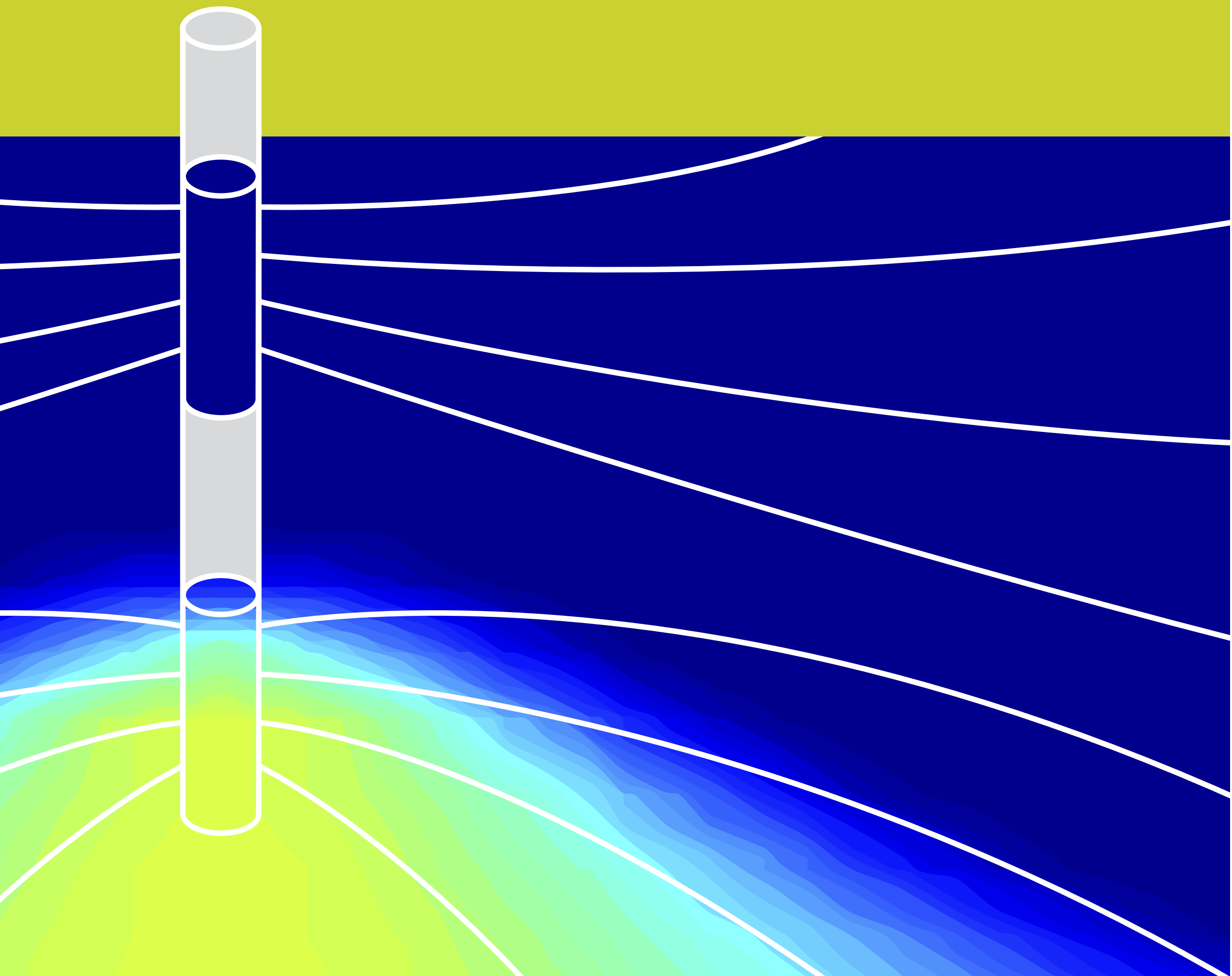
Sustainable conjunctive use of groundwater for additional irrigation

NAVEED ALAM



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Proefschrift

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To my late father – Mian Mahboob Alam

Summary

Currently millions of private wells in the Punjab are pumping groundwater as an additional source for irrigation to compensate for irregular surface water supply. Since the 1990s, most of them are skimming wells that aim to reduce the salinity of the pumped groundwater. However, salinization continues to rise over time, often above acceptable limit, which threatens food production.

This thesis aims to develop a solution to make groundwater use for additional irrigation sustainable, i.e., to limit the salinity of pumped water in the long run.

Based on a model analysis, it was shown that skimming technologies cannot prevent salinization, irrespective of parameters of subsurface, for which some unique pumping tests were analyzed and geophysical measurements were carried out in the Punjab.

Sustainability is sought in balancing both water and salt on the scale of field or farm. Both analytical and numerical models were used to show that the adopted concepts will work.

Samenvatting

In de Punjab pompen tegenwoordig miljoenen private putten grondwater als additionele bron voor irrigatie ter compensatie van onregelmatige aanvoer van oppervlaktewater via het bestaande irrigatiesysteem. Vanaf ongeveer 1990 zijn de meeste boeren overgestapt op "skimming wells", d.w.z. putten die het bovenste zoete grondwater afromen om zo het zoutgehalte van het onttrokken water zo laag mogelijk te houden. Desondanks schrijdt de verzilting voort, vaak tot concentraties boven wat acceptabel is, waardoor voedselproductie wordt bedreigd.

Dit proefschrift beoogt een oplossing te ontwikkelen die het gebruik van grondwater voor additionele irrigatie duurzaam maakt, d.w.z. die het zoutgehalte in het opgepompte water op de korte en de lange termijn onder een acceptabele grens houdt.

Op basis van de analyse van een model, kon worden aangetoond dat "skimming" technologieën verzilting niet kunnen voorkomen, ongeacht welke waarden de hydraulische eigenschappen van de ondergrond hebben, eigenschappen die zijn bepaald door analyse van enkele unieke pompproeven en van een zelf uitgevoerde geofysische meetcampagne in de Punjab.

De gezochte duurzaamheid kan worden bereikt door het in balans brengen van de water- en zoutonttrekking op de schaal van een perceel of een boerderij. Analytische en numerieke modellen zijn gebruikt om aan te tonen dat de geadopteerde concepten zullen werken.

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CHAPTER 1

Introduction

The use of irrigation for crop production in arid and semi-arid regions dates back to the dawn of the Neolithic agricultural revolution (8,000–5,000 BC). But the intensive development of water resources to permit greater agricultural development in virtually all regions of the world is of relatively recent origin, dating back only as far as the past century. The recent technological developments have made large-scale agricultural developments possible in water-scarce basins, such as the North China plain and the Indo-Gangetic plain. Presently, the emphasis has shifted from development towards efficient utilization of the water resources. Particularly, research in irrigation has focused on the potentially large benefits to be gained from efficient and sustainable conjunctive use of surface and ground waters. Mara (1988) estimates that a 20% increase in agricultural output is feasible in Pakistan through efficient conjunctive use of surface and ground waters.

Foster et al. (2010) defined the planned conjunctive use as primarily of relevance to larger alluvial plains, which often possess major rivers and important aquifers with large storage reserves in close juxtaposition, although conjunctive use potential could be raised in wide hydrogeological settings. They emphasized the analysis of the technical, institutional, social and economic factors when attempting to promote more rational and efficient conjunctive use.

There is no rigorous definition for ‘conjunctive use’ of groundwater and surface water. The primary characteristic of conjunctive use is that it usually aims to use the very large natural groundwater storage, which associated with most aquifers. The other benefits are related to buffer the availability of water supply during high flow as well as drought situations. The secondary feature of conjunctive use is that it is often the best way to combat some of the serious problems of groundwater salinization and waterlogging in alluvial plains (Foster et al., 2010).

Spontaneous conjunctive use for irrigation occurs widely and increasingly on alluvial plains through the private initiative of farmers in response to a combination of declining water levels in main irrigation canals and growing irrigation demand. While highlighting the significance of conjunctive use for the developing world, Foster et al. (2010) emphasized that conjunctive use of groundwater and surface water sources, in one form or another and with varying degrees of effectiveness, should be capable to:

- guarantee of water supply by taking advantage of natural groundwater storage in aquifers.
- achieve better delivery-timing of irrigation water because groundwater could be rapidly deployed to compensate for any shortfall in surface water availability at critical times during crop production.
- reduce environmental impact by counteracting land waterlogging and salinization, and excessive river flow depletion or aquifer overexploitation.

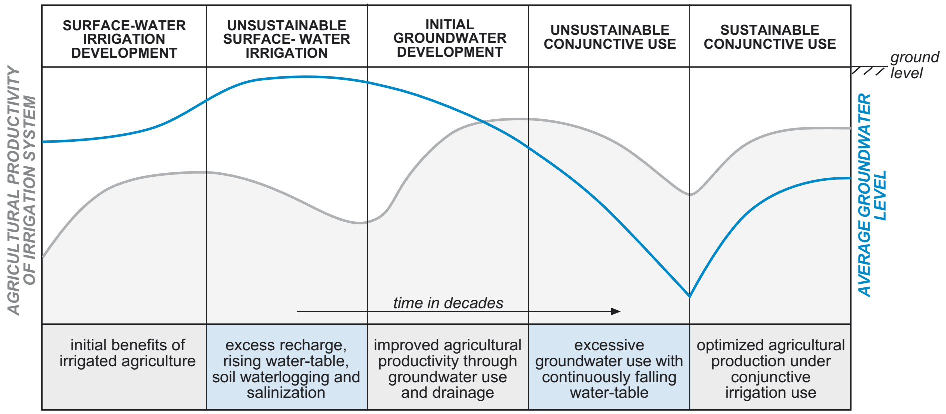

Figure 1.1: Typical evolution of spontaneous conjunctive use of groundwater and surface water for irrigation in a major alluvial plain (after Foster et al. [2010]).

The spontaneous use of groundwater sometimes causes aquifer depletion, which further complicates the deployment of cheap pumping units for irrigation on the one hand and induces high salt contents in groundwater abstraction on the other hand. Foster et al. (2010) presented the typical evolution of spontaneous conjunctive use of groundwater and surface water for irrigation in a major alluvial plain (Fig. 1.1).

The economical sustainable use of groundwater storage to confront increasing water demands due to population increase is urgently needed. Therefore, conjunctive use opportunities need to be much more systematically and vigorously pursued. Worldwide, conjunctive use trends were mostly adopted by accident (Foster, 2002) rather than by design; aquifer storage remains the most neglected component of the hydrological cycle by practicing water managers.

BACKGROUND AND JUSTIFICATION

Food production in Pakistan relies for a large percentage on the Indus valley, where large rivers split the region into islands called doabs. The doabs are densely populated and intensively irrigated, originally by surface water, but, since the 1960s, ever more by groundwater. The doabs have similar geology, which can be described as unconsolidated sediments of the Indus river branches, consisting of an alternation of sands and clays to several hundred meters depth. The groundwater system is essentially a single unconfined aquifer that is highly heterogeneous vertically due to the nature of the fluvial deposits (Bennett et al., 1967). The depth of the Indus Basin aquifer is several hundred meters at least; no test wells have ever been drilled below 450 m to reach the base of the aquifer, although petroleum explorations mention depths to bedrock between 1,500 and 4,500 m. The groundwater in the doabs is naturally salt as the rivers in this part of the Indus Basin infiltrate, so that the evaporation from the doabs causes an accumulation of salt water towards their center; whereas the native groundwater is deep and saline because of the marine origin. However, the large-scale surface water irrigation schemes in place since the late 1800s have, over time, leaked so much water that this by itself, and including irrigation return flow, has become a source of freshwater for farmers; this source is mainly concentrated along the course of the irrigation canals. The thickness of these fresh groundwater lenses varies from a few meters to more than 150 m (Asghar et al., 2002). In general, the areas with fresh groundwater are close to the rivers, which naturally infiltrate in the Punjab, while saline groundwater is typically present in the central and lower regions of the doabs. Due to irregular availability of water from irrigation canals, farmers installed wells predominantly as an extra and more reliable supply compared to the irrigation canal system. Secure supply is a major benefit and has contributed largely to the livelihoods of the farmers and the reliability of food production. This increasing groundwater usage has caused and causes salinity problems due to saltwater upconing on a wide scale, threatening food security and livelihoods in the long run. Hence, it is an important research topic to find sustainable conjunctive solutions that will allow farmers on the local scales as well as governments on the regional scale to act in the benefit of long-term and sustainable use of this valuable resource.

Highly mineralized areas of groundwater occupy more than 30% of the Indus Basin aquifer, mainly in the Punjab and Sind (Zuberi and McWhorter, 1973; Asghar et al., 2004). Nespak (1983) estimated that about 197 km^3 of fresh groundwater has accumulated as thin lenses on the top of native saline groundwater. Sufi et al. (1998) estimated that more than 20 km^3 of fresh groundwater is annually recharging these saline groundwater areas due to leaking canals. The uninterrupted extraction of groundwater to meet the increasing demand of freshwater for agricultural, industrial and domestic use, poses an enormous challenge to water managers, who have to make sure that the amounts necessary to meet future groundwater demand are recharged into the aquifer. Appropriate technologies and adequate operational strategies for sustainable extraction of this valuable resource have to be developed to overcome depletion and salinization to the extent possible to safeguard the important Indus Basin (Saeed et al., 2003a).

Several attempts have been undertaken by the Pakistani government since the early 1970s with often negative results. For instance, deep wells have been used to extract the freshwater that had previously leaked, but these wells eventually salinized. Some wells were specifically designed for the central saline areas of the Punjabi doabs to dispose of saltwater. These wells are now totally abandoned because they gradually moved the saltwater from the greater depths to the more shallow zones. To reduce salinity of the extracted water, the use of skimming wells or similar techniques is ubiquitous by farmers in the Punjab. However, despite using an often extended number of strainers (screens), farmers are experiencing difficulty in preventing or reducing the salinity caused by saltwater upconing from below. However, many of these skimming wells, especially those in the saline groundwater areas, are extracting from inappropriate depths and at inappropriate discharge rates. Above all, they use inadequate operational schedules (Saeed et al., 2002b), resulting in increasing salinities of the extracted water due to saltwater upconing. Due to this, a large number of wells have already been abandoned. Properly designed and operated wells will be of great help to the Punjabi farmers in their search for a guaranteed supply of freshwater from the groundwater when their crops need it. This study aims to show that long-term sustainable groundwater extraction in the Punjab (Indus Basin aquifer) is possible. Analytical as well as MATLAB-based numerical (SEAWAT) models were employed to show the results of the analysis.

OBJECTIVES

The greater objective of this thesis is to find out sustainable ways for long-term salt management in the important Indus Basin aquifer and other vertically heterogeneous aquifers. This thesis evaluates the existing practices of farmers in the Punjab (Indus Basin) and proposes solutions to ensure that the additional irrigation from groundwater remains possible in the future. In order to achieve this greater objective, this thesis sets the following main objectives:

- estimate the reliable aquifer parameters in the Pakistani Punjab (Indus Basin) aquifer for onward use in groundwater studies.
- determine usefulness of multidepth pumping tests to discern the impact of partial penetration and vertical anisotropy.
- evaluate skimming wells, scavenger wells and recirculation wells to prevent salinity in the extracted groundwater.
- estimate the potential of sustainable groundwater pumping on local and regional scales. This may include the development of scenarios, well design, pumping schedules and their consequences.

OUTLINE OF THESIS

Since building new dams has become ever more complicated owing to social, political and environmental concerns, water resources planning shifts its focus to emphasizing sustainable conjunctive use of groundwater to supplement surface water as well as to recharge the aquifer during periods of any surplus inflow. Groundwater, which has accumulated in formations over centuries, and is constantly being replenished by infiltration from different sources, is a resource unmatched in providing wealth; therefore, it needs to be explored and exploited with great care. In absence of any surface storage facilities, it is the only alternative storage to permit bridging of dry periods. Therefore, this research focuses on sustainable conjunctive use of this valuable resource to supplement the surface water for irrigation as an additional source in the important Indus Basin of Pakistan. The chapter (2) evaluates any substantial increase in the surface storage capacity of the basin and its effects on long-term groundwater balance and waterlogging using an irrigation-economic model. This chapter suggests guidelines to optimize the surface and subsurface reservoirs by considering the farmers' action in response to government policies.

Chapter (3) describes the study area of Chaj Doab, which a hydrologically representative doab in the Pakistani Punjab (Indus Basin). In this chapter, the measurements carried out during a field campaign in Chaj Doab in 2010–11 have been described and the applied time-domain electromagnetic (TDEM) technique is explained. This chapter details the field procedures, data acquisition and analyses procedures. The objective of this survey was to determine the spatial and vertical distribution of the groundwater salinity in the Punjab for onward use in groundwater models.

Representative hydraulic parameters necessary to evaluate groundwater use on the regional scale of the Pakistani Punjab are impossible to obtain under the intense dynamics of area-wide irrigation, where millions of wells are currently pumping groundwater. Chapter (4), therefore, reevaluates the US Geological Survey's single-depth pumping tests and recommended hydraulic parameters to be used in groundwater studies, at least as an initial estimate.

On the basis of single-layer early-time drawdown and late-time drawdown analytical methods, chapter (4) reevaluates the single-depth pumping tests to reach its conclusions. The piezometers in these single-depth pumping tests were screened only in the sandy layer and mostly at the center of the screen interval. Therefore, their characterization of the aquifer does not provide reliable information regarding the layered groundwater system. To get reliable information of hydraulic parameters and to discern the impact of partial penetration and vertical anisotropy, multidepth pumping tests (MDPTs) were interpreted on the basis of data from a network of 53 piezometers in different layers (chapter 5). The results of these unique four full-scale MDPTs provide detailed information on vertical and horizontal conductivities in the Indus Basin aquifer.

