Wadi System Components under Arid Climate to Estimate Transmission Losses and Groundwater Recharge through Analytic/Numeric Solutions

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ABSTRACT:

The **World Water Assessment Programme** (WWAP) is established to develop the tools and skills needed to achieve a better understanding of the basic hydrological processes and their components (rainfall, runoff, evaporation, transmission and recharge); management practices and policies that will help improve the supply and quality of global resources under scarce resources due to arid climate. Part 1 discusses the cycle elements in a summarized form.

Part 2 examines the infiltration-recharge processes under arid climatic conditions. Results presented are the outcome of long-term field investigations involving rainfall, runoff, infiltration and recharge characteristics at several sites of the experimental basin in the Kingdom of SA.

In estimating recharge, it is important to simulate the behaviour of the aquifer under transient conditions using analytical and numerical models, for the purpose of model calibration and mass balance prediction. A **numerical model** is applied in Part 3 to estimate recharge in an arid-zone wadi, and its validity is tested by comparing it with an **analytical solution** of the equations.

Overall this paper aims to partially fulfill some of the objectives of the WWA programme. Although scientists are working with wadis in the Arab region and other arid and semi-arid regions of the World much work still remains to be carried to develop some new techniques of resource exploitation.

Part 1: WADI SYSTEM COMPONENTS IN ARAB REGION

1.1. RAINFALL PROCESSES

1.1.1 Introduction

The Earth's atmosphere contains approximately 13,000 km3 of water. This represents 10 percent of the world's freshwater resources not found in groundwater, icecaps or permafrost.

- Table 1.1 illustrates how precipitation, in three relatively diverse climatic zones, generally either returns by evaporation or evapotranspiration back into the atmosphere, becomes surface water through runoff, or recharges groundwater.
- The precipitation in the Arab Region affected by topography and atmospheric circulation

Table 1.1 Precipitation distribution into surface water and groundwater components (by climate region)

	Temperate climate		**Semi-arid climate**		**Arid climate**	
	%	**mm**	**%**	**mm**	**%**	**mm**
Total precipitation	100	500–1,500	100	200–500	100	0–200
Evaporation/ Evapotranspiration	~ 33	160–500	~ 50	100–250	~ 70	0–140
Groundwater recharge	~ 33	160–500	~ 20	40–100	~ 1	0–2
Surface runoff	~ 33	160–500	~ 30	60–150	~ 29	0–60
Source: Hydrogeology Center, University Neuchâtel, 2003.						

1.2 RUNOFF PROCESSES

1.2.1 Introduction

Surface water exists in the form of river flow, flood, lakes and water store behind reservoirs; however the surface volume of water is very small by comparison with those in the other components of the world water alance. Global surface water show areas with abundant sources with zones of large flow in the tropics and middle latitudes while others with small flows over much of the remainder as given on a map presented by WWAP ver 2.1, 2002 and 2005. The variation in climate around the Earth leads to great variability in the stream flow which is in line with the rainfall pattern.

1.2.2 Runoff Hydrograph

It is essential in surface hydrology to study the factors that affect the rainfall-runoff relationship in specific catchments. These factors can be divided into to main categories or characteristics, namely those related to the rainfall (storm) and those related to the watershed. Runoff-infiltration-recharge process is complex and diffucult to quantify by conventional methods.

1.3 EVAPORATION

1.3.1 Introduction

Evaporation from the land surface is estimated by Shiklomanov (1999) to be 74,200 bcm a year, with the lowest of other estimates being 70,000 bcm. Direct measurement is not possible; indirect methods are developed.

1.3.2 Evaporation and Evapotranspiration

Measurements indicate that evaporation from free water surfaces along the southern and eastern coasts of the Mediterranean Sea ranges between 750 and 1000 mm/year. This value increases as one moves inland to reach 2000 mm/year or more. Concerning the interior of Africa, the annual evaporation may reach 3000 mm/year or more in the region of deserts but it drops progressively as rain and humidity increase in South Sudan to reach 1500 mm/year at the southern borders with Uganda. In Arabia and the Gulf Region, evaporation along the coast reaches 2500 mm/year and often the daily evaporation during summer becomes 15 mm and more as one travels inland to the desert.

Table 1.2 The evaporation rates in Oman and UAE.

STATION	ANNUAL EVAPORATION Mm	SITE LOCATION
Sharja	3414	Gulf coast
Kalba	3241	Gulf of Oman coast
Falaj Al-Muaalla	3705	38 km inland
Milayha	4202	53 km inland

1.3.3. Evapotranspiration and Soil Moisture

The processes of evaporation and transpiration (evapotranspiration) are closely linked to the water found in soil moisture; these processes act as driving forces on water transferred in the hydrological cycle. Movement through soil and vegetation is large and accounts for 62 percent of annual globally renewable freshwater. (Part 2 of this paper). Zero flux plain depth in wadi aquifers varies around 2 meters.

1.4 TRANSMISSION LOSSES (TL) AND RECHARGE PROCESS

1.4.1 Introduction

Groundwater is an important source of fresh water in arid and semi-aridregions. It is either the main source of fresh water, or a complementary source to surface water. It can be either renewable or fossil. Accordingly, groundwater protection should be one of the top priorities in such regions to ensure sustainability of developments. (Sorman et al. HSJ vol 38(3),1993).TL depends on geology, infiltration and soil moisture storage.(Part 3 of this paper).

