1977; Smith, 1992) for each crop type at each growth stage gives the readily available soil water for the crop.

The readily available soil moisture (RASM) may be envisaged as a tank from which water is removed daily to meet the crop requirements. If the RASM reaches zero

(i.e. falls below the wilting point), two scenarios in the sensitivity analysis are examined:

- (a) evaporation occurs at the potential rate for the crop, and
- (b) water is evaporated daily at one tenth of this rate.

The mean daily values ( $\text{mm day}^{-1}$ ) calculated for the full season for each crop are given in Table 3.

**Table 3** Mean daily evaporation ( $\text{mm day}^{-1}$ ) for the full crop season.

Crop	Full PE	1/10 PE
Supplementary irrigated summer sorghum/millet	9.4	7.6
Rainfed summer sorghum/millet	3.8*	2.7
Rainfed summer maize	8.9	7.1
Irrigated winter maize	4.7	3.8
Irrigated winter potatoes	3.4	1.6
Irrigated winter tomatoes	3.3	2.6
Qat**	6.8	2.2

\*Not taking into account 3.5 mm maximum mentioned in text.

\*\* A cash crop bush, similar to privet, the leaves of which are chewed by many Yemenis each afternoon due to its amphetamine/stimulant properties.

### Irrigation trends

Landsat TM data were selected for the peak central valley irrigation period (1986) and for recent times (1995). Summer and winter images permit rainfed and irrigated areas to be distinguished. The recent data facilitated groundtruthing of current water use during the summer and winter seasons of 1996. The main assumptions involved are:

- (a) In January, all vegetation is irrigated. Pixels with a high response in TM4 (Very Near Infrared) and a low response in TM3 (Red) are vegetation.
- (b) Pixels classified as "irrigated" are 100% irrigated, i.e. none are part irrigated.

The total irrigated area in the modelled part of the Al Hayma valley was  $3.7 \text{ km}^2$  for 1986 and  $4.3 \text{ km}^2$  for 1995 indicating a slight increase in irrigated area over the modelled period. A huge upstream shift in irrigation was also apparent (Handley & Dottridge, 1997).

Irrigated, rainfed and supplementary irrigated crops identified from the imagery, combined with farmers' comments regarding proportions of crops grown, permitted an assessment of the areal and temporal distribution of evaporation.

## GROUNDWATER FLOW MODELLING

### Steady state groundwater flow model

An essentially pre-groundwater development head distribution from 1976 was matched to within 5 m over a 240 m range using a steady state groundwater flow model. Aquifer geometry was determined from a resistivity survey correlated to borehole data, Leggette *et al.* (1981). The valley was modelled as comprising one aquifer (the

alluvium) because the volcanics are 300 times less permeable on average. Values of alluvium hydraulic conductivity from the more reliable pumping tests ranged from 333 to 3 m day<sup>-1</sup> with a mean of 42 m day<sup>-1</sup> and a median of 29 m day<sup>-1</sup>.

With evaporation from the rainfed and spate-irrigated crops set at the full evaporation rate when the RASM falls below zero, the entire wadi dries out whichever runoff scenario is considered (Table 4). This confirms the observations of Monteith (1991) that millet evaporation does not exceed 3 to 4 mm day<sup>-1</sup>. The "full evaporation rate" scenario was therefore excluded from further analyses.

Wadi flows were between those obtained by the SCS-TS-HWC method, and the same method but with a 10% maximum runoff/rainfall ratio, but were nearer to the former.

### Transient water balance model

Because of the problems of cells "drying up" and farmers importing water from several hundred metres away, a transient model was adopted which summed water inflows and outflows from each 100 × 100 m grid square on a basin scale rather than using the finite-difference method. This was considered appropriate for hydrograph calibration since water levels have only been monitored for the modelled period in wells clustered in the central Al Hayma basin and the Miqbaba basin.

Although no value of storage coefficient was available from pumping tests in the area, a rudimentary variation in specific yield covering the range indicated by the major soil type (14%–10%) was used. The assumptions were refined by modelling an

**Table 4** Steady state model results for various values of evaporation rate and run-on from valley flanks and evaporation from spate irrigated crops. (Model permeability 19 m day<sup>-1</sup> +/- 2 m day<sup>-1</sup>). Wadi flows in 1000 m<sup>3</sup> day<sup>-1</sup>.

Model Scenario	Steady State Groundwater Flow Model:			Runoff model flows 1983–1995:		
	Least stressed SCS-TS-HWC	Most stressed SCS-TS-HWC/5	Intermediate 10% max Q/P	SCS-TS-HWC	10% max Q/P	SCS-TS-HWC/5
Runoff from flanks	1.67e-3 m day <sup>-1</sup>	1.34e-3 m day <sup>-1</sup>	1.41e-3 m day <sup>-1</sup>			
Spate irrigated evaporation	1/10 if RASM<0 1.3e-4 m day <sup>-1</sup>	AE = PE if RASM<0 2.9e-4 m day <sup>-1</sup>	AE = PE if RASM<0 2.9e-4 m day <sup>-1</sup>			
Rainfed crop evaporation	1/10 if RASM<0 1.25e-3 m day <sup>-1</sup>	1/10 if RASM<0 1.25e-3 m day <sup>-1</sup>	1/10 if RASM<0 1.25e-3 m day <sup>-1</sup>			
Result	Model converged	Ran dry	Model converged			
Heads <5 m off target?	Yes	No	Yes			
Mass balance error	0.4%	-	0.05%			
Wadi Tanif	3.6	-	3.6	5	1.7	1
Wadi Ja'ashin	3.3	-	3.4	5.6	2	1.1
Wadi Hajib	1.6	-	1.6	4.1	1.5	0.8
Drain outflow	7.3	-	4.6			
Miqbaba outflow*	4.2	-	3.6			
Total flows**	12.4	-	10.8	21.2	7.5	4.2