Chapter (6) is the key to 'sustainable conjunctive use of groundwater for additional irrigation'. It is the salt balance of groundwater below an irrigated field. This chapter presents a mathematical tool to study the accumulation of salt in the groundwater below an irrigated field as caused by irrigation recirculation. This chapter concludes that sustainable conjunctive use of groundwater for additional irrigation requires long-term salt management that should be founded on the essential controlling factors as derived in the aforementioned chapter.

Chapter (7) aims to solve the longstanding problem of sustainable groundwater extraction in the Pakistani Punjab. This chapter presents and explores the use of “Balanced” scavenging wells to reduce salinization so that sustainable (everlasting) groundwater use is possible as an additional source for irrigation. This chapter shows that a long-term equilibrium can be reached in which the salinity of the extracted fresh groundwater does not exceed a preset limit, for which a value is chosen that is acceptable for irrigation. On the basis of the results of the analysis, this chapter further shows that skimming cannot, in the long run, prevent the salinization of abstracted groundwater to an unsuitable level for irrigation. This chapter concludes that the final (i.e., long-term) salinity in the saturated zone only depends on salt-carrying inflows and outflows. Final salinity does not depend on hydraulic parameters or initial groundwater salinity, which can only delay or speed up the process of salinization.

Finally, all results are brought together and the case studies are synthesized in chapter (8). Some practical issues concerning the disposal of drainage are discussed. The disadvantages of recirculation wells and scavenger wells are also discussed.

CHAPTER 2

Sustainable conjunctive use of surface and ground water: Modeling on the basin scale

N. Alam and T.N. Olsthoorn

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ABSTRACT

Farmers in the Indus Basin, Pakistan have generally switched to groundwater for additional water supplies due to the irregular supply of irrigation water; currently over 50% of the agricultural land in the basin is at least partially irrigated by tubewells. These wells pump fresh groundwater, which essentially is the result of massive leakage from irrigation canals into the originally saltwater aquifer since the inception of modern irrigation around 1870. Resalinization of the aquifer now threatens long-term prospects of this new groundwater resource. Since building new dams has become ever more complicated, water resources planning now focuses on sustainable conjunctive use of surface and ground waters. This chapter evaluates the raising of the Mangla dam, its effects on long-term groundwater balance and waterlogging using an irrigation-economic model. It suggests guidelines to optimize the surface and subsurface reservoirs by considering the farmer's action in response to government policies. In recent past, the Government of Pakistan decided to raise the height of the Mangla dam to substantially increase the storage capacity of the basin. This decision was based on basin-wide modeling of conjunctive use by using the General Algebraic Modeling System (GAMS)-based Indus Basin Model Revised (IBMR), which was updated for this purpose in 2000 and supplied with new data in 2002. The results of the analysis reinforced the decision to raise the dam height by 9 m instead of 12 m, which would increase water availability by 68% in the basin. One of the objectives of raising the dam height was to increase the sustainability of beneficial groundwater use in the basin by saving about 2 km^3/a of groundwater abstractions.

INTRODUCTION

The availability of small pumps and well drilling technology during the last four decades has made large-scale agricultural developments possible in large water-scarce basins, such as the Indus Basin, Pakistan. The fresh groundwater now available in the originally salty Indus Basin groundwater system originates from massive leakage of irrigation canals and partially also irrigation return flow since surface water irrigation started around 1870. This leakage has become a freshwater resource in its own right, to such an extent that over 50% of the irrigated crops are now at least partially supplied with groundwater (Khan et al., 2008). Therefore, the leakage has created a groundwater storage which is now utilized in conjunction with the surface water storage behind large dams such as the Mangla dam. Given this situation, the emphasis of the water resources authorities and planners has shifted from development of new dams towards efficient utilization of the available water resources, particularly focusing on the potential of the large benefits to be gained from efficient, conjunctive use of surface and ground waters. Mara (1988) estimates that a 20% increase in agricultural output value is feasible in the Indus Basin through efficient conjunctive use of groundwater and surface water. Among other advantages, such combined use increases the sustainability of the overall irrigation system and enhances crop security, which, by itself, is a major incentive for private investments and increased agricultural output value.

The agro-based economy of Pakistan mainly depends on the Indus Basin irrigation system (Fig. 2.1). It accounts for about 21% of the Pakistan's gross domestic product (GDP) and employs about 44% of its labor force. Pakistan measures about 80 million hectares (ha) of which 22 million ha are cultivated. Of this cultivated area, 19.6 million ha are irrigated (GOP, 2007). Major crops are wheat, rice, cotton, maize and sugarcane, which together occupy about 63% of the total cropped area (Alam et al., 2000).

Between 1981 and 2007, wheat and rice production also increased proportionally to population, which grew from 85 to 160 million in the same period (GOP, 2007). However, this agricultural production increased mostly because of the extra water that became available after the construction of the Mangla and Tarbela dams and the rapid growth of the number of groundwater pumping units, which increased to about 0.9 million in 2004 from 150,000 in 1975 (GOP, 2004) throughout the basin. Pakistan is running out of dam space owing to environmental concerns hampering or preventing construction of new dams and ongoing sedimentation of existing large reservoirs; Mangla reservoir, the second largest in the Indus Basin has already lost 21% of its reservoir storage capacity due to sedimentation (Nespak, 2003).

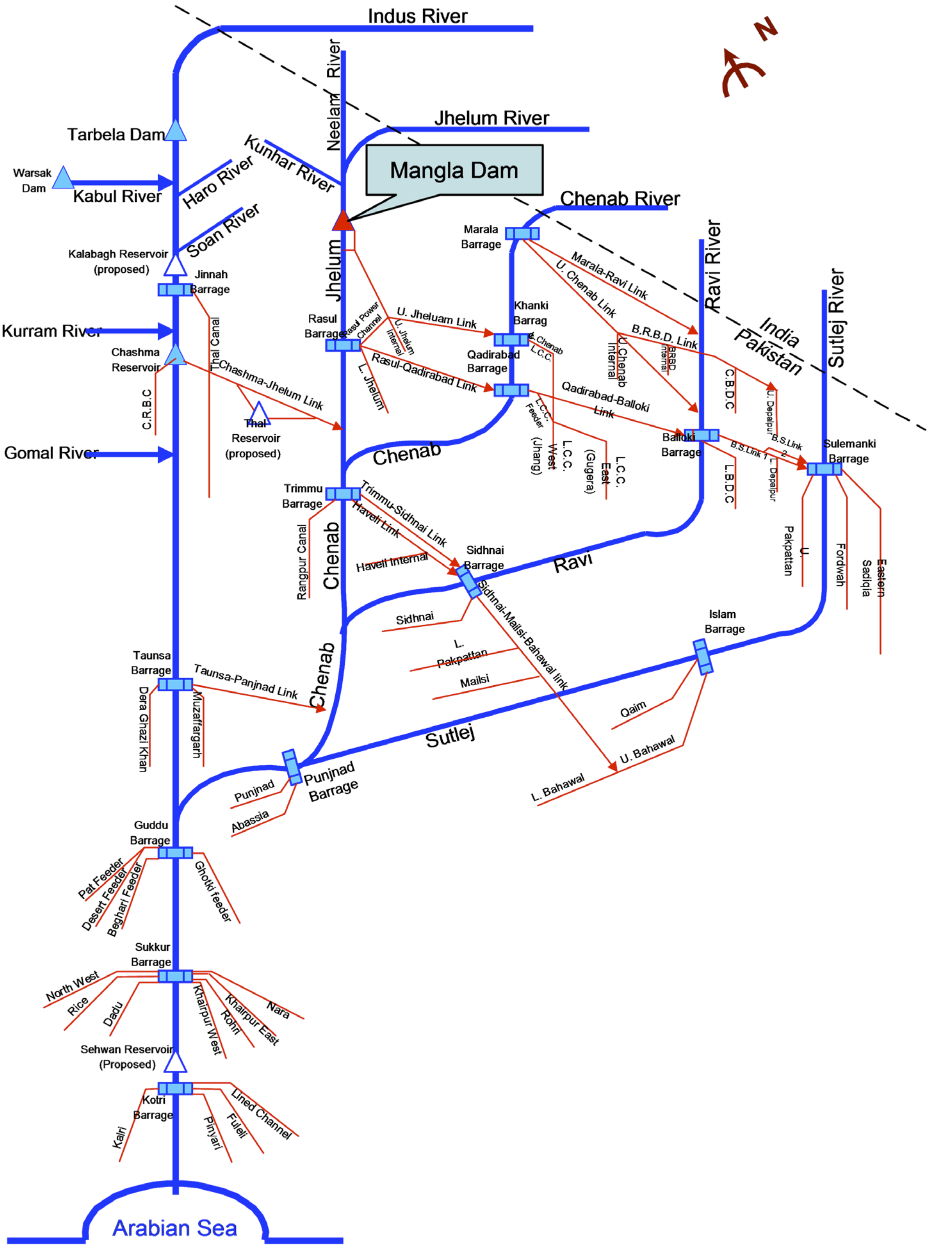


Figure 2.1: Indus Basin irrigation network and Mangla dam (after Water and Power Development Authority, Pakistan).

The Indus Basin receives on average 172 km^3/a of which 43 km^3/a flows out into the ocean, and of which only about 13 km^3/a are sufficient to maintain fisheries and sustain ecology (Bhatti et al., 2009). Hence there is 30 km^3/a potential.

Of the net inflow of 129 km^3/a, 49 km^3/a is used by crops (evapotranspiration from agricultural land). The remainder recharges the groundwater, either by leakage from canals (20 km^3/a) or as irrigation surplus (60 km^3/a). These estimates are based on WAPDA (2009) and Nespak (2009) databases.

MacDonald and Partners (1990) estimated that 79% of the area in Punjab and 29% of that of Sind have ground water that is suitable for irrigation. For these areas, conjunctive use of surface and subsurface reservoirs needs to be pursued much more systematically than in the past. The Indus Basin Model Revised (IBMR) is used as a quantitative tool to analyze the potential of improvements in the combined management of the available surface water and groundwater on the basin scale.

The IBMR model was developed by the Water and Power Development Authority (WAPDA) of Pakistan and the World Bank since the mid-1970s. The model was intended to predict the impact of different projects on agricultural production. It can also be used to predict groundwater and salt flows, waterlogging, groundwater salinization, and irrigation revenues. Mara and Duloy (1984) suggested that large gains in agricultural production and employment are possible, given more efficient policies as well as allocation and management of surface and ground waters. They presented some simulation results using the Indus Basin Model on an efficient conjunctive use for the irrigated agriculture of the Indus Basin, Pakistan.

They recommended enforcement of taxes and subsidies to control groundwater withdrawals. Ahmad and Kutcher (1992) used the IBMR to model the groundwater and salt flows in the Indus Basin. They estimated salt accumulation in the Punjab and Sind regions of Pakistan in both fresh and saline areas. They also analyzed the causes of waterlogging and salinity in the Indus Basin, Pakistan. Leichenko and Westcoat (1993) used the IBMR to conduct climate impact assessment. They considered the potential environmental effects of climatic change and water development in the delta region of the Indus Basin. They evaluated the potential changes in river inflows, canal diversions and groundwater balance under a range of climate change and water development scenarios. In conclusion, they formulated a national policy to restrict flows to the delta and suggested incorporation of climate impact assessment into water development planning. Hai (1995) used the IBMR to measure the impact of specific policy changes on cropping patterns, resource use, output levels, groundwater and salt balances by altering agricultural production technologies and resources. He concluded that sustainable agricultural production can be achieved through improvements in the level of resource use efficiency and careful monitoring of environmental issues. Rehman et al. (1997) developed some insights regarding the agricultural production potential for Rechna Doab, Indus Basin, Pakistan. They used the Indus Basin Model and concluded that an integrated approach is required that should focus on the conjunctive management of surface and ground waters in combination with increasing agricultural productivity — taking into account the deleterious effects of salinity so that increased crop yields can be achieved in a manner that supports sustainable irrigated agriculture. Jehangir et al. (2003) used the Indus Basin Model to assess the future net water requirements at the root zone level in Lower Chenab Canal (LCC) of the Indus Basin. They studied thirteen different scenarios of canal re-allocation to reduce the gap between net requirements and the total supplies in the irrigation system.

The rapid increase of groundwater irrigation over the last three decades has caused over-exploitation of the fresh water stored in the aquifer underlying the Indus Basin. This is evidenced by increased widespread salinization of tube-wells, which endangers the future benefits of the conjunctive use of surface and ground waters. As reduction of these groundwater extractions was deemed necessary and given the dam-related problems described above, it was decided shortly to raise Mangla Dam so that increased water demands could be met and corresponding over-exploitation of groundwater could be reduced.

The measure is the result of the analysis carried out by the simulation-optimization model IBMR, which was restructured and upgraded in the present study. Economic analysis was performed to find the best alternative of dam raising options. The expansion of the dam is currently underway and is expected to be completed in 2010–11. The model was also used to predict the groundwater balance and find optimal solutions for irrigation in the basin. To conclude, 2002 was taken as base year, while simulations for different scenarios span the period 2002–2020.

INDUS BASIN MODEL REVISED

Model description

The IBMR is a large-scale mathematical model for the Indus Basin based on linear programming to maximize benefits and minimize cost. It is written in GAMS — General Algebraic Modeling System (www.gams.com) by using semi-analytical techniques. It consists of about 2500 ordinary differential and algebraic equations and has been used by the World Bank and WAPDA in various studies among which the left bank outfall drain planning, on-farm water management, Kalabagh Dam design (Ahmad et al., 1990), and alternative salinity management projects (Rehman et al., 1997) are prominent (Ahmad and Kutcher, 1992).

The model divides the basin into nine agro-climatic zones (Fig. 2.2). These nine separate zone models are interlinked through a surface-storage and distribution model, which contains the entire system of river reaches, main canals, and groundwater storage, running with a monthly time-step over the reference period (Mara and

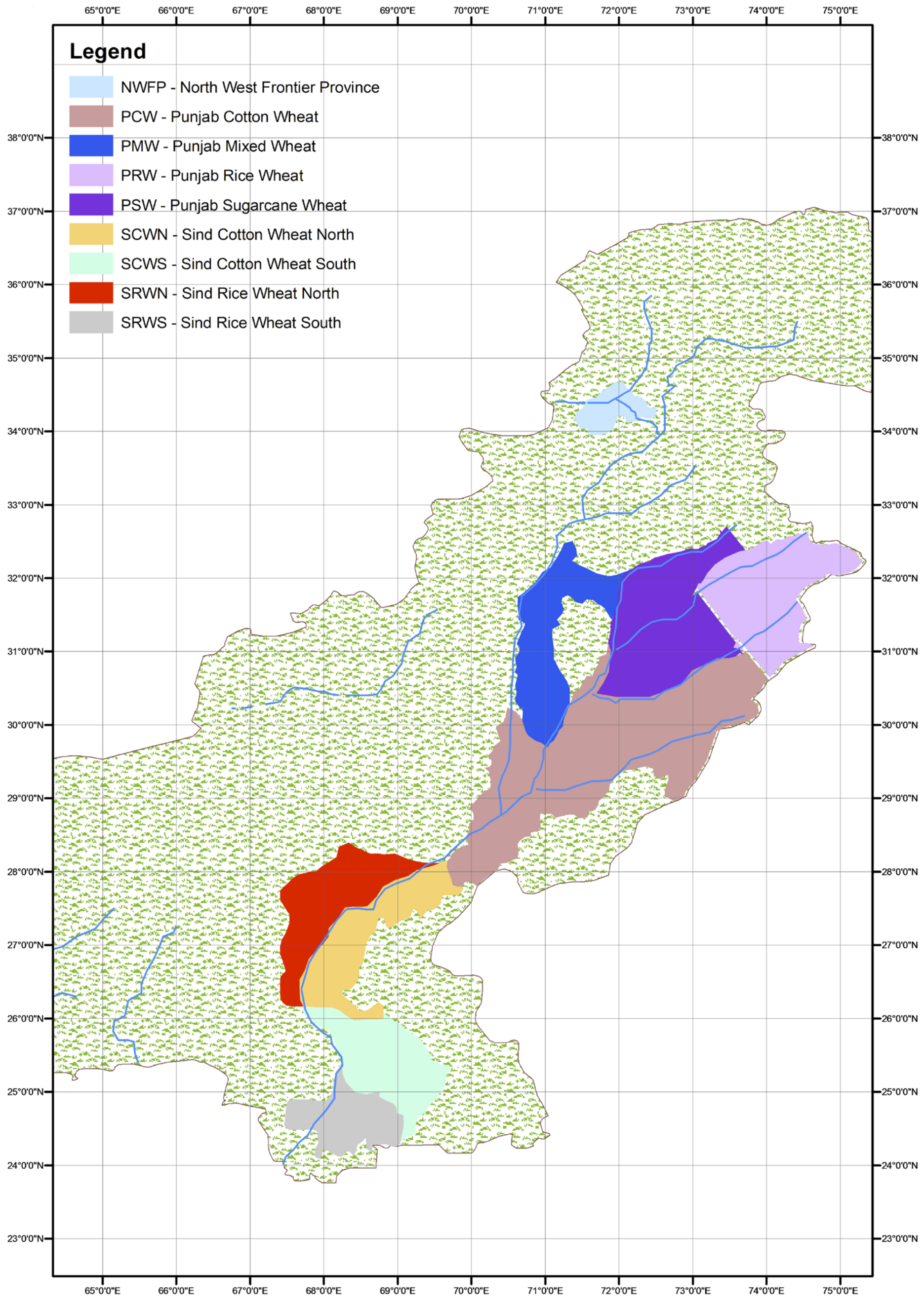


Figure 2.2: IBMR agroclimatic zones of Indus Basin (after International Water Management Institute, Pakistan).