1.4.2 Groundwater

The science base: from maps to models

Especially in the developing world, conceptual (and thus numerical) models of the groundwater flow system for mapped aquifers cannot always be established with sufficient confidence or in adequate detail as a result of:

- lack of knowledge of three-dimensional geology;
- inadequate monitoring of groundwater levels; and
- insufficient data on hydraulic head variations with depth, that control flow patterns from recharge to discharge areas.

1.5 GROUNDWATER FLOW PROCESS

1.5.1 Global Groundwater Flow Occurrence

Shallow aquifer systems have near-surface water tables that are strongly linked to and interchange with surface water bodies. Map presented in reference IGRAC (2004) identifies the thirty-six Global Groundwater Regions over Globe where the mean rate of recharge in (mm/year) is 0-20 at large grounwater reserves in arid zones.

1.5.2 Regional non-renewable aquifers

A good understanding of the present state of the system is generally based on clear identification of boundaries, flow rates, and hydraulic characteristics. In arid zones, recharge is very limited and recovery time of pumping (in aquifer tests) is very long which result in a poor estimation of flow (water balance) and hydraulic properties. (Part 4 of this paper) At present, groundwater resources in the Arab Region, in general, and in the Arabian Peninsula in particular, are under critical conditions as volumes withdrawn far exceed their natural recharge resulting in a continuous decline in groundwater levels and quality deterioration in most of the countries due to sea water and connate waters encroachment.

1.6 CONCLUSIONS

Although hydrologists have been working with wadis for a long time in the Arab Region and other arid and semi-arid regions of the world, much work remains to be done to develop adequate techniques of resource exploitation which recognize the susceptibility of wadi systems to over-exploitation and ensure their sustainable development. Many workers have reviewed the state-of-the-art, and identified future needs (Al-Weshah 2002a, Wheater and Al-Weshah, 2002b).

1. Major areas of need in the Arab Region include improved data management systems and data collection networks in wadi basins. There is a need for improved measurement techniques for wadi flow, wadi sediment load and groundwater response. In addition to conventional measurements there is a need to measure other aspects of wadi hydrology such as watershed characteristics including vegetation cover, topography, soil characteristics, geology and land use.

2. High quality research is needed to investigate processes such as spatial rainfall, infiltration and groundwater recharge. Both detailed research and regional analyses are required for a better understanding of wadi hydrology.

3. Modeling of wadi aquifer systems is an effective tool for the sustainable management of wadi systems. Development of rainfall-runoff models appropriate for wadi catchments is a basic need. However, there are still many uncontrolled or unknown elements that hinder understanding of physical systems, such as.

- Variability in space and time
- Lack of adequate database and data collection in various parts of the world

Part 2: ESTIMATION OF WADI RECHARGE FROM CHANNEL LOSSES

In this part of the study an existing data base created by data loggers for a typical representative basin in southwestern Saudi Arabia was used to examine the infiltration-recharge processes under arid climatic conditions. Results presented are the outcome of long-term field investigations involving rainfall, runoff, infiltration and recharge characteristics at several sites.

2.1 METHODOLOGY

Transmission loss assessment in ephemeral streams of arid regions is difficult due to the transient nature of the surface and subsurface flow processes. However, simplified procedures based on the mass balance approach provide a reasonable estimate of mean infiltration losses. If T_L represents the cumulative volume of transmission loss, V_{UP} the cumulative upstream inflow volume, V_{DS} the cumulative downstream outflow volume and V_{TR} the tributary runoff contribution to the main channel, then it follows by mass balance that:

$$T_L = V_{UP} - V_{DS} + V_{TR} \qquad \text{Eq 2}$$

Large variations in transmission loss occurred due to varying runoff magnitude and spatial variability. Runoff availability was shown to have a dominant influence on the amount of transmission loss and subsequent recharge. Runoff information was therefore classified into four groups based on runoff volumes recorded at the upstream and downstream stations, as shown in Table 2.1.

Table 2.1. Runoff-transmission loss-recharge data for events classified into four groups