\*5600 m<sup>3</sup> day<sup>-1</sup> observed (1974). \*\*including minor wadi flows.

**Table 5** Results of transient modelling (1987 × 5).

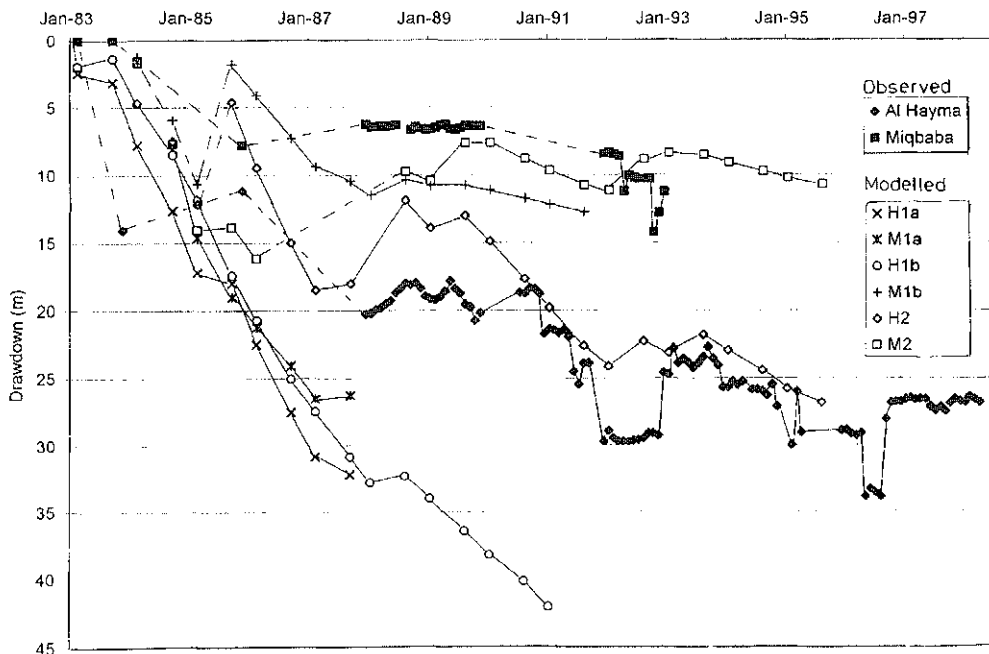
Variables		Modelled drawdowns	
Runoff	Specific yield	Al Hayma	Miqbaba
10% max Q/P	0.10	8.3	2.5
10% max Q/P	0.14	6.5	2.0
SCS-TS-HWC	0.10	5.6	2.6
SCS-TS-HWC	0.14	4.1	0.8
Target 5-year drawdowns (m year <sup>-1</sup> )		4.0	1.0

average rainfall year (1987) for five years consecutively (Table 5). Model drawdowns were calculated using the “static” level from the steady-state model and average drawdowns in the observation wells in the two basins were used as the target.

To model the complete thirteen-year record, irrigated areas were determined for 1983–1987 from the 1986 satellite image and from 1991–1995 from the 1995 image. The intervening period was taken as a 50/50 mixture of the 1986 and 1995 irrigated areas. The three scenarios tested are given in Table 6. The analyses all assumed the evaporation falls to 10% of the demand when the RASM is below zero. The hydrographs for each method are compared with the target hydrographs for Al Hayma and Miqbaba in Fig. 2. Scenario 2 gave the closest match to the observed data.

**Table 6** Scenario examined in transient modelling of 1983–1995.

Scenario	1a	1b	2
Runoff	10% max Q/P	10% max Q/P	SCS-TS-HWC
Specific yield	0.1	0.14	0.1

**Fig. 2** Observed and modelled drawdowns.

## CONCLUSION: WHO TOOK THE WATER?

In the estimation of Leggette *et al.* (1977),  $8 \text{ Mm}^3 \text{ year}^{-1}$ , and an effective end to irrigated farming, was a “reasonable objective” for abstraction from the area included in this study. If the relatively undeveloped situation of 1976 is taken as a starting point, three sustainable yields are suggested:

- (a)  $2.7\text{--}1.7 \text{ Mm}^3 \text{ year}^{-1}$  if abstraction for the city is not to detract from agriculture,
- (b)  $4.2\text{--}3.0 \text{ Mm}^3 \text{ year}^{-1}$  if no outflow from Miqbaba is to occur,
- (c)  $5.9\text{--}3.8 \text{ Mm}^3 \text{ year}^{-1}$  if irrigated farming ceases.