Duloy, 1984). The model simulates recharge to and discharge from groundwater and estimates water balances of the groundwater and surface water reservoirs. The model aims at distributing the available water optimally for agriculture, bearing in mind the groundwater storage and pumping capacity available in each zone. There are nine zone models, that are mapped (combined) into three province models, namely Punjab (containing four zone models: PMW, PCW, PSW, and PRW), Sind (containing four zone models: SCWN, SRWN, SCWS, and SRWS), and NWFP (which is a single zone representing the whole province).

Concept and mathematical background

The IBMR model quantifies the water flows to the aquifer and computes the water budget for each of the nine zones. The groundwater balance can be written as

$$\Delta S = R_r + R_c + R_w + R_p + R_i + R_t - D_e - D_d - D_t - D_x \tag{2.1}$$

where ΔS is the net change in groundwater storage, R_r the recharge due to river seepage, R_c the recharge due to canal seepage, R_w the recharge from water-courses and irrigation fields, R_p the recharge from precipitation, R_i the recharge from lateral flows from adjacent zones, R_t the recharge from tube-well operations, D_e the discharge from evaporation and transpiration, D_d the discharge from subsurface drainage, D_t the discharge by tube-wells, D_x the discharge from lateral flows to adjacent zones (Ahmad and Kutcher, 1992).

The method used in IBMR to estimate evaporation and transpiration is based on Gardner and Fireman (Ahmad and Kutcher, 1992) who estimate groundwater discharge D_e [L] as:

$$D_e = \frac{E \times 10.637}{H^{2.558}} \tag{2.2}$$

where E is evaporation [L] and H is depth to the water table [L]. Because the zones are mostly separated by rivers, lateral movement between adjacent zones is negligible, i.e., only about 2% of the volume of annual groundwater recharge (Ahmad and Kutcher, 1992). IBMR computes the water table depth H_t [L] as:

$$H_t = H_{t-1} + \frac{\Delta S}{A \times c} \tag{2.3}$$

where A is total area and c is the phreatic storage coefficient. The evaporation and the water table depth are interrelated variables as shown by Eqs. (2.1)-(2.3); and are computed iteratively. D_e is computed from Eq. (2.2) given H_{t-1} [L], which is then used to compute H_t from Eq. (2.3). The new estimate of D_e for the next iteration is made using the average of H_t and H_{t-1}. H_t is calculated again using Eq. (2.3) and this procedure is repeated until the convergence of H_t and D_e (Ahmad and Kutcher, 1992).

Model reformulation

The IBMR model was reformulated and upgraded in the current study. The reformulation includes water allocations in accordance with Water Apportionment Accord 1991 (an agreement between provinces regarding distribution of water), multi-objective reservoir's operation and decision making, and Mangla dam raising aspects.

The updated IBMR represents hierarchical two-stage decision making — termed as multi-level programming. This formulation can be generalized as: the objective of decision making at the highest level (government) is to select a plan of action that optimizes its objective subject to rational reactions by the stakeholders at the lowest level, i.e., the farmers. The model contains nodes to distribute surface water according to the requirements of representative farms. The network is used to develop efficient water allocation schemes to optimize the regional use of available water resources. This necessitates knowledge of the water requirements of individual farms. Water use on the level of individual farms needs to be modeled, as farmers react without recognizing their individual impact on the (future) groundwater system and freshwater yields. Also, for this reason, the government should monitor the long-term consequences of water allocation schemes and investments (Bisschip et al., 1982) to ensure predictions keep up with actual developments in the water resource, water demand and actual water use. This multi-level structure of the IBMR model can mathematically be written in abstract form as follows

$$Q_{21}z + Q_{22}x = d_2, \quad x \geq 0 \tag{2.4}$$

$$\begin{aligned} &\{\underset{z|(x,j)}{Minimize}\ k^T z + j^T z, \\ s.t. \quad &Q_{11}z + Q_{12}x = d_1, \quad z \geq 0\} \end{aligned} \tag{2.5}$$

where x is a vector which can be thought of as a list of all parameters to be optimized at the top level such as water allocations; z is the response by stakeholders optimized for their short-term benefit; j is taxes and/or subsidies; d_2 and d_1 are vectors of available water resources at the highest and lowest levels respectively; k is a vector of expenditure and prices; Q_{21}, Q_{22}, Q_{11} and Q_{12} are physical constraints and those due to policies of government and response of stakeholders at the top and bottom of the decision-hierarchy. Eq. (2.4) is the objective function at the top level (i.e., government), which describes allocation of water with respect to the constraints as of Eq. (2.5); and Eq. (2.5) is objective function at stakeholder level, which describes the demand of water by representative farms. Both have to be optimized in conjunction to maximize the economic value produced under the restrictions of available water resources and limitations of the distribution system, which now includes groundwater as an extra reservoir (Bisschip et al., 1982).

Model inputs

The IBMR encompasses agriculture, irrigation, economics, and hydrology components. Therefore, the required data were obtained from various institutions such as the IRSA (Indus River System Authority), PMD (Pakistan Meteorological Department), NARC (National Agriculture Research Center), PCRWR (Pakistan Council of Research in Water Resources), MINFAL (Ministry of Food, Agriculture and Livestock, Government of Pakistan), FBS (Federal Bureau of Statistics), PC GOP (Planning Commission, Government of Pakistan), WAPDA (Water and Power Development Authority), IWMI (International Water Management Institute), SOP (Survey of Pakistan), NESPAK (National Engineering Services of Pakistan), ASP (Agricultural Statistics of Pakistan) and then much data processing was carried out. The IBMR model was then used to simulate potential agricultural production and net economic benefits over the period 2002–2020, through optimization of water availability in surface and groundwater reservoirs (Alam, 2003).

RESULTS AND DISCUSSION

Economic appraisal

The model was used to determine the level of increase of the crest level of second largest dam in the Indus Basin, the Mangla Dam (latitude 33°8′32″N and longitude 73°38′40″E). The analysis showed that raising the dam by 9 m and 12 m would increase water availability in the Indus Basin by 68% and 76%, respectively. The IBMR model has been used to determine the expected additional irrigation revenues. The cost of the 9-m and 12-m raising alternatives was estimated at about US$ 520 million and US$ 645 million, respectively, with annual operation and maintenance expenditure of about US $ 3.1 million (Nespak, 2003). The final dam height increase decision was 9 m, which was based on the economic internal rate of return (EIRR) for the two dam levels and four different financial scenarios (Fig. 2.3). The actual groundwater use has increased the EIRR of the 9-m dam height increase relative to the 12-m option because of the relatively low cost of surface storage and more direct benefits to the farmers. This has been a consequence of including groundwater in the IBMR model.

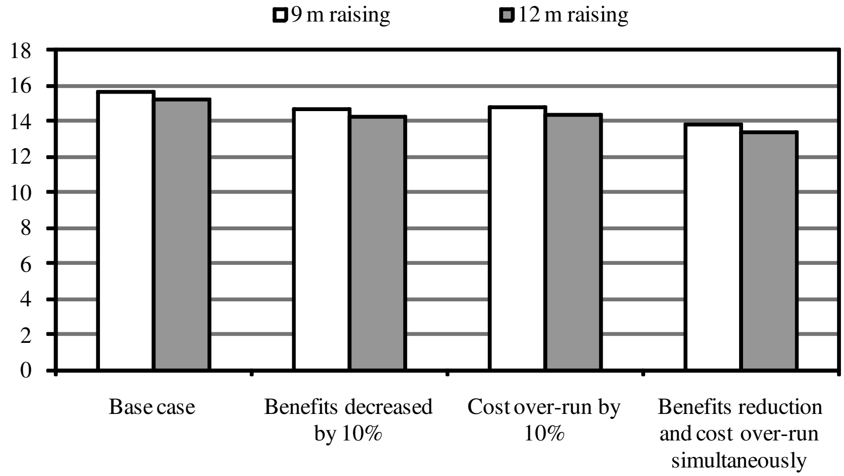


Figure 2.3: Economic internal rate of return — EIRR (%)

Groundwater balance

Table 2.1 depicts the net balance of the groundwater of the seven affected zones in the Indus Basin (Eq. 2.1) for 2002 and the year 2020, with and without the increase of the height of the Mangla Dam by 9 m. The year 2002 was a very dry year with large depletion of the groundwater volume due to intensive pumping. In contrast to this, year 2020 in the model simulations uses average weather conditions, so that the net volume taken from groundwater is less than 2002, despite increased demands. The table also compares the situation in 2020 with and without the increase of the height of the Mangla Dam. The groundwater availability benefits all zones, except SRWN where the growth of the number of tube-wells outperforms the increased supply of irrigation water apart from the raised dam. The significant change appears in zone PSW, in which inflow would be increased by 4.3% and outflow decreased by 7.1% by 2020. To conclude, inflows would be increased by 1.1% and outflows decreased by 2.6% to the aquifer underlying the Indus Basin. In total, the increase of the dam height by 9 m is predicted to generate a saving of around 2 km^3/a of groundwater, which by itself reduces the deterioration of the valuable groundwater resource caused by salinization and increase of the pumping cost.

Waterlogging

A positive groundwater balance signals a rising water table, providing a rough estimate of the magnitude and the change in waterlogging (Leichenko and Westcoat, 1993), a severe problem in the Indus Basin. A negative groundwater balance in 2002 in the zones PCW, PSW, PRW and SCWS suggests the risk of severe over-exploitation. These zones can be improved by raising the dam, the table indicates this for the zones

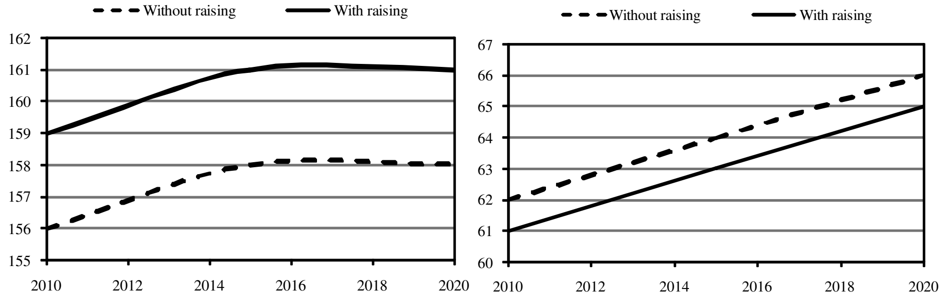
Table 2.1: Groundwater balance components (km^3) in agroclimatic zones between 2002 and 2020 — with and without scenarios of 9 m raising of the Mangla dam (Figure 2.2 for zone description and spatial reference).

Scenarios	**Components**	**PCW**	**PSW**	**PRW**	**SCWN**	**SRWN**	**SCWS**	**SRWS**
Base case: 2002	Recharge	24.2	9.45	7.37	9.41	6.93	6.24	5.3
	Discharge	30.85	15.37	14.55	8.46	5.99	6.83	4.76
	Groundwater balance	−6.66	−5.91	−7.18	0.94	0.94	−0.59	0.54
Without dam raising: 2020	Recharge	28.18	11.28	8.04	9.92	8.18	6.77	5.27
	Discharge	30.77	12.41	12.33	9.4	6.63	6.95	4.76
	Groundwater balance	−2.59	−1.13	−4.29	0.52	1.55	−0.18	0.52
With dam raising: 2020	Recharge	28.09	11.77	7.99	9.93	8.11	7.35	5.38
	Discharge	29.65	11.53	11.42	9.26	6.94	7.29	4.76
	Groundwater balance	−1.56	0.24	−3.43	0.67	1.16	0.05	0.62

PSW and SCWS. The performed study suggests as the following water management options: (1) to extract the groundwater from zones having a positive balance, and (2) to restrict groundwater abstraction from the zones that are already over-pumped to increase their subsurface storage. These suggestions can of course only be realized with well-planned enforced pumping schedules at different spatial scales through taxes and subsidies. Implementation of such measures would take a number of years.

Optimization of irrigation under conjunctive use

The IBMR model was designed to use surface and ground waters conjunctively. It optimizes the surface and subsurface stocks to maximize revenues, by evaluating the farmer's actions in response to government policies to allocate surface water and regulate or stimulate groundwater use. The country's water demands are projected to increase from 205 to 240 km^3 between 2002 and 2020 (simulated demand as per the model, keeping growing population needs). Increase of surface water availability



(a) Surface water (b) Groundwater

Figure 2.4: Simulated water use (km^3) trend under the conjunctive regime.

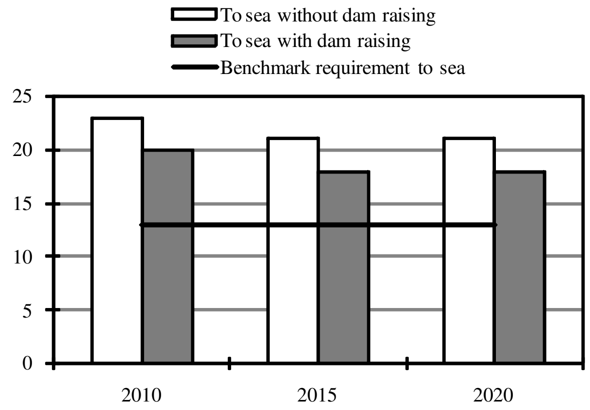


Figure 2.5: Outflow to sea (%) against benchmark requirements.

would decrease reliance on groundwater. The simulated surface and groundwater use as projected by the model [Figs. 2.4(a) and 2.4(b)] predicts this for the coming years. Conserved groundwater can be utilized in future, to increasing food security during dry periods. The model also depicts that basin outflow to the ocean will be reduced by about 14% by raising the dam, which is a net increase of available amount of irrigation water (Fig. 2.5).

SUMMARY AND CONCLUSIONS

Pakistan must achieve extra storage, because sedimentation has reduced the storage capacity of reservoirs in Pakistan by over 20%, while water demands are increasing. As development of new dams is very difficult owing to social, political and environmental concerns, enhancing the capacity of existing reservoirs is a good alternative, but cannot provide a complete solution. Conjunctive use with groundwater is necessary, thus utilizing the freshwater leakage into the naturally salt aquifer that has occurred and has taken place since the beginning of surface water irrigation around 1870. The EIRR analysis recommends to increase the height of the Mangla dam by 9 m. This increases its live storage capacity by 3.5 km^3, which is about 68% of the current storage capacity (Nespak, 2003). The model predicts additional annual benefits of about US$ 98 million by 2020 (Fig. 2.6). The groundwater balance indicates that over-exploitation of groundwater in agro-climatic zones of Punjab would reduce significantly. Consequently, an extra saving of about 2 km^3/a of groundwater will enhance its future utilization. The IBMR model is now a proven tool to optimize the use of Pakistan's water resources available from different sources in economic terms and suggests the policy guidelines. The IBMR-based techniques

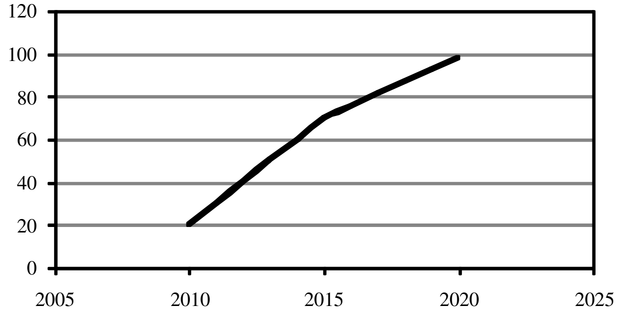


Figure 2.6: Additional irrigation revenues (million US $) due to dam raising.

can generally be applied to the other irrigation systems operating in semiarid and arid environments.

CHAPTER 3

Site description and measurements

ABSTRACT

Time-domain electromagnetic (TDEM) is useful in mapping sand and gravel aquifers, clayey layers restricting groundwater flow, salt water intrusion, vertical profile of electric resistivity of subsurface, and depth to bedrock. TDEM involves generating an electromagnetic field that induces a series of currents in the earth at increasing depths over time. These currents, in turn, create magnetic fields. By measuring these magnetic fields, subsurface properties and features can be deduced at great depths. A field campaign was carried out in one of the representative doabs of the Pakistani Punjab (Indus Basin aquifer) in 2010–11, in which about 600 TDEM soundings were undertaken at 14 sites. The objective of this survey was to estimate the spatial and vertical distribution of the groundwater salinity for onward use in groundwater models as well as to explain the current saltwater distribution in terms of groundwater history and extraction of freshwater. This chapter concludes that fresh groundwater ($EC \leq 1.5$ dS/m) was not available in the central area of the doab except at locations Chak 31 and 142sb where it was present in a layer of thickness of about 15–20 m; groundwater of only marginal quality ($EC \leq 3$ dS/m) barely suitable for irrigation was available up to a maximum depth of about 35 m. The surveyed sites Luck and Seeray that are close to the river Chenab, and therefore, had fresh groundwater available over the entire depth of the investigation. The presence of high levels of groundwater salinity in the central areas of the doab, just few meters below the screen of wells, make them highly vulnerable for the agricultural use even if these wells are shallow-depth skimming wells. This is concluded on the basis of the geophysical monitoring of skimming wells in the Punjab.