Event no.	Date (day, month, year)	Runoff volume (m^3 x 10^6)			Transmission loss, T_L (MCM)	Max. channel flow width, MFW (m)	Antecedent conditions, ANTEC	Depth to water table, D (m)	Groundwater recharge depth, GWR (m)
		Upstream B412, V_{UP}	Downstream B405, V_{DS}	Tributary runoff, V_{TR}					
Group 1: Inflow = 0									
15	23.4.86	0,00	0,279	1,670	1,39	31,00	0,61	2,42	0,07
16	7.5.86	0,00	0,048	0,021	0,00	27,00	0,75	2,51	0,00
17	30.7.86	0,00	0,144	0,900	0,76	30,00	1,00	3,68	0,09
23	15.4.87	0,00	0,003	0,000	0,00	25,00	0,27	1,95	0,09
24	9.5.87	0,00	0,316	0,150	0,00	31,00	0,92	2,40	0,08
Group 2: Outflow = 0									
4	23.4.85	0,146	0,00	0,091	0,24	80	0,72	2,10	0,08
6	1-2.5.85	0,185	0,00	0,00	0,19	21	0,19	1,80	0,18
12	4-5.4.85	0,136	0,00	0,00	0,14	25	0,14	3,93	0,03
Group 3: Inflow > Outflow									
1	25.1.85	0,453	0,062	0,287	0,68	55	1,00	4,88	0,26
2	4-5.4.85	0,290	0,062	0,021	0,25	48	1,00	4,43	0,17
5	28.4.85	0,120	0,068	0,028	0,08	65	0,41	1,94	0,09
7	5.5.85	0,086	0,048	0,191	0,23	50	0,19	1,67	0,23
8	14.5.85	0,078	0,036	0,388	0,43	51	0,61	1,49	0,15
9	21-22.5.85	0,620	0,116	0,146	0,65	49	0,47	1,42	0,16
10	26.5.85	0,208	0,034	0,341	0,52	56	0,27	1,42	0,10
13	7.4.86	0,867	0,279	0,095	0,69	62	0,19	3,88	0,16
18	1-2.3.87	0,415	0,013	0,160	0,56	47	1,00	5,12	0,11
19	3-4.3.87	1,278	0,514	0,500	1,26	64	0,00	5,08	0,37
21	8.3.87	0,584	0,250	0,116	0,45	55	0,00	3,63	0,50
22	9-11.4.87	2,950	1,970	0,288	1,27	63	0,10	3,71	0,77
27	25.5.87	0,210	0,133	0,083	0,16	52	0,08	1,58	0,12
Group 4: Inflow < Outflow									
3	10.4.85	1,260	2,601	1,298	0,00	80	0,35	3,75	1,12
11	19.12.85	0,757	1,567	0,681	0,00	70	0,00	3,34	0,52
14	13-14.4.86	1,037	1,672	2,021	1,39	76	0,45	3,48	0,72
20	7.3.87	0,274	0,562	0,461	0,17	60	0,20	4,16	0,13
25	11-12.5.87	1,750	1,960	1,841	0,63	80	0,10	2,23	0,48
26	23.5.87	0,032	0,073	0,091	0,05	48	0,10	1,47	0,06

For the first group of storms (5), no inflow hydrograph was recorded at the upstream runoff station (B412) and outflow runoff volumes are less than the average 0.45 x 10^6 m^3. Channel flow is mainly produced by tributary basin runoff resulting from intermittent storms. The storms in groups 2 and 3 are the second set and comprise 16 events. Runoff volumes at the upstream station are greater than those downstream. In group 2 there are only three events, with no runoff at the downstream station; all the inflow volume was transmitted to the subsurface during propagation. Two sub-groups are noted in group 3, dependent on whether the inflow volume was smaller or greater than the average runoff volume. In subgroup 3a groundwater table rises ranged between 0.10 and 0.23 m, in contrast to those in the second subgroup where increases were in the order of 0.16 to 0.77 m. In the last group (4), runoff volumes at the downstream station were much higher due to the significant percentage of surface flow from intermittently contributing basins. As a result of this, the groundwater table rose between 0.06 and 1.12 m in response to the large amount of water being recharged.

The analysis of results indicates that the predominant parameters controlling the magnitude of transmission loss and groundwater recharge are the flood hydrograph and soil characteristics. Hydrograph shape is determined by wadi channel width, depth and duration of inundation.

Relationship between transmission loss and upstream flow

Regression analyses were carried out using a combination of parameters.The adopted procedure relates the magnitude of transmission loss (T_L) to the dependent parameters upstream volume (V_{UP}), antecedent conditions (ANTEC) and active channel width (ACW)*;* for the 27 observed events T_L can be predicted by the equations:

$T_L = 0.19 + 0.47\ V_{UP}$ Eq 3

$T_L = 0.18 + 0.48\ V_{UP} + 0.019\ ANTEC$ Eq 4

$T_L = 0.043 + 0.45\ V_{UP} + 0.05\ ANTEC + 0.02\ ACW$ Eq 5

The regression equations for the grouping of storms as well as the confidence limits (upper and lower) at the 50% level are shown in Figure 2.1.