The last option matches the impact assumed by Leggette *et al.* (1981) but is only 60% of their “reasonable objective”.

In reality farmers greatly increased the irrigated area in Al Hayma after 1976 and the city commenced abstraction in 1982–1983. Figure 3 demonstrates the relative impact of each. Although the design city abstraction was never approached, groundwater mining commenced immediately. Coupled with competition for the dwindling resource, the aquifer was effectively depleted by 1987. The modelling suggests it would take four years for the Miqbaba basin to recover and Al Hayma nine years if abstraction for the city remained at the (low) 1995 level and if irrigated agriculture ceased. The demise of this particular resource has had the single biggest impact on many of the wider water management issues.

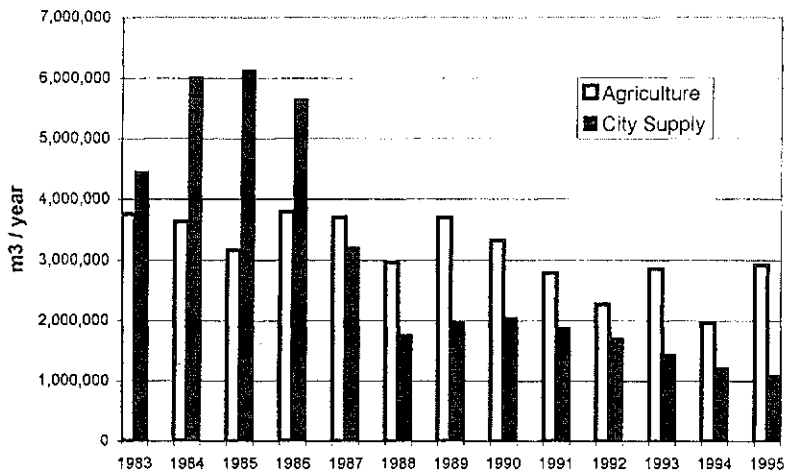


Fig. 3 Abstractions from Hayma - Miqbaba Aquifer: Scenario 2.

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## REFERENCES

- Abbott, P. F. & Tabony, R. C. (1985) The estimation of humidity parameters. *Met. Magazine* 114, 49–55.  
 Al Derwish, A. M. (1995) Estimation of groundwater recharge to aquifers of Sana'a basin, Yemen. Ph D Dissertation,

University College, London.

- Dar El-Yemen (1997) Hydrogeological and land-use studies of the Ta'iz region (Upper Wadi Rasyan catchment). *UNDDSMS Project YEM/93/010 Strengthening Of Water Resources Management Capabilities*. Vol. I: *Main Report*. Vol II: *Supporting Data*. UNDP.
- DHV (1993) Runoff assessment in areas with scarce flow measurements. *YEM/87/015 Final Report*. UNDP.
- Doorenbos, J. & Pruitt, W. O. (1977) *Crop Water Requirements*. Irrigation and Drainage Paper no. 24. FAO, Rome.
- Handley, C. D. & Dottridge, J. (1997) Causes and consequences of extreme water shortage in Ta'iz, Yemen. In: *Groundwater in the Urban Environment: Problems, Processes and Management* (ed. by J. Chilton *et al.*) (Proc. IAH Nottingham Cong., September 1997). Balkema, Rotterdam.
- Leggette, Brashears & Graham (1977) Hydrogeologic Investigation for Well Field Development in Al Hayma Basin. National Water and Sanitation Authority, Ministry of Electricity and Water, Republic of Yemen.
- Leggette, Brashears & Graham (1981) Well field development in Al Hayma Basin. Summary Report. National Water and Sanitation Authority, Ministry of Electricity and Water, Republic of Yemen.
- Mockus, V. (1972) Estimation of direct runoff from storm rainfall. In: *National Engineering Handbook, Section 4. Hydrology*, US Dept Agric., National Technical Information Service, Washington.
- Monteith, J. L. (1965) Evaporation and environment. In: *State and Movement of Water in Living Organisms* (19th Symposium of the Society for Experimental Biology), 205–234. Cambridge University Press.
- Monteith, J. L. (1991) Weather and water in the Sudano-Sahelian Zone. In: *Soil Water Balance in the Sudano-Sahelian Zone* (ed. by M. V. K. Sivakumar, J. S. Wallace, C. Renard & C. Giroux) (Proc. Workshop at Niamey, Niger, February 1991), 11–29. IAHS Publ. no. 199.
- Monteith, J. L. & Unsworth, M. H. (1990) *Principles of Environmental Physics*, second edn. Edward Arnold, London.
- Noman, S. A. (1982) Review of hydrogeological studies conducted in the Sana'a Basin, Yemen Arab Republic. ACSAD II(2), Deuxieme Symposium Arabe sur les Ressources en Eau, Rabat, 17–21 Septembre 1981, 210–231.
- Smith, M. (1992) CROPWAT: A Computer Program For Irrigation Planning and Management. FAO, Rome.