INTRODUCTION

The Time-Domain Electromagnetic (TDEM) method has been used in different forms for subsurface exploration since many decades. Improved electronics, development of efficient and effective field equipment nowadays integrated with computer interpretation such as tomography allow users to acquire high-quality data over depths down to several hundred meters and more. TDEM techniques have several advantages over the more traditional Direct Current (DC) resistivity technique. TDEM does not require large electrode arrays whereas DC resistivity requires long electrode spreads with lengths that ranges between 3 and 5 times to the depth of exploration; therefore, the investigation of depths to 100 m requires an area of around 300 m for placing electrodes. To the contrary, TDEM techniques can easily attain depths of exploration up to approximately 100 m with a 25-m transmission loop.

The TDEM method is a geophysical technique, which, through measurements at the ground surface, enables obtaining the vertical distribution (one-dimensional depth layering) of the electrical resistivity of the formations in place. It provides a gross approximation of an electrical log as performed in a borehole without the expense of drilling and logging. Since formation resistivity is a function of formation lithology, porosity, and pore fluid conductivity; the in-situ determination of formation resistivity offers a means to infer the quality of groundwater by using physical and/or empirical relationships.

The Chaj Doab is an area enclosed between the rivers Jhelum and Chenab. It is one of the most intensively developed and productive irrigated areas of the Indus Basin (Fig. 3.1). Its gross command area is about 1 million hectares, out of which 87% forms the culturable command area. It has two main irrigation canal systems called Upper Jhelum Canal and Lower Jhelum Canal systems. These systems were designed to supply 4.4 km^3/y to the area. The soils of the area range from coarse to moderately fine sand, with a predominance of moderately coarse-textured soil classes (Sarwar et al., 2004). The climate of the area is subhumid in the north to semiarid in the south and is characterized by a large seasonal variations in temperature, rainfall and evapotranspiration.

Because the irrigation water demand exceeds the available supply of canal water, farmers use groundwater as an additional source for irrigation. Currently, farmers are extracting groundwater through wells, which combined pump approximately 4.9 km^3/y (Sarwar et al., 2004). To control waterlogging and to meet irrigation water demand, 138 public wells, having depths between 60 and 75 m were installed during the 1970s. But, most of them had to close at the request of farmers because the salinity of the pumped groundwater, which increased over time, had reached unacceptable levels. As a consequence, farmers shifted to installing shallow skimming wells, with

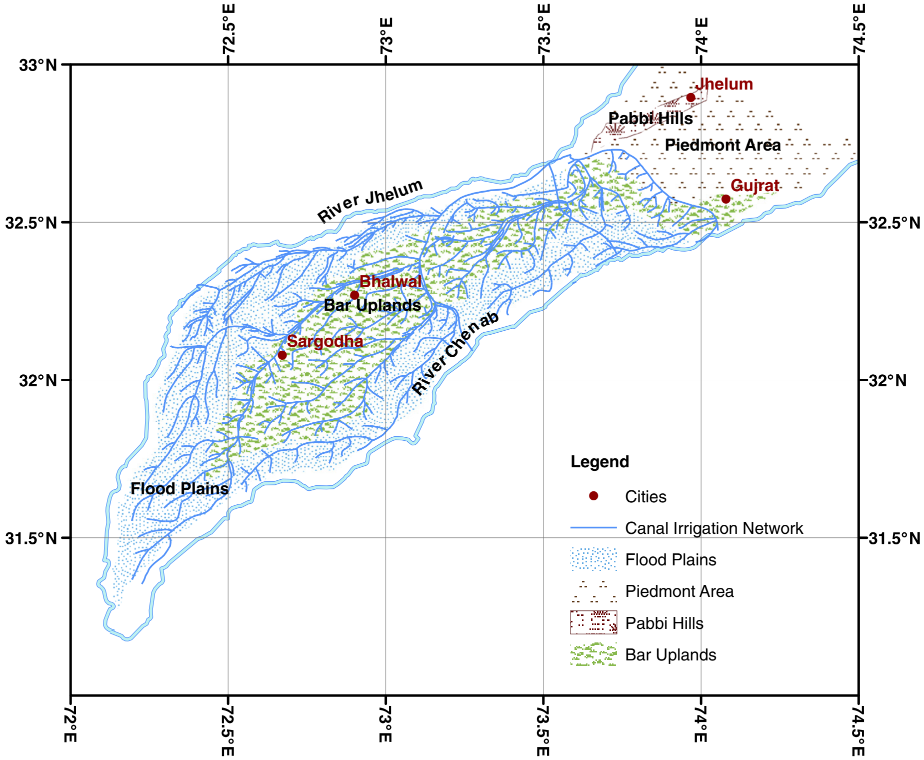


Figure 3.1: Chaj Doab, its physiographic units and canal irrigation network (after Kidwai [1963] and PID [2010]).

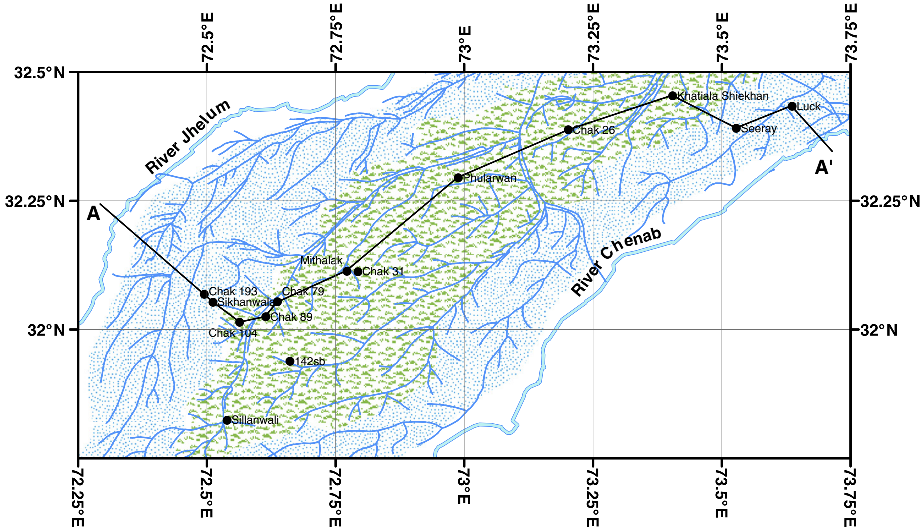


Figure 3.2: Fig. 3.1 is zoomed in for a close-up to show the TDEM surveyed sites, where black dots represent the survey sites.

screen depths between 10 and 40 m that pumped up groundwater with salinity much less than the previously installed public tubewells (Saeed and Ashraf, 2005; Saeed et al., 2003b).

The objective of this chapter is to explore the vertical profile of the electrical resistivity of subsurface by geophysical measurements. This electric resistivity distribution indicates the thickness of groundwater layers having freshwater or brackish water as well as depth to salt water. Because of the similarity of the Punjabi doabs, we assume that the Chaj Doab is representative for the Punjab aquifer in general.

This chapter aims to provide a comprehensive summary of the field procedures, data acquisition technique and interpretation method applied with approximately 600 TDEM soundings undertaken at 14 sites throughout the Chaj Doab. Figure 3.2 shows the locations of the 14 sites.

HYDROGEOLOGICAL BACKGROUND

The area of the Chaj Doab is about 1.3 million hectares between longitudes 72°00′ – 74°15′E and latitudes 31°00′ – 33°00′N (Fig. 3.1). The principal cities are Jhelum, Gujrat and Sargodha; agriculture is the major economic activity. The natural surface gradient of Chaj Doab ranges from about 0.4 m/km in the northeast to 0.2 m/km at the southwest and averages about 0.3 m/km, excepting for the piedmont areas (Fig. 3.1). The central area of the doab is called the “Bar Uplands” and is bounded on either side by the “Flood Plains”. This central area is about 2–10 m higher than the adjacent flood plains. Studies such as Kidwai (1963) and Greenman et al. (1967) describe the geology and hydrology of the Punjab respectively; the deposition of alluvium by rivers of the Indus River system and its ancestral tributaries remained continuous throughout the Pleistocene age. Depth to bedrock is unknown in the Punjab. The alluvium contains medium sand to silty clay, but sandy sediments predominate (Greenman et al., 1967). Based on his drilling campaign in 1950s and 1960s, Kidwai (1963) concluded that the alluvium is present throughout the Punjab to at least the depth of about 450 m. The exact depth of the aquifer is unknown; as no test well was ever drilled deeper than 450 m, no one has reached the bedrock. Hydraulic characteristics were determined by field and laboratory methods; pumping tests were also carried out (Bennett et al., 1967). These tests established conclusively that the aquifer is in effect regionally an unconfined system (Alam and Olsthoorn, 2014b; Bennett et al., 1967).

The groundwater near the center of the doabs is naturally salt as the rivers in this part of the Indus Basin infiltrate, so that the evaporation from the doab causes an accumulation of salt water towards its center. However, the large-scale surface-water irrigation schemes have over time leaked so much water, that it together with irrigation return flow, has become a source of freshwater to local famers. The saline zones in the Chaj Doab coincide to a large degree with the boundaries of the bar uplands (central zone) that are 2–10 m higher than the adjacent river-abandoned flood plain. The flood plains adjoining the bar uplands are locally low enough to be subjected to periodic inundation by flood water, some of which infiltrates to join the groundwater. But the height of the interfluves prevent direct recharge of the flood waters. Moreover, climatic conditions result in the relative stagnation of groundwater under flat hydraulic gradients beneath the bar uplands and increasing mineralization in the direction of flow. The distribution of fresh and saline groundwater zones is locally controlled by the presence of clay deposits within the alluvium. If these are situated in proximity of the river, they may effectively reduce recharge and restrict the circulation of freshwater (Greenman et al., 1967).

MATERIALS AND METHODS

TEM-FAST 48 HPC

TEM-FAST 48 HPC is a portable TDEM equipment developed by the AEMR Ltd. (http://www.aemr.net), which was used in the present work. It provides the possibility to start the measurements of the decay from 4 μs, which determines the minimum time of registration of a signal. This parameter distinguishes this device from the other available equipments in the market (TEM-FAST, 2006).

Field procedure

The field procedure involves placing a loop of wire or antenna typically 25 × 25 m at ground surface. A steady current in the transmitter loop is abruptly turned off to initiate a changing magnetic field. This creates a magnetic pulse or transient in the ground. Measurements are carried out with the same transmitter loop. The receiver electronics average the signal over tens or hundreds of repetitions to increase the signal-to-noise performance of the instrument. Data were recorded digitally for further processing and interpretation. A portable computing device was used to monitor the signal and its processing in the field, the condition of the equipment, data quality and signal stacking to provide the best signal-to-noise ratio. Electromagnetic noise was also measured, which is important in data averaging or filtering. To ensure the quality and stability of the data, experimental curves were taken twice at some locations.

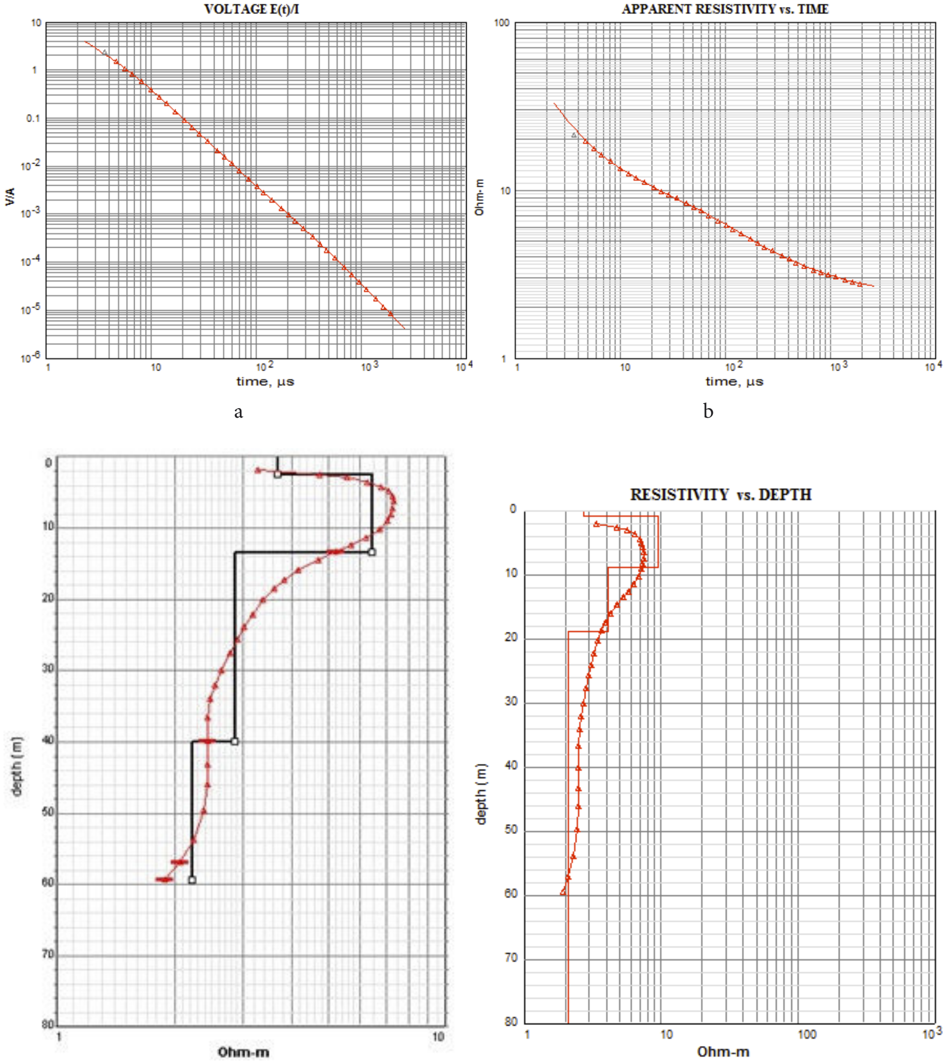
Data processing

The selected locations were mostly rural and were free from any type of major noise. However, some experimental curves recorded noisy data that affected the late-time registrations of the transient signal. Some experimental curves also suffered from subsurface-induced polarization, which also affected the late-time data. Only distortion-free data were used for the inversion to determine the resistivities. Data acquired by TEM-FAST instrument was processed by using TEM-RES program (TEM-RES, 2007), which intends to model and interpret the experimental curves as obtained by using the TDEM device.

Interpretation

A typical example of the results is shown in Fig. 3.3; inversion along with transformation and apparent resistivity curves of all soundings are recorded in Alam (2011). Given the geology of the study area, i.e., layered groundwater system, the models normally satisfy the observations with a relatively small number of layers, usually between 3 and 5.

A single-loop configuration as adopted in TEM-FAST ensures a minimum influence on measurements, therefore data interpretation within a 1-D model class gives quite satisfactory results (Barsukov et al., 2007). A hypothetical layered earth model is generated and then the theoretical response for that model is calculated. The model is then refined until the calculated response matches the observed or measured field response. The model refinements can be made using an automated iterative process called "inversion". Fig. 3.3(a) shows the decay of the magnetic field over seven decades during the course of the recording from 4 µs to 2,000 µs. Fig. 3.3(b) shows a plot of the same data converted to "late-stage" apparent resistivity. The values of resistivity and layer thickness are calculated by minimizing the misfit between the calculated and experimental data while taking into account the measurement accuracy as well as any a priori information. The determination of the initial model is based on the available information about the smooth section or pseudo-section $\rho(h)$ as shown in Fig. 3.3(c). The horizontal red markers in the curve correspond to the depths, where the second derivative of $\rho(h)$ is equal to zero (knee points). The smooth red curve is the transformation and represents the approximate inverse image of the measurements towards a resistivity versus depth profile and the black vertical line is the starting model. Fig. 3.3(d) shows the model geoelectric section used to calculate the model response. The piece-wise homogeneous plot represents the 1-D layered model (geoelectric section) that optimally interprets the measurements and produces the late-time apparent resistivity response as shown in Fig. 3.3(b).



a

b

c

d

Figure 3.3: TDEM interpretation process, which models a geoelectric section.
(a) Decay of magnetic field.
(b) Apparent resistivity [ohm-m] as a function of time [μ-sec]. The bullets represent the late-time apparent resistivity (raw data) and the continuous red curve represents the response of the layered 1-D model, which interprets the measurements and is shown in (d).
(c) Determination of the initial model in 1-D inversion. The horizontal red markers in the curve correspond to the depths, where the second derivative of $\rho(h)$ is equal to zero (knee points). The smooth red curve is the transformation and black vertical line is the starting model.
(d) Modeled geoelectric section. The smooth curve is the transformation and represents the approximate inverse image of the measurements towards a resistivity versus depth profile. The piece-wise homogeneous plot represents the 1-D layered model (geoelectric section) that optimally interprets the measurement and produces the late-time apparent resistivity response as shown in (b).