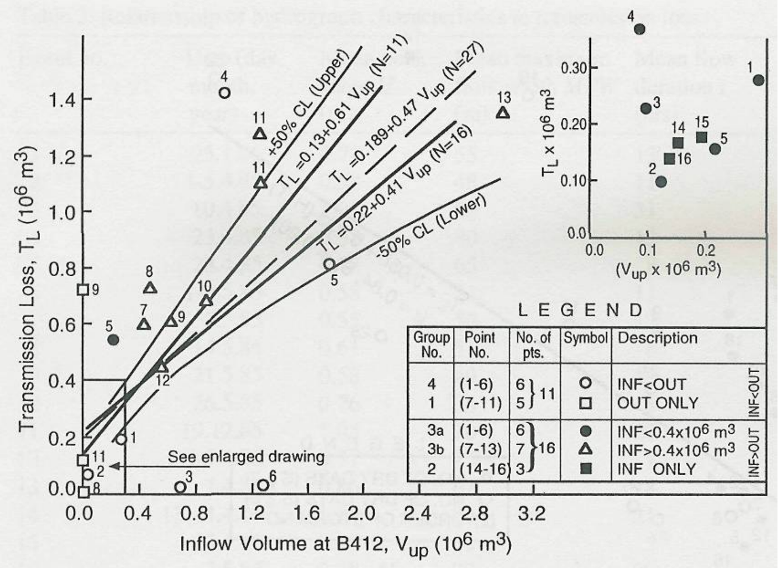

Figure 2.1. Relation of transmission loss to inflow runoff volume

Development of the above regression equations requires the availability of upstream information which may be lacking in arid regions. To overcome this problem additional equations were developed, and presented in Figure 2.2, to estimate inflow (V_{UP}) using outflow information (V_{DS}) and tributary basin precipitation (IP).

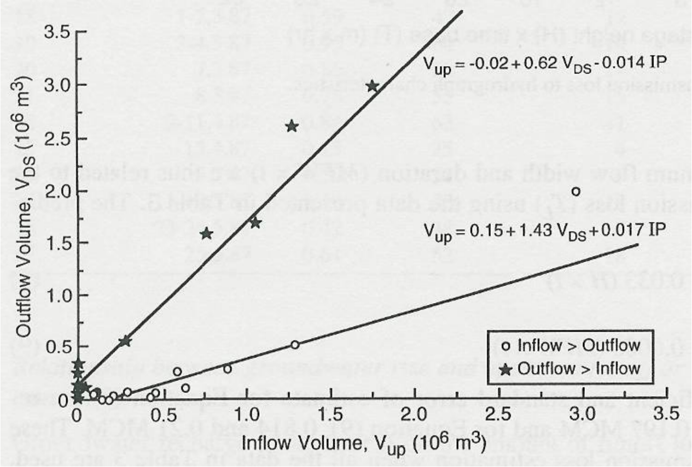

Figure 2.2. Relation of outflow runoff volume to inflow runoff volume

Relationship between transmission loss and upstream hydrograph characteristics

The relationships between flood hygrograph, channel and alluvial characteristics and transmission loss were also examined by regression analysis using data from the 27 observed events. Regression equations developed to relate transmission loss (T_L) to the hydrograph characteristics of stage height (H) and duration of flow (t) are shown in Figure 2.3.

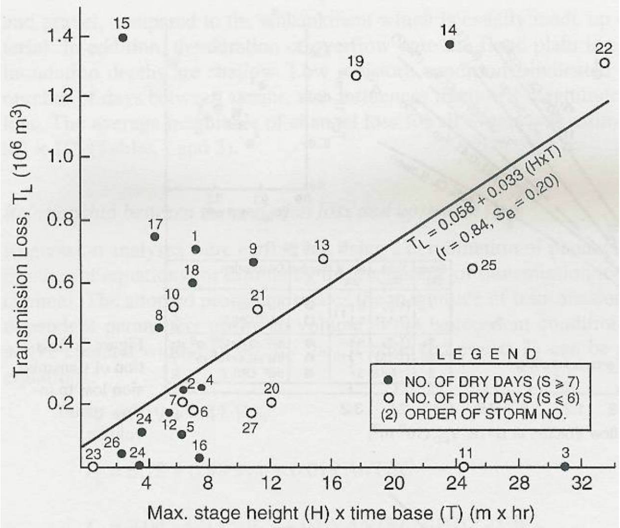

Figure 2.3. Relation of transmission loss to hydrograph characteristics,

Relationship between groundwater rise and upstream runoff or with transmission loss

Groundwater recharge is dependent on the amount of runoff lost from the wadi bed and soil profile characteristics. The interdependence of groundwater recharge (GWR), transmission loss (T_L) and inflow volume (V_{UP}), as shown in Figure 2.4.

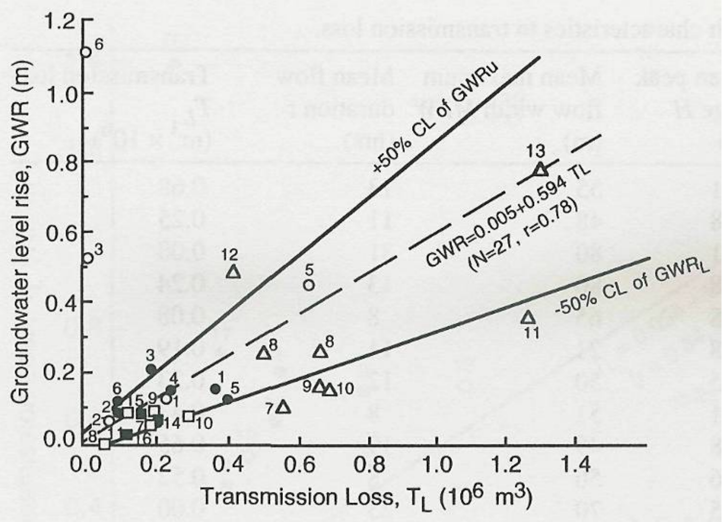

Figure 2.4. Relation of transmission loss to groundwater level rise,

2.2 CONCLUSIONS

Infiltration recharge through wadi beds in arid regions is a complex process due to the transient nature of hydrodynamic flow both on the surface and in the subsurface soil profile.