Hydrogeological interpretation of the subsurface resistivity

It is generally known that the subsurface resistivity may vary over a wide range. In the doabs with so much brackish and salt water, salinity is dominating the *EC*-profiles while the *EC* of the Punjab formation itself does not vary between wide ranges. Based on this finding, it is impossible to translate an interpreted geoelectric log of resistivities into a useful information regarding subsurface salinity without an independent source of information, such as, groundwater samples and geological logs. The relation between groundwater resistivity and electrical conductivity was measured by Sikandar et al. (2010) in the Chaj and Rechna Doabs; they derived the relation in equation (3.1) between resistivity and electrical conductivity of their groundwater samples:

$$\sigma_{gw} = -1.035 \ln \rho + 5.43 \tag{3.1}$$

where σ_{gw} is the electrical conductivity (*EC*) of the groundwater (dS/m) and ρ is the resistivity of the formation (ohm-m).

To map groundwater suitable for irrigation in the Punjab (Indus Basin), the Water and Power Development Authority (WAPDA) of Pakistan has classified the criteria as defined in Table 3.1. Using their criteria and the correlation developed by Sikandar et al. (2010), the interface between fresh and brackish groundwater zones as well as between brackish and salty zones can be established. These relationships were validated with the groundwater quality data collected by WAPDA during previous years as well as with *EC*-logger registrations in the current work.

Table 3.1: Groundwater suitability criteria (after WAPDA [2012]).

Description	Groundwater *EC* [dS/m]	Groundwater quality
Usable	≤ 1.5	Freshwater
Marginal	1.5 – 3.0	Brackish water
Hazardous	> 3.0	Saltwater

RESULTS AND DISCUSSION

A summary of 600 TDEM investigations undertaken in the Chaj Doab is presented in this section. The summary includes the results of geoelectrical inversions that yielded vertical resistivity profiles which could then be translated into the groundwater *EC* using the relation as mentioned in the previous section. The *EC*-profiles indicate the thickness of the freshwater zone, the brackish water zone and the depth to the salt water in the selected locations of the Chaj Doab. The details of the experimental curves are recorded in Alam (2011) along with their interpretations.

Standard TDEM interpretations are based on subdivision of the subsurface in distinct layers, as it is usually in agreement with the layered structure of formations consisting of sediments. In the case where the formation resistivity is dominated by salinity of the groundwater, this may not generally be valid a priori, since the expected salinity distribution may be more gradual and less layered. However, it is generally not possible to determine a smooth resistivity-depth distribution from TDEM profiles, due to equifinality issues. In such cases, the resistivity-depth curve, which is derived directly from the apparent resistivity versus time curve registered by the TDEM device, may represent the subsurface resistivity depth distribution better than the layered inversion. This means that the smooth curve in Fig. 3.3(c)-(d), as derived directly, i.e., in the field, from the curve in Fig. 3.3(b), may be more realistic than the interpreted layered inversion that is also shown in Fig. 3.3(d). Therefore, when interpreting the TDEM in the Punjabi situation, we have to both regard the smooth curves and their layered inversions (chapter 7, where both the smooth resistivity-depth curve and interpreted layered inversion was used).

Table 3.2 gives a summary for all 14 sites, with name, location, the results of the geoelectric inversions, i.e., number of modeled layers, the derived thickness of modeled layers and their formation resistivities. Note that model here means the inversion model of the resistivity profiles, which basically corresponds with thickness of the unsaturated (dry), the fresh and the brackish zones and the depth to the salt water. It has nothing to do with groundwater model layers and very little with geological layers.

The depth to saltwater could be determined at 12 sites. The other two sites, i.e., Luck and Seeray, did not show saltwater down to the investigated depth of about 100 m. This was expected, because these two sites are (1) in the upper part of the doab, and (2) near to the river Chenab (Fig. 3.2). The upper part of the doab has more recharge, and the groundwater near the rivers is generally fresh to great depths because these rivers continuously infiltrated, at least in the past, causing any saltwater to be pushed down over several hundred meters (Greenman et al., 1967). This situation was, therefore, confirmed at these sites with this TDEM campaign. The TDEM surveyed sites in the central region of the doab except sites ‘Chak 31’ and ‘142sb’ did not show any fresh groundwater; these sites are highly salt-contaminated. This too corresponds to the original situation, in which the combination of infiltration from the rivers and evaporation throughout the doab causes accumulation of the saltwater towards the center and lower parts of the doab (Fig. 3.5). The presence of fresh groundwater at the sites “Chak 31” and “142sb” deviates from the general pattern in the original doab, which suggests local factors, i.e., recharge of freshwater

Table 3.2: Summary of geoelectric inversions. The presented values are based on the average of all soundings belonging to each site.

Longitude	**Latitude**	**Site (Nr of TDEM soundings)**	**Resistivity of the layers**						**Thickness of the layers**					
			Ohm-m						**m**					
			ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	t_1	t_2	t_3	t_4	t_5	t_6
72.77218°	32.11297°	Mithalak (78)	6.5	38	4.2	2.2	1.9	–	2.2	12	8.5	11.8		
72.79327°	32.11251°	Chak 31 (28)	13.75	78	15	10	5.33	2.95	4	16	11	11.37	3.97	
72.66118°	31.93802°	142sb (56)	13	41.5	4.59	1.83	1.22	1.27	4	20	6.38	5.73	1.82	
72.49477°	32.06803°	Chak 193 (15)	4.5	22.5	35.01	14	9.41	–	1.75	24.5	22	32		
72.51159°	32.05325°	Sikhanwala (36)	26	21	17	4	–	–	9.5	11.5	13.5			
72.9884°	32.29464°	Phularwan (129)	4	22.5	10	9	9.9	3	1.5	11	31	38.25	37.5	
72.636936°	32.053626°	Chak 79 (4)	13	28	15.75	–	–	–	4	30.5				
72.614327°	32.024851°	Chak 89 (4)	8.5	32	10	4	1.3	–	3	14.5	9	15		
72.563445°	32.014255°	Chak 104 (4)	12	26	3	–	–	–	2	36				
72.539252°	31.824074°	Sillanwali (8)	27.5	32	24.5	3.5	–	–	7	6.75	22.75			
73.6367°	32.43299°	Luck (48)	43.5	117	36	164	150	–	10.5	14.5	28	14.25		
73.52827°	32.39064°	Seeray (99)	34	91.5	37	75	47	–	8	19	30.5	20.25		
73.40459°	32.45367°	Khatiala Shiekhan (56)	12	41	12	100	–	–	4	19	10			
73.20178°	32.38797°	Chak 26 (66)	14	146	22	19	6	2.25	4	17.25	17	26.5	13.75	

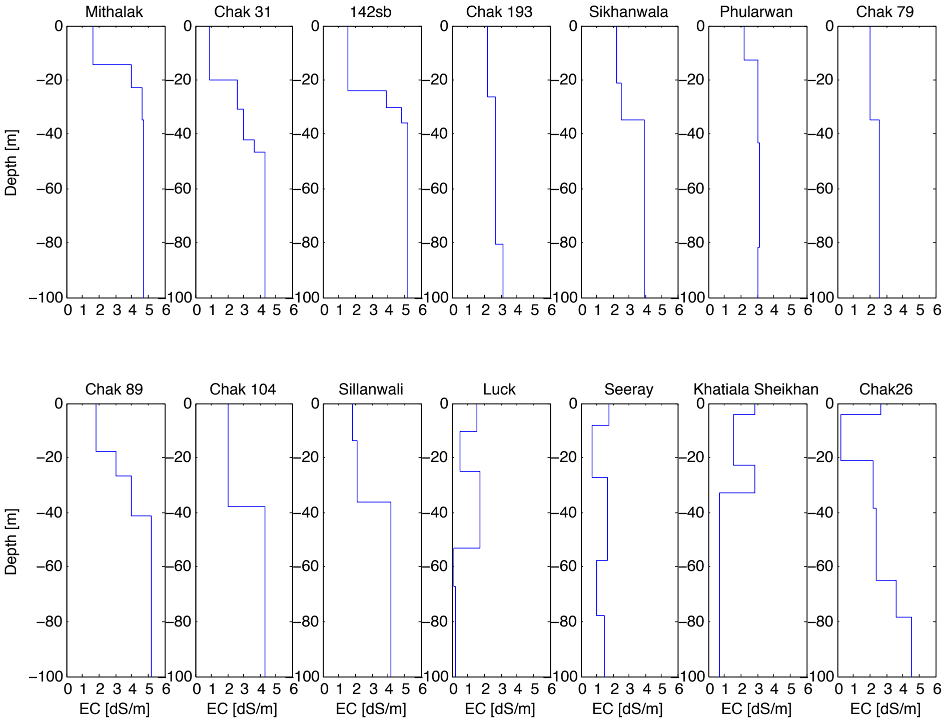


Figure 3.4: Vertical profiles of the groundwater salinity at specified locations in the Chaj Doab (Refer to Fig. 3.2). *EC* is the electrical conductivity of the groundwater that is translated from the geoelectric sections.

by leakage of irrigation canals and irrigation return flow. Brackish groundwater, however, was observed at all sites except Luck and Seeray, which are near to the Chenab river.

Figure 3.5 shows a cross-sectional view along line AA′ in Chaj Doab (refer to Fig. 3.2 for cross-sectional location). It can be observed from the cross section that the fresh groundwater below the rivers was available up to the entire depth of investigation. The infiltration of the freshwater from the rivers is largely downward and outward towards the central area of the doabs. This infiltration of river water together with evapotranspiration are the main causes forcing the native deep saltwater into shallow layers at the center of the doab, as it is evident from Fig. 3.5. On the basis of 158 test holes in the Chaj Doab sampled in the 1950s, Asghar and Hamid (1960) concluded that the native saltwater is present in a narrow 35 km wide and 70 km long elongated area in the center of the doab, around Sargodha and Bhalwal; the presence of saltwater in the shallow zones of the central and lower parts of the doab can be seen in Fig. 3.5. Groundwater of acceptable quality (< 1.5 dS/m) was found near to sources of freshwater recharge, i.e., canal leakage from Northern Branch is visible at

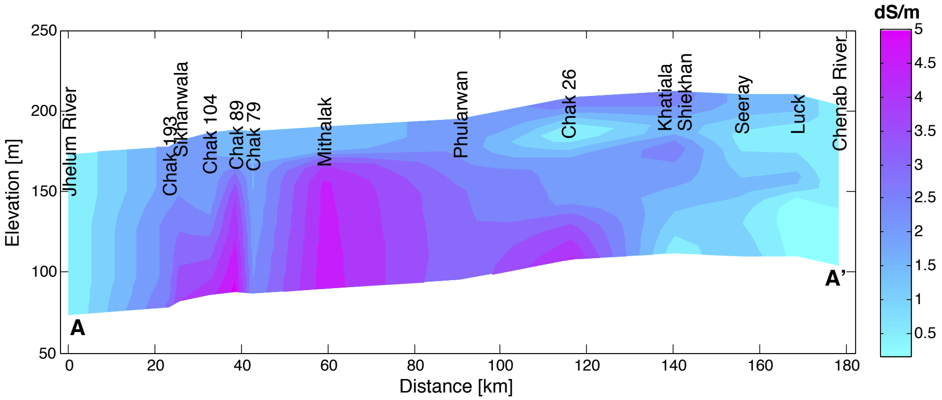


Figure 3.5: Vertical distribution of the electrical conductivity (*EC*) of the groundwater, which is profiled along a section *AA′* (refer to Fig. 3.2).

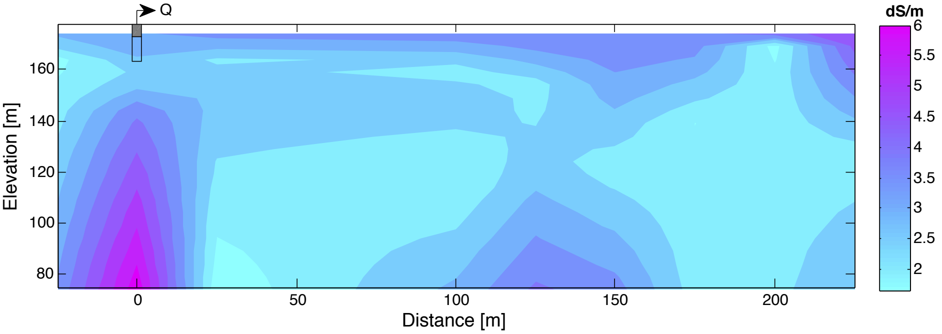


Figure 3.6: Saltwater upconing beneath a typical skimming well in the Punjab. This *EC*-profile is based on TDEM measurements at a farm in Chak 193.

Chak 79 (Fig. 3.5), which is still in accordance with the earlier findings of Greenman et al. (1967).

To evaluate the impact of skimming wells on the depth of saltwater, i.e., indications of upconing, TDEM measurements were also carried out beneath the skimming wells. Figure 3.6 shows the measured *EC*-profile at site Chak 193, about 16 km on the southwest of Sargodha, where TDEM profiles were registered at an interval of 25 m. The figure clearly suggests upconing below the skimming well as indicated. The similar pattern was observed at three other sites with skimming wells, i.e., Chak 31, 142sb and Sikhanwala. There were other sites where the salinity below a skimming well did not show clear upconing, however, this may well be due to the general practice in the Punjab, to relocate wells after they have become too saline. Many farmers possess several wells, that are used in time-staggered fashion. The profile in Fig. 3.6 is likely typical for skimming wells in the Punjab that have been in use for more extended times.

Farmers in the Punjab rely on skimming wells to prevent or reduce rapid deterioration of the groundwater quality. That was also the case at the aforementioned location. However, Alam and Olsthoorn (2014a) showed that skimming by itself cannot prevent salinization of the well, as it is clearly the case in this profile. The depth to water table at that site was 4 m; the actual skimming well had 6-strainers between 6 and 15 m deep. The local sources of recharge to the aquifer are the rainfall and leakage of the freshwater from the irrigation canal system, and to some extent also irrigation return flow. Figure 3.6 shows that saline groundwater has risen below the skimming well. The presence of groundwater with high salinities at shallow depths as indicated in the profile of Fig. 3.5, in fact, just few meters below the screen of skimming wells used in the area, make such wells highly vulnerable for the agricultural use.

This TDEM campaign revealed that (1) the depth to water table varies between 3 and 7 m below ground surface, (2) fresh groundwater ($EC \leq 1.5$ dS/m) was not available in the central area of the doab with the exception of locations Chak 31 and 142sb where it has a thickness of about 15–20 m (Fig. 3.4), (3) in the central part of the doab only a marginal quality of groundwater ($EC \leq 3$ dS/m) is available throughout these sites down to a maximum depth of about 35 m (Fig. 3.4), and (4) sites that are close to the river like Luck and Seeray have only fresh groundwater over the entire depth of the TDEM investigation, which is about 100 m (Figs. 3.4 and 3.5). The fresh-brackish as well as brackish-saline interfaces were not uniform over the doab; their position is expected to depend on groundwater pumping, recharge on local scales, distance from rivers, presence of irrigation canals and its leakage as well as clay content in the subsurface. These TDEM interpretations can be used as input for the initial salinity distribution of local and regional groundwater models (chapter 7).

CONCLUSIONS AND RECOMMENDATIONS

The TDEM technique is an effective method to estimate the vertical salinity distribution of the subsurface; the results can be translated into a model of the geology. TDEM should be validated on the hand of groundwater salinity samples, borehole and borelog information, which is not hard to obtain in the Punjab, as it was done by Sikandar et al. (2010) and Alam (2011). The quality of TDEM interpretations depends to compare them with the relevant independent subsurface information, such as geological and borehole data, groundwater samples and *EC*-logger registration. The principal findings from this TDEM campaign are summarized as follows.

The current TDEM campaign detected mostly four subsurface layers in the Chaj Doab aquifer, which we interpreted as (1) dry material above the water table and a surficial aquifer below it, (2) fresh groundwater in saturated sand and gravels,

Table 3.3: Resistivity ranges of the formation and groundwater salinity.

Resistivity ohm-m	Groundwater *EC* dS/m	Possible quality of groundwater
< 10	> 3.0	Saltwater
10 – 45	1.5 – 3.0	Brackish water
> 45	≤ 1.5	Freshwater

(3) brackish groundwater, and (4) saline groundwater. The range of the formation resistivities used to interpret the groundwater salinity in the Chaj Doab aquifer are given in Table 3.3.

Our TDEM measurements indicate that brackish and saline groundwater occur at depths between a few to perhaps tens of meters below the screen of skimming wells, which make them vulnerable to salinization. The distribution of freshwater and saltwater as determined with the TDEM in 2010–11 is still in agreement with the findings of Greenman et al. (1967), which were concluded in the 1960s. This typical distribution found in all Punjabi doabs is explained by the infiltration from the rivers balancing the evaporation within the doabs, which causes the accumulation of saltwater towards their center. Infiltration of rivers thus drives the deep native saltwater into the more shallow layers in the center of the doabs, as it is evident from Fig. 3.5.

The described campaign was a major effort, however, a modern and the most efficient utilization of this technique can be made through air-borne TDEM geophysics (Viezzoli et al., 2009; Abraham et al., 2012). These air-borne methods provide a full 3D salinity distribution over entire areas in a few days for a low price per unit length of surveyed area. Such methods are probably the only way to obtain a full 3D image of the brackish and salt water distribution and, therefore, of the situation in which the agriculture of the Punjab finds itself today, i.e., being currently dependent on groundwater for additional irrigation and at the same time being plagued by increasing salinities. This situation warrants a careful management of fresh groundwater that originates from canal leakage in areas in which naturally only salt groundwater is present, i.e., the center of the doabs. Such airborne methods are probably essential to come up with consistent areal salt and brackish water management. They are also necessary to monitor area-wide progress or regression over longer periods of time. It is believed, that given the importance of mapping of brackish and salt groundwater, such campaigns deserve or require priority by the Pakistani government. At least our TDEM campaign has shown the feasibility of such mapping.

CHAPTER 4

Re-evaluating the US Geological Survey's pumping tests (1967) in the Punjab region of Pakistan for use in groundwater studies

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ABSTRACT

In 1967, the US Geological Survey (USGS) published the results of 141 pumping tests carried out throughout the Pakistani Punjab to establish representative hydraulic parameters of its large aquifer. Many authors have since concluded that the USGS had over-estimated the horizontal hydraulic conductivity (k_r) by 25–100%, leaving vertical anisotropy and aquifer depth unresolved. No test wells have ever been drilled below 450 m to reach the base of the aquifer, although petroleum explorations mention depths between 1,500 and 4,500 m. After comparison and re-evaluation of all related papers, this study concludes that the USGS interpretation was correct, that its hydraulic values still stand without change, and that the USGS's applied distance drawdown interpretation is valid to prevent influence of partial penetration on the results. This study also uniquely resolved vertical anisotropy and aquifer thickness by using early- and late-time drawdowns separately and proper scaling of the coordinates, which has often been omitted. With appropriate scaling, all interpretations match the data. The representative hydraulic aquifer values are: $k_r = 65$ m/d, vertical anisotropy $k_r / k_z = 25$ and aquifer depth 500–1,500 m. The conclusion is that these values can be used, at least as first estimates, for groundwater studies in the Pakistani Punjab.

INTRODUCTION

Punjab is the breadbasket of Pakistan where groundwater is very important. Assessment of groundwater resources requires models with aquifer parameters that cannot today be determined on a regional scale due to the influence of intense human activity on the natural hydrological system of the area. Therefore, researchers often refer to the original pumping tests carried out by the US Geological Survey (USGS; Bennett et al., 1967) in the 1950s and 1960s to obtain representative values for the Punjab. These tests have been re-evaluated by different authors, who have caused confusion by concluding that Bennett et al. (1967) had consistently over-estimated horizontal hydraulic conductivity (k_r) by 25–100%. This study reviewed all published papers and reports regarding pumping tests in the Punjab. Contrary to those previous findings, this study concludes that USGS did an accurate job and thus their values should be used as being representative on a regional scale.

Assessing hydraulic properties of the Punjab aquifer in Pakistan was one of the facets of the hydrological investigations carried out between 1954 and 1963. Extensive pumping tests were carried out to ascertain the state of the aquifer and to quantify its hydraulic parameters. Bennett et al. (1967) provided a comprehensive summary of their analysis. The work consolidated the research that had been carried out over a decade. Their results have since been widely used in many reports. The horizontal conductivity of the alluvial sediments was determined from 141 pumping tests done throughout the Punjab. Screens 30–60 m long were used, with tops between 25 and 45 m below ground surface. Bennett et al. (1967) determined the conductivity by dividing the transmissivity as obtained from the pumping tests by the screen length. They thus assumed that the influence of flow through layers above and below the screen is limited within several hundred meters from the pumping well, generally less than 120 m, at least in a highly vertically anisotropic system, as is the case in Punjab. Distance-drawdown curves were used to analyze these pumping tests. Generally, the top of the screen coincided with the elevation below which coarser sediments are present (over a depth range of 30–60 m below ground surface), sufficient to accommodate the desired screen length of 30–60 m. The influence of layers below this level is, therefore, less known. Based on the heterogeneous nature of the aquifer and its layered structure, it can safely be assumed that the permeability of the shallow layers was substantially less, which suggests that flow is essentially horizontal and limited to the zone between the top and the bottom of the screen.

Based on the vertical drop of head over the (resistant) layers between water table and screen, Bennett et al. (1967) derived vertical conductivities between 0.3 and 26 m/d. They then used the ratio of the horizontal conductivity over the screen length and vertical conductivity over the top layers as vertical anisotropy, yielding values between 3 and 195. However, they explicitly considered these anisotropies as the ratio of the overall lateral permeability to its overall vertical permeability, and not to the true anisotropy ratio at any particular point (Bennett et al., 1967, page G53).

Subsequent analysis by USGS using analog models confirmed that Bennett et al. (1967) were correct to within 10–30% (Mundorff et al., 1972). Later researchers reexamined these pumping tests claiming that Bennett et al. (1967) overestimated the horizontal hydraulic conductivity by a factor up to two. However, none of these studies take vertical anisotropy into account. If they had done so, their results would have come closer to those of Bennett et al. (1967).

There is a fundamental difference between the analysis by Bennett et al. (1967), who proved the division of transmissivity by screen length was correct, and other users, who used type curve matching without considering vertical anisotropy. Bennett et al. (1967) in fact determined horizontal hydraulic conductivity, whereas other authors determined transmissivity. Without a clear knowledge of aquifer depth, the two cannot be matched. The other authors can only be correct to the extent that the flow is essentially horizontal within the distance of their piezometers.

Hydrogeologists usually analyze pumping tests by applying analytical solutions that are valid for completely penetrating wells, on which corrections for partial penetration may be applied. These corrections are steady state, if applied. Such procedures may give fair results when the well penetration is small and known. Such procedures cannot be applied when aquifers are of large unknown thickness. Therefore, without sufficient information about the nature of the flow system, the measured drawdown trends cannot be interpreted uniquely. Arbitrary use of such drawdown measurements may give erroneous results, which has also happened in the case of the Punjab. Arif and Rehman (1960) and Arif (1966) applied the Theis method, which is not applicable due to vertical flow caused by partial penetration. Based on their interpretation of the pumping tests, Bennett et al. (1967) indubitably indicate that the Punjab aquifer is vertically anisotropic. Their interpretation was in accordance with the geological evidence as described by Kidwai (1963). Despite this, Chaudhari (1966), Kruseman and de Ridder (1990) and Boonstra (1992) estimated the hydraulic conductivity from the early-time analysis while neglecting the vertical anisotropy.

The different values from the aforesaid interpretations of aquifer tests of the Punjab create a state of confusion concerning which values to use in groundwater studies. The challenge of the present study is to estimate more accurately the representative hydraulic conductivity, the vertical anisotropy and the effective thickness of the aquifer in the Punjab, so that these will be suitable for utilization in future groundwater studies.

SITE DESCRIPTIONS

Fig. 4.1 shows the location of the Punjab aquifer, where the aforesaid 141 pumping tests were carried out. Fig. 4.1 also shows the testing sites Janpur (BWP9), Chilian wala (C-21; situated in Chaj Doab) and Harrapa (B-9; situated in Bari Doab). The pumping wells of those pumping tests were only screened in the upper 120 m of unconsolidated alluvial deposits. Bennett et al. (1967) described the lithology of the Punjab aquifer: "The unconsolidated alluvial deposits of the Punjab, consisting mainly of interbedded and lenticular sands, silts, and clays, extend to depths of one thousand to several thousand feet over most of the area. They constitute a very extensive heterogeneous unconfined aquifer". Fig. 4.2 gives a schematic view of the USGS Punjab test wells. Mostly, 25-m blank pipe was installed at each pumping well site called 'housing pipe' by Bennett et al. (1967). The depth of the housing pipe was extended beyond 25 m in case clay or high-resistant material was present so that the pumping-well screen should be totally within the permeable deposits. The screen usually ranged between 30 and 60 m in length, depending on local geology. The

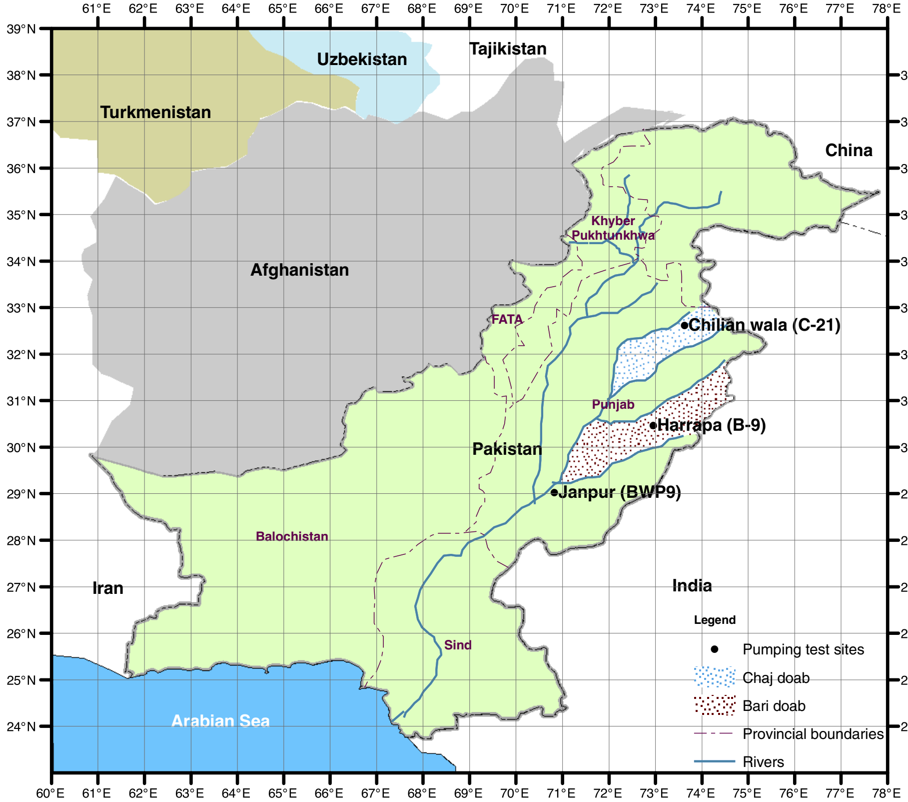

Figure 4.1: Location of the Punjab aquifer and three pumping test sites.

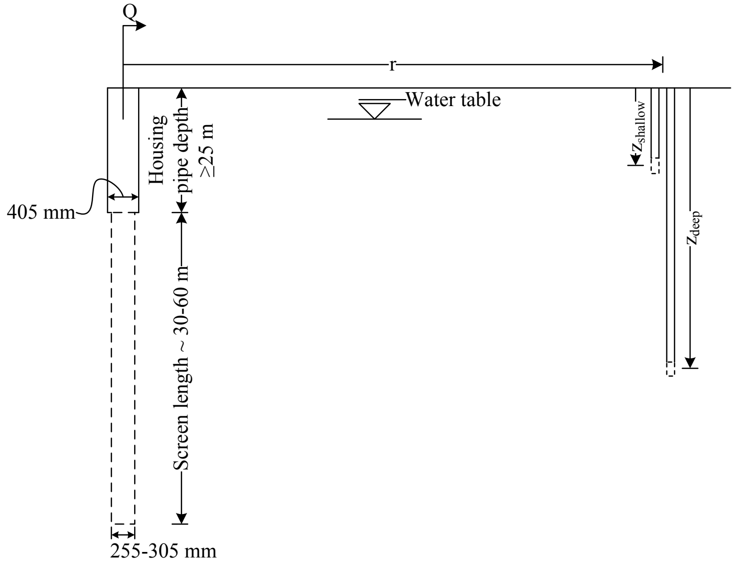

Figure 4.2: Schematic view of the USGS 'regular' and 'special' pumping test sites in Punjab. Only the 'special' tests used shallow observation wells.

number of observation wells installed at each test was between 4 and 8. Most commonly, the regular observation wells were installed at radii of 30.5, 61, 91.5, 122, 183, 245 and 760 m from the pumping well (Bennett et al., 1967). The observation wells were generally deep (z_{deep}; Fig. 4.2) and equipped with a short screen with elevation coinciding with the center of the screen of the test pumping well. Constant pumping was maintained in each test. The discharge at the pumping well (Q) varied from test to test, between 2,450 and 9,800 m^3/d, and the pumping continued for 4–8 days (Bennett et al., 1967).

Janpur (test BWP9)

Kruseman and de Ridder (1990) described the lithology of the Janpur site: "The alluvial sediments of the basin are hundreds to more than 1,000 m thick and consist of medium sand with lenses of coarse and fine to very fine sands and incidentally clay or loam. A top layer of clay and loam of several meters thick usually covers the aquifer." The location of the Janpur site is shown in Fig. 4.1; the well geometry, discharge and the details of observation wells are shown in Tables 4.1 and 4.2.

Chilian wala (test C-21)

This chapter reevaluates a pumping test conducted at Chilian wala (test C-21) in 1959. Its location is shown in Fig. 4.1; the well geometry, discharge and the details of observation wells are shown in Tables 4.1 and 4.2.

Table 4.1: Pumping well geometry, discharge and duration of constant rate pumping tests. These tests were conducted as: Janpur (BWP9) in 1976, Chilian wala (C-21) in 1959 and Harrapa (B-9) in 1962 (refer to Fig. 4.2). *NR* not reported.

Test		**Design parameters of pumping well**				**Pumping duration**	**Depth to water table**	**Max. drawdown in pumping well**
Test name	**Site (Fig. 4.1)**	**Screen top^a**	**Screen bottom^a**	**Discharge**	**Radius of pumping screen**			
		m	**m**	**m^3/d**	**mm**	**min.**	**m**	**m**
BWP9	Janpur	−20	−60	6,350.4	*NR*	6,000	*NR*	*NR*
C-21	Chilian wala	−53	−86.5	5,434.5	127.5	11,520	1.5	4.3
B-9	Near Harrapa	−18.3	−54.9	6,679.2	152.5	21,000^b	10.7	14.0

Notes:

[a] Screen top and bottom are expressed in terms of elevation with respect to the ground surface, which is taken as datum (Refer to Fig. 4.2).

[b] The original test data up to 600 minutes can be found in Chaudhari (1966).

Table 4.2: Design parameters of observation wells (refer to Fig. 4.2).

Pumping test site (test name)	**Observation well ID**	**Radial distance of observation well, r^a**	**Measuring depth, z^b**
		m	**m**
Janpur (BWP9)	–	15.2	−45
	–	30.5	−45
	–	91.5	−45
Chilian wala (C-21)	O1	30.5	−70
	O2	122	−70
	O3	61	−70
	O4	183	−70
	O5	245	−70
	O7	122	−70
Near Harrapa (B-9)	–	30.5	−45
	–	61	−45
	–	91.5	−45

Notes:

[a] Radial distance is measured with respect to the center of the pumping well (Refer to Fig. 4.2).

[b] Measuring depth of observation wells is expressed in terms of elevation with respect to the ground surface, which is taken as datum (Refer to Fig. 4.2).

Near Harrapa (test B-9)

Fig. 4.2 also schematically shows the layout of the so-called 'special' tests in the Punjab in 1962. For these, shallow observation wells were installed below the water table ($z_{shallow}$; Fig. 4.2) in addition to the regular observation wells as discussed previously.

This was done at 19 sites in Bari Doab. Each shallow observation well was paired to its deeper companion at the same radial distance. The number of these pairs varied between two and ten (Bennett et al., 1967). This chapter reevaluates a pumping test conducted near Harrapa (test B-9) in 1962. The location of test B-9 is shown in Fig. 4.1; the well geometry, discharge and the detail of observation wells are shown in Tables 4.1 and 4.2.

EXISTING CALIBRATIONS

Arif and Rehman (1960) carried out a preliminary analysis of the Punjab pumping tests using methods of Theis (1935) and of Cooper and Jacob (1946), assuming that the conditions appropriate for these methods closely match field conditions. The storage coefficients thus obtained were very small, indicating confined conditions, whereas the geological evidence indicated the aquifer to be unconfined. Their analysis gave high transmissivities, which do not agree with those obtained from the distance-drawdown methods used by Bennett et al. (1967). Bennett et al. (1967) applied the distance-drawdown method to avoid the aforesaid difficulties in obtaining results from time-drawdown curves, because aquifer thickness, anisotropy and certain other factors were generally unknown. However, distance-drawdown results are also prone to errors.

Bennett et al. (1967) concluded that the distance-drawdown data for observation points within 120 m from the pumping well fell on a straight line in almost all cases after a sufficient duration of pumping. They evaluated the pumping tests in Punjab by the distance-drawdown techniques of Cooper and Jacob, except that the length of screen was used rather than the aquifer thickness. This method was mainly based on the following assumptions: horizontal radial flow, equal in magnitude to the pumping discharge, limited to the depth interval of the screen, and only between the well and a point at a distance 120 m. The linearity of the semilog distance-drawdown curves, especially those for the tests in which observation wells were installed at short distances from the pumping well, suggests that these assumptions were satisfied in the majority of the tests. Therefore, Bennett et al. (1967) computed the transmissivities (kD) essentially over the screen length and thus estimated the average horizontal hydraulic conductivity k_r of the Punjab aquifer as 65 m/d. Bennett et al. (1967) further estimated a representative value k_z of 3 m/d for the material between the water table and the top of the well-screen, by using the Jacob's graphical method for semi-confined flow with leakage proportional to drawdown, which is similar to Hantush's solution (Hantush and Jacob, 1955). This resulted in a vertical anisotropy of 25. Moreover, from the vertical head difference between deep and shallow observation wells, Bennett et al. (1967) derived a solution for the determination of k_z and found an average value of 4.5 m/d.