Transmission loss resulting from channel flow is found to be controlled by the inflow hydrographs of upstream and tributary basins. The hydrograph influences channel bed infiltration by controlling the width, depth and duration of flow. Runoff volume governs the channel wetted perimeter in relation to infiltration opportunity in space. Large floods are thus expected to induce higher transmission losses from the wadi channel.

The contribution of transmission loss to alluvial aquifer recharge depends on runoff volume and duration, soil profile characteristics and depth to water table. The present study indicates that various magnitudes of transmission loss and consequent groundwater recharge may result from similar runoff hydrographs due to the influence of channel and soil characteristics.

Various regression equations for predicting transmission loss have been suggested, depending on the availability of data for controlling parameters such as inflow volume, active flow width and antecedent soil conditions. The best estimate can be achieved using the equation involving inflow volume, active flow width and antecedent soil conditions.

Equations were also developed to relate groundwater recharge amount to transmission loss, antecedent conditions and depth to water table. These equations allow estimates to be made of transmission loss magnitude or groundwater table rise when limited information is available on stage height and duration, antecedent conditions and depth to the water table.

In conclusion, the data analyses showed that the magnitude of transmission losses, and the resulting groundwater recharge expected under arid conditions, can be reasonably predicted using the equations formulated in this study. It is also considered that the equations can be used to estimate recharge in areas with similar hydrological and morphological characteristics. Furhter details are presented in the report and paper supplied in the list of references Part 2.

Part 3: GROUNDWATER RECHARGE ESTIMATION FROM EPHEMERAL STREAMS

3.1 INTRODUCTION

The **calculated recharge values** matched the piezometric levels observed at a well site at the edge of the wadi channel. The total recharge depths found by integration in the time domain provided a good estimate of the transmitted volume of water per unit length of wadi channel. The findings were confirmed by runoff volume measurements at gauging stations located in the basin.

However, it is difficult to estimate recharge directly because recharge to a water table involves transfer of the infiltrated water from the ground surface through the unsaturated zone. Both the depth of groundwater level and the properties of the unsaturated soil can vary greatly owing to horizontal and vertical heterogeneity. A model of the process in discrete numerical form are compared with observations in a well located at the edge of the recharge area. However, because there are assumptions in the theory on which this model is based, the model is validated by comparing its results with the analytical solution of **Ortiz et al. (1978).**

Then, a **numerical approach** is applied which is an extension and numerical form of an integral formulation **(Morel-Seytoux and Miracapillo 1988; Morel-Seytoux et al. 1988).**

3.2. Analytical Solution used for comparison

The results from the analytical solution by **Ortiz et al. (1978)** were presented as **dimensionless curves** at the centre of the mound, and **water table profiles** were generated by the solutions and represented by figures. These profiles may be used to estimate the height of the mound or to determine the aquifer properties from observed data.

The water table profile is approximated below the infiltration basin by a line at a distance Zrf above the initial water table location and by the profile h(x, t) in the region not below the direct infiltration.

The origin for the x-axis is at the limit of the infiltration boundary of the area of width 2B. The rapid change in water table elevation in the region of sharp curvature of the flow is represented by the head drop, ΔH which is a function of time and equal to Then, the mathematical solution of the problem is decomposed into two parts.

$$\Delta H(t) = [Z_{rf}(t) - h(x = 0, t)] \qquad \text{eq 6}$$

The schematic representation of the flow geometry, water table and water content profiles (Morel-Seytoux 1988) is shown in Fig. 3.1.

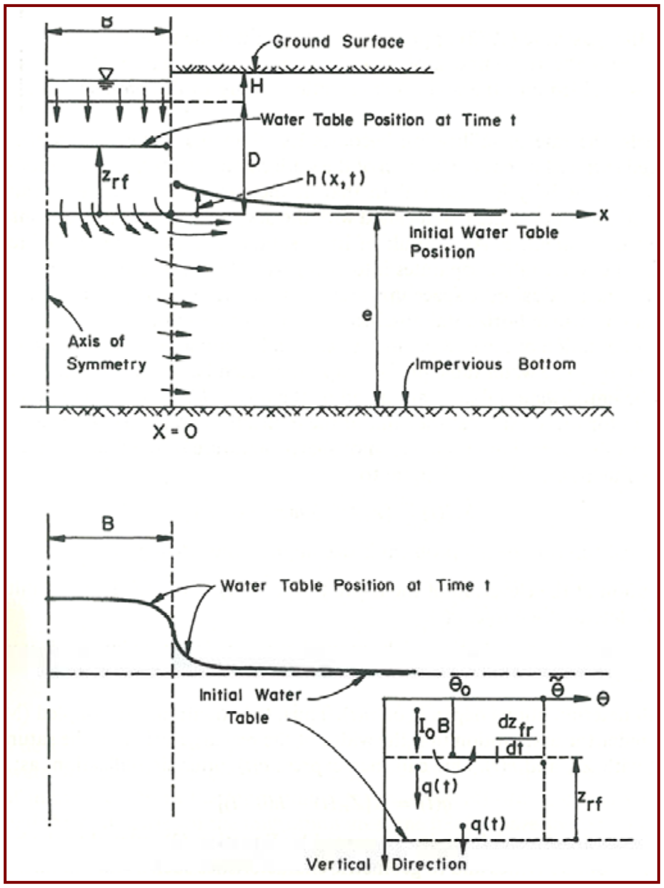

Figure 3.1. Schematic representation of cross-section and water table profile

3.3. Formulation and Solution of Numerical solution

3.3.1 Constant Recharge Rate, I_o

It is easier to solve the integro-differential **Eq. 2** numerically in discretized form (Morel-Seytoux and Miracapillo 1988). This provides q(t) at discrete time intervals. The numerical solution of the original **Eq. 2** for q(t) is done using physically measurable parameters; the half-width of the channel (B), saturated effective conductivity (K), saturation deficit, transmissivity (T), drainable porosity and recharge rate (I0) as shown by **Eq. 3.**

$$KBI_0 t = B(\breve{\theta} - \theta_0)q(t) + K\int_0^t q(\tau)d\tau + \left[\frac{2KB(\breve{\theta} - \theta_0)}{\sqrt{T\pi\phi}} * \int_0^t \sqrt{t - \tau}\,\frac{\partial q(\tau)}{\partial \tau}d\tau\right] \qquad \text{Eq 7}$$

$$q(t) = \frac{KBI_0 t}{[A]} - \frac{K}{[A]}\sum_{v=1}^{t-1} q(v) - \frac{2BK(\breve{\theta} - \theta_0)}{[A]\sqrt{T\phi\pi}}[B] \qquad \text{Eq 8}$$

$$[A] = \left[(\breve{\theta} - \theta_0)B + K + (2BK(\breve{\theta} - \theta_0)/\sqrt{T\phi\pi})\Delta(1)\right] \qquad \text{Eq 9}$$

$$[B] = \left[\sum_{v=1}^{t-1}[q(v) - q(v-1) * \Delta(m) - q(t-1)\Delta(1)]\right] \qquad \text{Eq 10}$$

$$\Delta(m) = \frac{2}{3}\left[m^{\frac{3}{2}} - (m-1)^{\frac{3}{2}}\right]; \qquad m = (t - v + 1) \qquad \text{Eq 11}$$

$$\Delta(1) = 0.667 \qquad \text{Eq 11}$$

The other differential equations derived for Zrf(t) and h(t) are also integrated at discrete time intervals using the following equations:

$$Z_{rf}(t) = \frac{I_0 t}{\Delta\theta} - \frac{\sum_{v=1}^{t} q(v)}{\Delta\theta \;\; B} \qquad \text{Eq 12}$$

$$\Delta H(t) = \left[Z_{rf}(t) - h(x = 0, t)\right] \qquad \text{Eq 13}$$

The application of the solution for q(t) under a clogged surface layer condition in an alluvial channel is given by Sorman et al. (1990).

3.3.2 Transient Recharge Rate, I_o

Following the steps described earlier in the derivation of **Eq. 2**, the unknown q(t) is expressed similarly in terms of the known transient recharge rate, I_o (t), as:

leading after integration, to

$$KB\int_0^t I_0(\tau)d\tau = B(\breve{\theta} - \theta_0)q(t) + K\int_0^t q(\sigma)d\sigma + \left[\frac{2KB(\breve{\theta} - \theta_0)}{\sqrt{T\phi\pi}} * \int_0^t \sqrt{t-\sigma}\,\frac{\partial q(\sigma)}{\partial\sigma}d\sigma\right] \qquad \text{Eq 14}$$

The integro-differential **Eq. 6** can be expressed in discrete form (Morel-Seytoux and Miracapillo 1988; Morel-Seytoux et al. 1988) as for the steady case.

The solution for q(t) is provided by **Eq. 7** in discretized form, where it can be solved numerically for any input parameters using a computer program coded by the authors:

$$q(t) = \frac{KB}{[A]}\sum_{v=1}^{t} I_0(v) - \frac{K}{[A]}\left[\sum_{v=1}^{t-1} q(v)\right] - \frac{2KB(\breve{\theta} - \theta_0)}{[A]\sqrt{T\phi\pi}}[B] \qquad \text{Eq 15}$$

where [A], [B] and Δ(m) are the same as in the case of steady recharge.

3.4.Case Study

Analytical and numerical solution techniques are applied here to fulfil the objectives of the paper.

- **First**, the results obtained from the numerical solution are compared with the analytical results under the assumption of a constant rate of recharge, at discrete times.
- **Secondly**, the numerical solution technique is used with the field data collected at a well site in Wadi Tabalah to estimate the transient recharge rates.

Before presenting the results for comparison, a **brief description of the field site** is given.

3.5. Field Site Description

For calibrating the numerical model and comparing it with the field data, a detailed investigation of the mechanism that relates infiltration to recharge is required. An experimental site in Wadi Tabalah, as shown in **Fig.3 2**, was selected along the main channel.

Wadi Tabalah has a 1270 km² drainage area which is a subcatchment of Wadi Bishah, located in the south-western part of the Kingdom of Saudi Arabia. A channel reach of 2500 m in length on the alluvial channel was instrumented with data logger units. These were used to monitor the hydrological records of rainfall and surface flow. There were also seven observation wells drilled in the channel and instrumented as shown on the layout map of **Fig. 3.2**.