Arif (1966) analyzed some of the Punjab pumping tests to address the aforementioned uncertainties. He examined the effects of anisotropy with an electric analog model by looking at vertical components of flow and partial penetration of both the pumped and observation wells. He concluded that: (1) equations of radial flow do not provide the exact solution to the analysis of the aquifer tests in the Punjab where an unconfined and anisotropic aquifer predominates, (2) the response initially corresponds to that of a confined elastic aquifer and later on as a water table aquifer, (3) the pumping tests in an unconfined aquifer require much more time to reach equilibrium, and (4) observation wells beyond 120 m did not agree with the results of nearer wells. Arif (1966) determined the transmissivity values, from the partially penetrating wells using Theis's method, the delayed yield method of Boulton (1963) and from step-drawdown tests. These different analyses yielded consistent results for transmissivities, which lie between 2,400 and 6,450 m^2/d, with an average value as 4,000 m^2/d. The average horizontal conductivity was 40 m/d for an average assumed thickness of aquifer that lies between 90 and 120 m. Chaudhari (1966) and Arif (1966) observed that the usefulness of Arif's method (Arif, 1966) depends on how accurately the aquifer thickness and the anisotropy ratio are known. Since these were essentially unknown from the start, their estimation likely affects the conclusions.

Chaudhari (1966) analyzed four specially designed long-duration pumping tests that were conducted in Bari Doab. He indicated that vertical components of flow caused by partial penetration and storage coefficient (which is variable due to slow drainage) are the two major factors controlling the aquifer response, which makes the Theis' method inapplicable. He concluded that: (1) the effect of partial penetration on drawdown is very significant during the initial pumping period, whereas the effect of delayed yield is insignificant, (2) the partial penetration effects decrease rapidly with increasing distance from the pumping well, (3) the early-time data of pumping tests up to 40 minutes gave an accurate value of hydraulic conductivity, elastic storage and the most probable effective depth of the aquifer, (4) observation wells beyond 1.5 times the aquifer depth from the pumping well, with adjustment for delayed yield, gave good values of specific yield and transmissivity, (5) the use of near-well data, in case of partial penetration, and the distal well data, at later times, for the case of delayed yield provide the best means to determine the aquifer characteristics. He further determined that the effects of anisotropy and vertical components of flow due to lowering of the water table are so small relative to the partial-penetration influence, that they do not affect the early data analysis. He estimated the average hydraulic conductivity as 19.75 m/d (which is about half the value obtained by Bennett et al. (1967) at the same location), the elastic storage coefficient between 0.0001 and 0.005, and the specific yield as 0.2–0.25. The effective depth of the aquifer ranged from at least 220 m to probably over 450 m. Some hydrologists, for instance Arif (1966) and Chaudhari (1966), have tried to estimate effective aquifer thickness. They could not estimate the exact value for the Punjab aquifer, because the pumped water is initially from elastic storage and only later on from phreatic storage.

Based on analog models that used only input from recharge and outflow across the screen, Mundorff et al. (1972) concluded that the distance-drawdown method, as adopted by Bennett et al. (1967), overestimates the horizontal conductivity values of the anisotropic Punjab aquifer by 10–30% when observation wells are within 120 m from the pumping well.

Next to pumping tests, other methods were also searched to determine hydraulic conductivities of the Punjab aquifer. Other studies tried to estimate conductivities of the Punjab aquifer in fact by model calibration as explained by Alam and Olsthoorn (2014a). No studies could be found using methods like grain size analysis, slug test and isotopic profiles.

RECALIBRATION APPROACH

Hydraulic parameters such as horizontal hydraulic conductivity (k_r), vertical hydraulic conductivity (k_z) and specific storage (S_s) were interpreted using type curves constructed from Hantush's modification of the Theis method for early-time drawdown (Hantush, 1961a,b). Since they depend on the penetration of the pumping screen and the depth of the piezometer, type curves for each case were prepared separately. Besides, at early time, type curves do not depend on aquifer thickness. So the said three parameters can be determined if a value for the vertical anisotropy is assumed. From a set of realizations for each pumping test, the one that best matches the observed data is selected. The steady-state distance-drawdown on semilog scale, for different vertical anisotropies together with available data, is plotted as an independent check of the USGS's distance-drawdown method. Effective thickness of the aquifer is determined in a second step by using Hantush's modification of the Jacob method (Hantush, 1961a,b), which is useful for late-time drawdown and which depends on depth. The estimated value of effective depth represents the most appropriate value. For ease of reference, Hantush's modification of the Theis method will be referred to in the following sections as 'early-time drawdown' and Hantush's modification of the Jacob method as 'late-time drawdown'.

EARLY-TIME DRAWDOWN AND LATE-TIME DRAWDOWN ANALYTICAL SOLUTIONS

The effect of partial penetration in pumping wells is common in deep aquifers and induces the vertical velocity and, therefore, the Dupuit assumption of horizontal flow is not valid. Hantush (1961a,b) has provided two different analytical solutions to cope with the situation. The scaled solutions of Hantush's modifications of the Theis and Jacob methods, along with assumptions, governing equations, boundary and initial conditions are given in the following subsections.

Assumptions, boundaries and initial conditions

The following assumptions and conditions should be satisfied in order to use Hantush's modifications of the Theis and Jacob methods:

- Pumping rate should be constant throughout the test.
- Flow towards the well should be transient.
- Aquifer should be homogenous, anisotropic and infinite in areal extent.
- Aquifer should be exhibited as having a confined elastic behavior.
- The piezometric surface should be horizontal or nearly horizontal before the start of the pumping test.
- Aquifer thickness should be uniform over the area of influence.
- The time of pumping should be relatively short for Hantush's modification of the Theis method (Eq. 4.1) and be relatively long for Hantush's modification of the Jacob method (Eq. 4.11). The time of pumping for the scaled solutions of these methods are formulated as shown in Eq. (4.10) and Eq. (4.13).

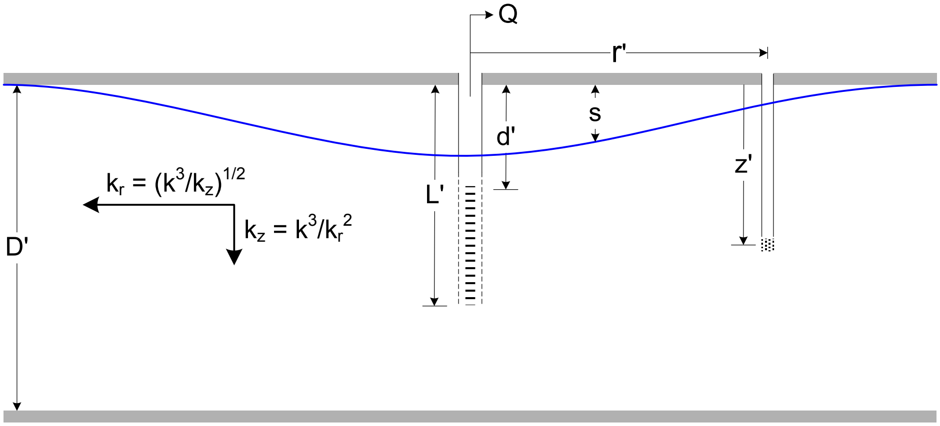

Figure 4.3: Definition sketch of recalibration model. Refer to Table 4.3 for the notation used in this figure.

Early-time drawdown in partially penetrating wells

The drawdown *s* at any radial distance *r′* and any depth *z′* for a partially penetrating well (Hantush, 1961a,b; Kruseman and de Ridder, 1990) in an anisotropic deep aquifer can be written (Table 4.3 and Fig. 4.3 are referred for notation) as:

$$s = \frac{Q}{8\pi(L'-d')} E\left(u, \frac{L'}{r'}, \frac{d'}{r'}, \frac{z'}{r'}\right) \tag{4.1}$$

where,

$$E\left(u, \frac{L'}{r'}, \frac{d'}{r'}, \frac{z'}{r'}\right) = M(u, B_1) - M(u, B_2) + M(u, B_3) - M(u, B_4) \tag{4.2}$$

$$u = \frac{r'^2 S_s}{4kt} \tag{4.3}$$

$$S_s = \frac{S}{D'} \tag{4.4}$$

and, S_s is the specific storage and *S* is the storage coefficient.

$$B_1 = (L' + z')/r' \tag{4.5}$$

$$B_2 = (d' + z')/r' \tag{4.6}$$

$$B_3 = (L' - z')/r' \tag{4.7}$$

$$B_4 = (d' - z')/r' \tag{4.8}$$

$$M(u, B) = \int_u^\infty \frac{e^{-y}}{y} erf\left(B\sqrt{y}\right) dy \tag{4.9}$$

This method is applicable for a relatively short period of pumping, i.e.,

$$t < \frac{(2D-L-z)^2 S_s}{20k_z} \tag{4.10}$$

or, when the aquifer is infinitely deep, i.e., $D = \infty$.

Late-time drawdown in partially penetrating wells

The drawdown *s* at any radial distance *r′* and any depth *z′* for a partially penetrating well (Hantush, 1961a,b; Kruseman and de Ridder, 1990) in an anisotropic aquifer can be written (Table 4.3 and Fig. 4.3 are referred for notation) as:

$$s = \frac{Q}{4\pi k D'} \left\{ W(u) + f_s\left(\frac{r'}{D'}, \frac{L'}{D'}, \frac{d'}{D'}, \frac{z'}{D'}\right) \right\} \tag{4.11}$$

Table 4.3: Notation (refer to Fig. 4.3).

Symbol	Explanation	Units
s	Drawdown in the aquifer at any time and at any measuring point	m
Q	Constant pumping rate	m^3/d
t	Time since the start of pumping test	d
k	$= \sqrt[3]{k_r^2 k_z}$	m/d
k_r	Horizontal hydraulic conductivity of the aquifer	m/d
k_z	Vertical hydraulic conductivity of the aquifer	m/d
D'	$= D\sqrt{\frac{k}{k_z}}$	m
D	Thickness of the aquifer	m
r'	$= r\sqrt{\frac{k}{k_r}}$	m
r	Radial distance of any observation point from the center of the pumping well	m
z'	$= z\sqrt{\frac{k}{k_z}}$	m
z	Depth of penetration of any observation point with respect to the ground surface	m
L'	$= L\sqrt{\frac{k}{k_z}}$	m
L	Depth of penetration of the pumping well (i.e., distance between the top of the aquifer and the bottom of the well screen)	m
d'	$= d\sqrt{\frac{k}{k_z}}$	m
d	Distance between the top of the aquifer and the top of the well screen	m
S_s	Specific storage of the aquifer	m^{-1}
S	Storage coefficient of the aquifer	–
K_0	Zero-order modified Bessel function of the second kind	–
$W(u)$	Exponential integral function, commonly called the well function and is defined as $W(u) = \int_u^{\infty} \frac{e^{-y}}{y} dy$	–
$M(u, B)$	Infinite integral and is defined as $M(u, B) = \int_u^{\infty} \frac{e^{-y}}{y} erf\left(B\sqrt{y}\right) dy$	–

where $W(u)$ is the Theis well function, and

$$f_s = \frac{4D'}{\pi(L'-d')}\sum_{n=1}^{\infty}\left(\frac{1}{n}\right)K_0\left(\frac{n\pi r'}{D'}\right)\left\{cos\left(\frac{n\pi z'}{D'}\right)\right\}\left\{sin\left(\frac{n\pi L'}{D'}\right) - sin\left(\frac{n\pi d'}{D'}\right)\right\} \tag{4.12}$$

This method is applicable for a relatively long period of pumping, i.e.,

$$t > \frac{D^2 S_s}{2k_z} \tag{4.13}$$

The aforementioned solutions are scaled, by applying coordinate transformation for the vertical anisotropy, as follows:

$$k = \sqrt[3]{k_r k_r k_z} \tag{4.14}$$

where k_r is the horizontal hydraulic conductivity and k_z is the vertical hydraulic conductivity, and other terms are as

$$D' = D\sqrt{\frac{k}{k_z}} \tag{4.15}$$

$$L' = L\sqrt{\frac{k}{k_z}} \tag{4.16}$$

$$d' = d\sqrt{\frac{k}{k_z}} \tag{4.17}$$

$$r' = r\sqrt{\frac{k}{k_r}} \tag{4.18}$$

$$z' = z\sqrt{\frac{k}{k_z}} \tag{4.19}$$

The aquifer depth can approximately be determined from the following equation, when early-time drawdown curve starts deviating from the type curve.

$$D \cong \frac{1}{2}\left(L + z + r\sqrt{\frac{k_z}{k_r}}\sqrt{5\frac{1}{u_{dep}}}\right) \tag{4.20}$$

where, $1/u_{dep}$ is the value of $1/u$ from the type curve, where the data curve starts departing from the type curve.

TIME-DRAWDOWN DYNAMICS IN PARTIALLY PENETRATING WELLS

Fig. 4.4 shows the transition from early-time drawdowns to late-time drawdowns. This figure shows the early-time drawdowns (Eq. 4.1), the late-time drawdowns (Eq. 4.11), the simulated (MODFLOW) drawdowns, and the theoretical drawdowns as calculated by Boonstra (1992), which are also shown in Table 4.4. Boonstra (1992) calculated the aforementioned theoretical drawdowns by using the parameters as shown in Table 4.5. On perusal of Fig. 4.4, it is clear that the early-time drawdowns (Eq. 4.1) do not depend on the depth of the aquifer until 117.6 minutes as estimated from Eq.

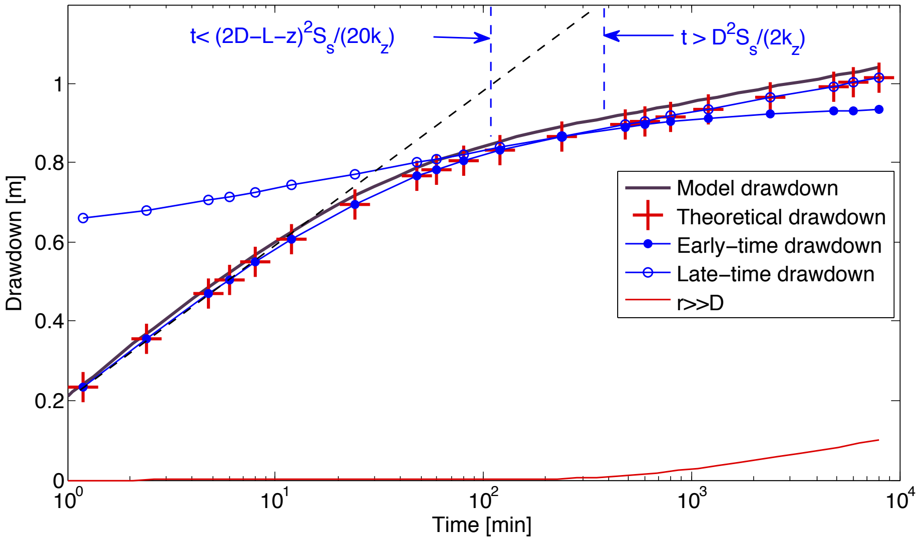

Figure 4.4: Time-drawdown dynamics in a partially penetrating well. The *black dotted line* represents the drawdown in case the aquifer depth is equal to the screen depth.

Table 4.4: Theoretical drawdown values (after Boonstra [1992]: reprinted with permission from Elsevier).

Time (min.)	Drawdown (m)	Time (min.)	Drawdown (m)
1.2	0.233	120	0.832
2.4	0.355	240	0.867
4.8	0.471	480	0.897
6	0.506	600	0.906
8	0.551	800	0.918
12	0.609	1,200	0.936
24	0.697	2,400	0.965
48	0.766	4,800	0.994
60	0.784	6,000	1.003
80	0.806	8,000	1.015

(4.10) when the early-time drawdown curve starts deviating from its corresponding theoretical drawdown. The transition time between $t < (2D - L - z)^2 S_s / (20k_z)$ and $t > D^2 S_s / (2k_z)$ coincides with the time when the drawdown from the bottom of the aquifer starts reflecting. Fig. 4.4 confirms the exact match between theoretical drawdowns and analytical solutions (Eqs. 4.1 and 4.11) and the nearly perfect fit between the model and analytical solutions. Early-time drawdown follows the theoretical drawdown until $t < (2D - L - z)^2 S_s / (20k_z)$. Then there is a transition time period between $(2D - L - z)^2 S_s / (20k_z)$ and $D^2 S_s / (2k_z)$ and thereafter, the late-time

Table 4.5: Parameter values used by Boonstra (1992) to calculate the theoretical drawdowns as shown in Table 4.4.

Parameter	Value	Units
Q	6,350	m^3/d
k_r/k_z	1	–
k_r	30	m/d
D	400	m
S	0.04	–
S_s	1×10^{-4}	m^{-1}
L	60	m
d	20	m
z	40	m
r	20	m

drawdown starts following the theoretical drawdown from $t > D^2S_s/(2k_z)$ (i.e., 384 minutes) onwards to the end of the test.

The black dotted line in Fig. 4.4 is the drawdown in case the aquifer depth is equal to the screen depth. Similar behavior is observed with the red curve, which is also a Theis curve, valid for distances much greater than the aquifer depth, where partial penetration does not play any role.

Fig. 4.5 ($k_r/k_z = 4$), Fig. 4.6 ($k_r/k_z = 200$) and Fig. 4.7 ($k_r/k_z = 10$) show the comparison of measured drawdown with numerical and analytical drawdowns for the pumping sites Janpur (BWP9), Chilian wala (C-21) and Harrapa (B-9), where early-time drawdowns (analytical drawdowns) match with the model and observed drawdown, i.e., the results coincide with the early-time drawdown only; the late-time drawdown is beyond the duration of the pumping test. This implies that 4 and 8 days pumping tests in case of Janpur and C-21 were too short to reach late-time drawdowns, which are necessary to determine the effective aquifer depth. As a consequence, Eq. (4.13) or Eq. (4.20) can be used to determine the approximate depth of the aquifer at the end of the test, which in fact means a minimum depth (Refer to Tables 4.6 and 4.7).