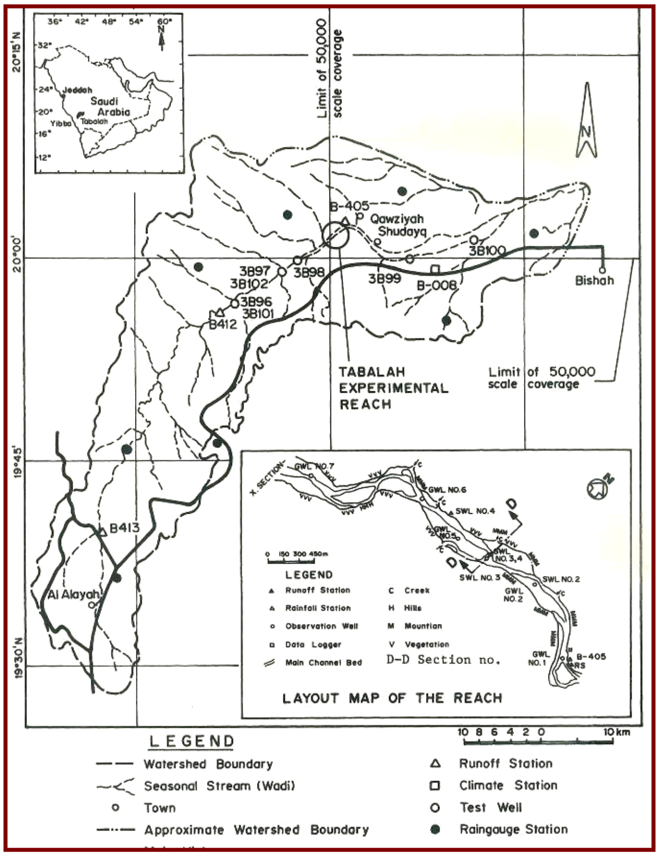

Figure 3.2. Wadi Tabalah and layout map of the reach

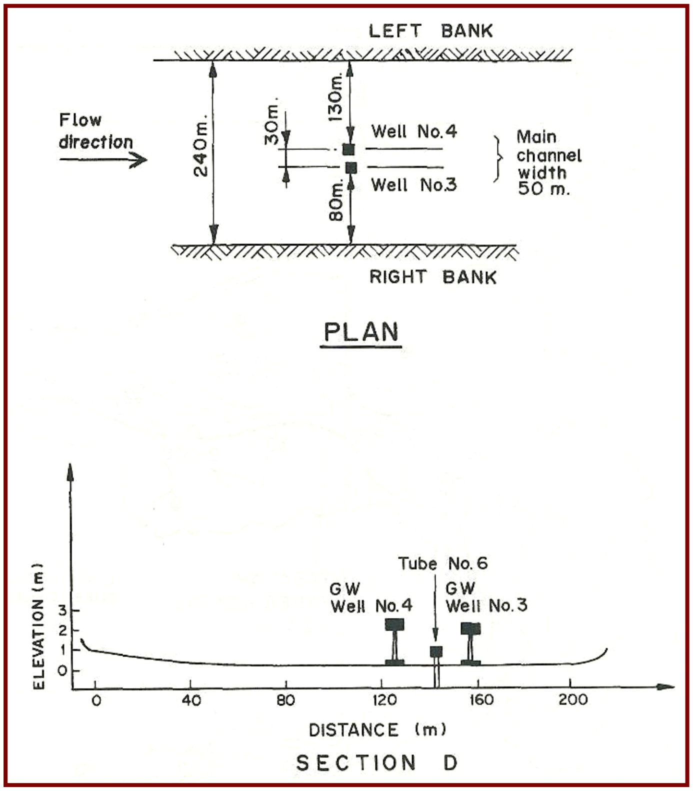

Figure 3.3. Plan and cross-sectional view of Section D

Fig. 3.3 shows the selected well locations. Well 4 was placed at about 130 m from the left bank and well 3 was drilled at about 30 m from well 3, towards the right bank.

3.5.2 Comparison of the numerical approach with the analytical solution

Keeping this objective in mind, the groundwater rise was calculated at the centre of the mound, Zrf (t); under the infiltrating wadi channel; and at the edge of the recharge area, h(t). Three rates of flux, 0.015, 0.02 and 0.03 m/h, were used in a computer program to solve **Eq. 2.**

The rise of the groundwater table at the edge and at the centre of the recharging wadi bed are very close for the two solution techniques, for the given soil characteristics and channel geometry provided in **Table 3.1.** But the results are not so good as the value of I0 increases.

Table 3.1. Input parameters for comparison of analytical and numerical solutions

Description	Symbol	Units	Case	
			$I_0 = 0.02$ m/h	$I_0 = 0.03$ m/h
Deep percolation rate	i	m/day	0.48	0.77
Isotropic saturated porosity	K	m/day	25.00	25.00
Drainable porosity	Sy_2	-	0.25	0.25
Specific yield	Sy_1	-	0.15	0.15
Ratio	Sy_2/Sy_1	-	1.67	1.67
Aquifer diffusivity	α_1	m²/day	2000.00	2140.00
Recharge	$R = i/Sy_1$	m/day	3.20	5.14

Half of recharge strip	w = B	m	25.00	30.00
Transmissivity	T	m²/day	300.00	320.00
Saturated flow depth	$H_0 = D$	m	12.00	12.80

3.5.3 Comparison of the numerical solution with field observations

The groundwater data at several well locations collected during the experimental period (1985-1987) were processed to select storm data, and are presented in **Fig. 3.4** to show the cumulative well responses along the wadi reach.

The rates of well responses were derived to develop well hydrographs. The input model parameters determined from field surveys and laboratory analysis are given in **Table 3.2.**

Table 3.2. Input parameters for use in the numerical solution

Description	Symbol	Units	Value
Depth of saturated flow	D	m	12.00
Saturated hydraulic conductivity	K	m/day	24.00
Vertical hydraulic conductivity	K_v	m/day	13.68
Ratio	K_h/K_v	-	3.00
Half of channel width	B	m	25.00
Soil porosity	Φ	-	0.30
Saturated moisture content	θ	-	0.25
Initial moisture content	θ_0	-	0.10
Saturation deficit	Δθ	-	0.15

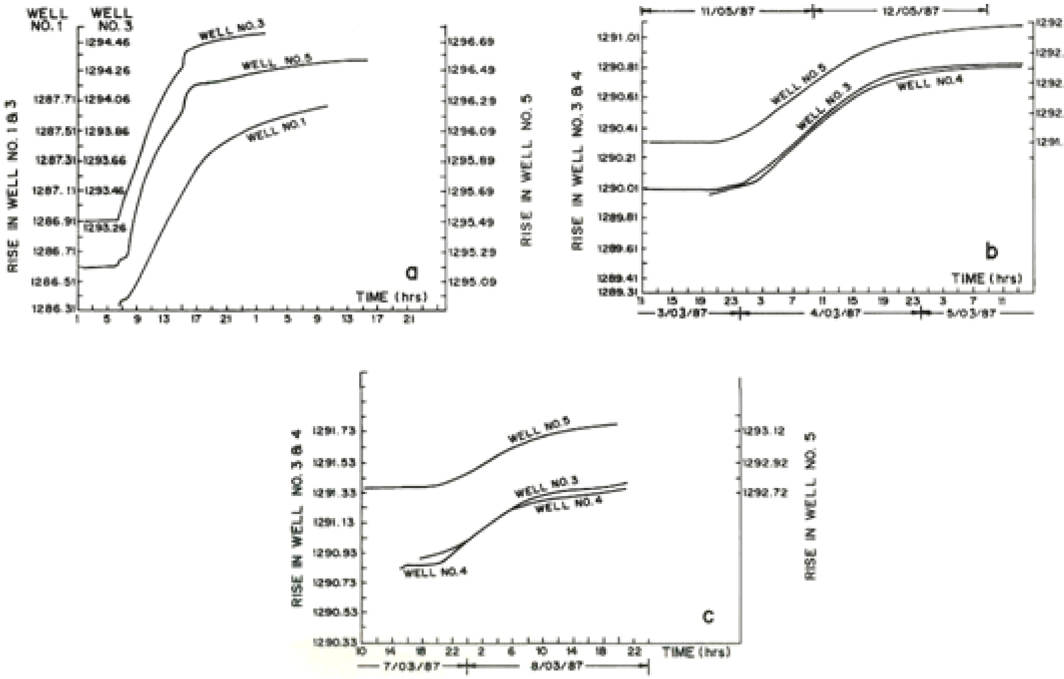

Figure 3.4. Observed groundwater rises at different wells for three events

3.6.Discussion

Comparison of the analytical solution with the numerical technique for constant recharge rate, and the numerical solutions with the transient recharge rates from observed data **(Table 3.3),** have both shown that a versatile numerical technique can be used reliably to estimate recharge rates under arid climatic field conditions.

The results indicate that mound heights at the centre of the recharge area, Zrf , and at the edge, h(0, t), are almost identical for the set of hydraulic and soil parameters.Given the proven validity of the numerical model for the parameter values corresponding to field conditions, piezometric level observations in one of the wells (3) at the edge of the recharge zone were used to infer the pattern of variable recharge rates. For that purpose, the observed groundwater table levels at well 3 are tabulated at two-hourly time intervals for 11 May 1987 in **Table 3.3.**

Table 3.3 Grounwater table levels , recharge rates at the center and edge

Symbol	Description	Time (hours)						
		2	4	6	8	10	12	14
$I_0(t)$	(m/h) recharge rate	0.022	0.055	0.045	0.040	0.035	0.032	0.028
$Z_{rf}(t)$	(m) centre	0.277	1.294	1.483	1.673	1.740	1.752	1.770
h(t)	(m) edge	0.204	0.590	0.835	1.025	1.145	1.217	1.250
q(t)	(m^2/h) specific discharge	0.073	0.704	0.648	0.648	0.596	0.536	0.494
Groundwater table rise	(m) observed at well 3	0.210	0.600	0.860	1.000	1.140	1.200	1.250

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