For relatively short periods of pumping, Eq. (4.1) states that the drawdown around a partially penetrating well would be the same as though the aquifer was infinitely deep. The contribution of flow towards the well screen originates from elastic storage (Fig. 4.4); it does not matter if the aquifer is confined or unconfined as long as Eq. (4.10) holds. Eq. (4.1), therefore, can be used for both the confined and unconfined aquifer until the time specified in Eq. (4.10). Equation (4.10) shows that the time limit of the early-time drawdown depends on the penetration depth of the pumping well, the depth of the piezometer, the thickness of the aquifer, the specific storage and the vertical hydraulic conductivity of an anisotropic aquifer.

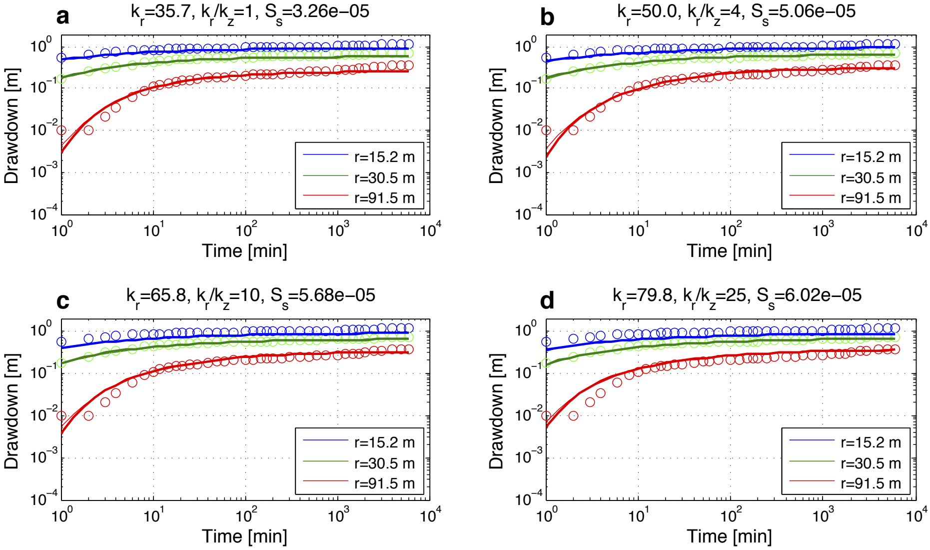

Figure 4.5: Comparison of measured drawdown at Janpur (BWP9) with numerical and analytical models. Anisotropy factors **a** 1, **b** 4, **c** 10 and **d** 25. *Hollow circles* represent the observed data, *thick lines* represent the analytical solution (Hantush's modification of the Theis) and *thin lines* represent the numerical results. Notice, however, that these *thin lines* are almost completely hidden by *thick lines*; they are only visible near the well screens, and thus represent a good match of numerical results with the analytical solution.

For relatively long periods of pumping, Eq. (4.11) shows that the rate of change of drawdown is similar to the case where the pumping well is completely penetrating the aquifer, i.e., when the partial penetration affect has attained its stationary value. The effect of partial penetration is apparent from the point where the drawdowns start to deviate from the early-time drawdown curve (Eq. 4.1 and Fig. 4.4), which is intended for an infinitely deep aquifer, i.e., $D = \infty$. This deviation may, however, also be due to vertical drainage. The same general behavior may be observed when a well completely penetrates a water-table aquifer. Since the examination of the tests at sites Janpur and C-21 reveals that the complete deviation of the departure curve is beyond the duration of the pumping tests, advanced standard methods of water-table aquifer interpretations as provided by Neuman (1974, 1975), Moench (1997) and Moench et al. (2001) are not applicable here. Also, the code WTAQ (Barlow and Moench, 1999) requires the depth of the aquifer prior to the analysis. The match between the modeled drawdowns with the early-time analytical drawdown (Figs. 4.5, 4.6 and 4.7) shows that the partial penetration effect is transient till the end of the pumping tests, as no reflection from the bottom of the aquifer is observed. Furthermore, the effect of recharge from the water table was not significant during the entire pumping tests,

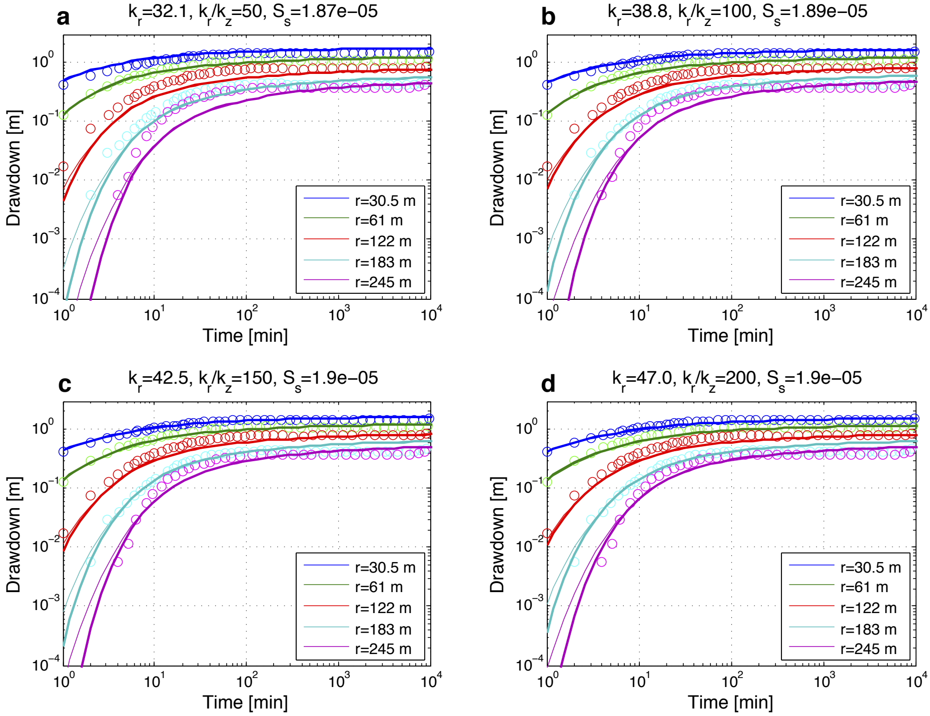

Figure 4.6: Comparison of observed behaviour with numerical and analytical models at Chilian wala (C-21). Anisotropy factors **a** 50, **b** 100, **c** 150 and **d** 200. *Hollow circles* represent the observed data, *thick lines* represent the analytical solution (Hantush's modification of the Theis method) and *thin lines* represent the numerical results. Notice, that these *thin lines* are almost hidden by *thick lines*, only visible at some locations, and thus represent a near match of numerical results with the analytical solution.

Table 4.6: Interpretation of Janpur (1976) pumping test (BWP9: observation well at $r = 30.5$ m) for different anisotropic factors using Hantush's modifications of the Theis and Jacob methods (Fig. 4.5).

	Units	$k_r/k_z = 1$	$k_r/k_z = 2$	$k_r/k_z = 4$[c]	$k_r/k_z = 10$	$k_r/k_z = 25$
k_r (Type-curve)[a]	m/d	35.7	43.4	50.0	65.8	79.8
k_z (Type-curve)[a]	m/d	35.7	21.7	12.5	6.6	3.2
S_s (Type-curve)[a]	m^{-1}	3.26×10^{-5}	4.04×10^{-5}	5.06×10^{-5}	5.68×10^{-5}	6.02×10^{-5}
D[b]	m	3,000	2,100	1,425	1,000	675

Notes:

[a] Early-time drawdown by using Eq. (4.1).

[b] D is the effective thickness of the aquifer and is determined by Eq. (4.13). The pumping test is too short to reach late-time drawdown, which, in fact, means a minimum depth (Hantush, 1961a).

[c] $k_r / k_z = 4$ is the final result.

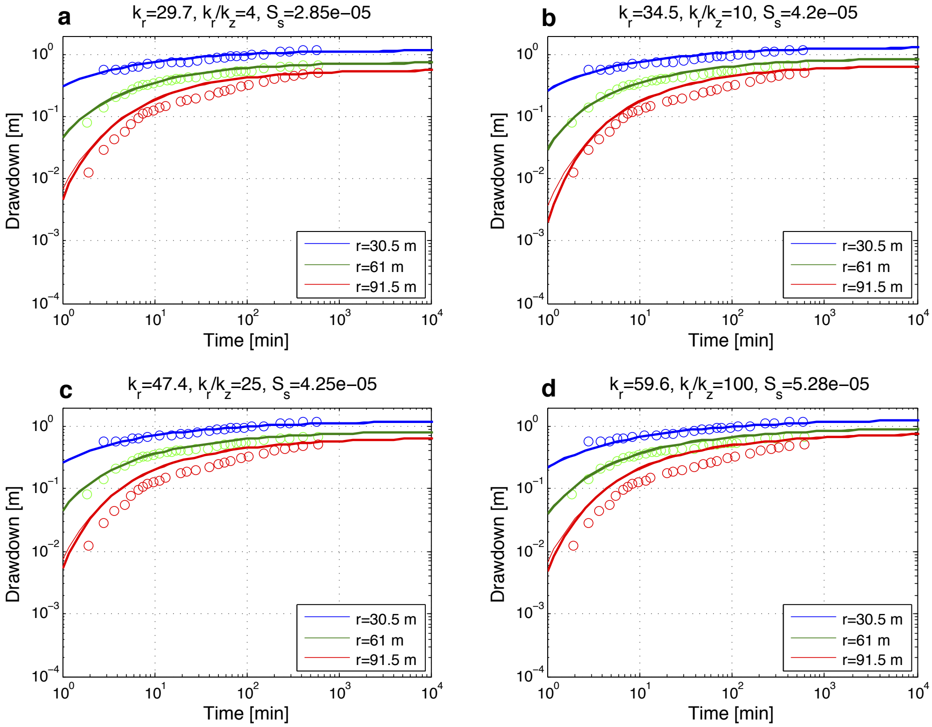

Figure 4.7: Comparison of drawdown measurements with numerical and analytical models at Harrapa (B-9) (Bari doab). Anisotropy factors **a** 4, **b** 10, **c** 25 and **d** 100. *Hollow circles* represent the observed data, *thick lines* represent the analytical solution (Hantush's modification of the Theis method) and *thin lines* represent the numerical results. Notice that these *thin lines* are almost hidden by *thick lines*, and thus represent a good match of numerical results with the analytical solution.

which implies that the early-time analytical solution gives reliable results for the Punjab pumping tests.

INTERPRETATION OF PUNJAB PUMPING TESTS

Bennett et al. (1967) showed that vertical anisotropy is important, and therefore, they reverted to the steady distance-drawdown method to prevent influence of anisotropy on their horizontal conductivities. Although the other authors who interpreted the Punjab pumping tests had a much broader aim of determining aquifer parameters, including aquifer depth, none of them has taken vertical anisotropy into account, which explains much of the differences between their results and that of Bennett et al. (1967). This study presents the analyses as in the following subsections, where vertical anisotropy is an important factor as it should be.

Interpretation of the available pumping test data was made using MODFLOW invoked through mfLab (Olsthoorn, 2013) as well as with analytical solutions such as Hantush's modifications of the Theis and Jacob methods for partially-penetrating wells. Since these analytical methods have been derived for isotropic conditions, they invariably yield unrealistic results if not properly scaled to compensate for anisotropy. This study shows the differences (Eqs. 4.1–4.20) and also compares these analytical solutions with MODFLOW, which make it possible to evaluate all pumping tests in the Punjab aquifer for which data are still available.

Janpur pumping test

First, the published data of the Janpur (BWP9) pumping test conducted in 1976 was used. The Water and Power Development Authority (WAPDA), Pakistan, performed this test; it was not done by Bennett et al. (1967). The test BWP9 was interpreted by Kruseman and de Ridder (1990) and Boonstra (1992). Kruseman and de Ridder (1990) estimated the hydraulic conductivity, specific storage and aquifer thickness using Hantush's modification of the Theis method. Boonstra (1992) estimated the hydraulic conductivity, the storage coefficient and the aquifer thickness using Hantush's modification of the Jacob method, using late-time drawdowns; however, vertical anisotropy was not considered.

Kruseman and de Ridder (1990) concluded that Hantush's modification for the Theis method, applied to three different piezometers, yielded consistent values for the hydraulic conductivity and the thickness of the aquifer, whereas the values estimated for the specific storage increase slightly with distance from the well. They did not provide a plausible cause of this gradual increase with distance. The reason is that if the actual thickness of aquifer is large, then the computed drawdowns, with increasing radial distance, would be less than it should be, and, in order to compensate for it, one should use a higher storage coefficient. This is the probable reason why Kruseman and de Ridder (1990) found increasing S_s values for piezometers further away, when they matched them individually with transient data only. They would have found the same storage coefficient for these piezometers, if they had applied sufficient vertical anisotropy of the aquifer as was necessary to compensate for the real situation.

Boonstra (1992) compared both modifications (i.e., Hantush modifications of the Theis and Jacob methods) for partially penetrating wells in the Indus Basin. Although early time drawdowns of the Hantush's modification for the Theis method are independent of aquifer thickness, Boonstra (1992) concluded that Kruseman and de Ridder (1990) overestimated the aquifer thickness. Boonstra (1992) further concluded that Hantush's modification for the Jacob method provided reasonable results. Since the assumptions underlying the derivation of both analytical modifications are purely suitable for isotropic media, it is not possible to conclude something about the effective thickness of the Punjab aquifer based on these analytical solutions without scaling them first, which was not done. This effect of scaling can be seen in Table 4.6, which summarizes the results. Boonstra (1992) estimated the aquifer thickness of the Punjab at Janpur as 400 m by using Hantush's modification of the Jacob method (late-time drawdown); however, he neglected the effect of vertical anisotropy in the Punjab aquifer, which led to erroneous results.

This study concludes that it is impossible to determine the aquifer thickness with confidence without a plausible independent estimation of vertical anisotropy. Table 4.6 shows indeed that aquifer thickness strongly correlates with vertical anisotropy, so it cannot be determined independently. Fig. 4.5 shows the computed and measured drawdowns for the parameter values in Table 4.6. The observed data, with anisotropy factor of 4, best matches the analytical and numerical solutions. This study also applied the Bennett et al. (1967) distance-drawdown method to estimate the hydraulic conductivity at Janpur (Fig. 4.8). This method has given the transmissivity value as $T = 2{,}020$ m^2/d ($T = 2.3\,Q/(2\pi s_{log})$), which is not the true transmissivity of the whole aquifer but rather the most probable value of the aquifer opposite the well-screen while assuming horizontal flow within a radial distance of 90–120 m. Bennett et al. (1967) proved that the semilog plot of the distance-drawdown curve up to a radial distance of about 120 m falls on a straight line. They also concluded that the hydraulic conductivity may better be obtained by dividing this transmissivity by the screen length. Therefore, k_r of the Punjab aquifer at Janpur can be estimated as 50.5 m/d given the screen length of 40 m. To conclude, in the case of Janpur, the USGS's method (Bennett et al., 1967) reasonably estimates the value of k_r with a difference of 1% with respect to the third case in Table 4.6.

Moreover, Fig. 4.8 is an independent check of the USGS's (Bennett et al., 1967) distance-drawdown method, using steady-state drawdown and assuming the aquifer thickness being equal to the screen length and using the parameters for the third case (Table 4.6) at 3,000 minutes (steady state). This shows that USGS's (Bennett et al., 1967) distance-drawdown method, with piezometers less than 120 m away, gives a reliable estimate for the k_r in Janpur with screen partially penetrating and a deep aquifer. Fig. 4.8 shows distance-drawdown curves for the full 3D-case and according to Bennett's approach (Bennett et al., 1967); the distance-drawdown points should fall on a straight line, which Fig. 4.8 approximately shows. Bennett et al's approach depends on vertical anisotropy; the uncertainty of this approach will be decreasing as long as the vertical anisotropy tends to infinity (Fig. 4.9). In Fig. 4.9, the final vertical anisotropy is 200 and all drawdowns up to radial distance of 120 m must fall on a straight line. The uncertainty of Bennett's approach increases as the vertical anisotropy decreases.

Table 4.7: Interpretation of USGS pumping test (C-21: observation well O3 at r = 61 m and 70 m deep) for different anisotropic factors using Hantush's modifications of the Theis and Jacob methods (Fig. 4.6).

	Units	$k_r/k_z=1$	$k_r/k_z=50$	$k_r/k_z=100$	$k_r/k_z=150$	$k_r/k_z=200^c$
k_r (Type-curve)[a]	m/d	7.1	32.1	38.8	42.5	47.0
k_z (Type-curve)[a]	m/d	7.1	0.6	0.4	0.3	0.3
S_s (Type-curve)[a]	m^{-1}	6.12×10^{-6}	1.87×10^{-5}	1.89×10^{-5}	1.90×10^{-5}	1.90×10^{-5}
D[b]	m	4,300	725	600	500	500

Notes:

[a] Early-time drawdown by using Eq. (4.1).

[b] D is the effective thickness of the aquifer and is determined by Eq. (4.13). Pumping test is too short to reach late-time drawdown, which in fact, means a minimum depth (Hantush, 1961a).

[c] $\frac{k_r}{k_z}=200$ is the final result.

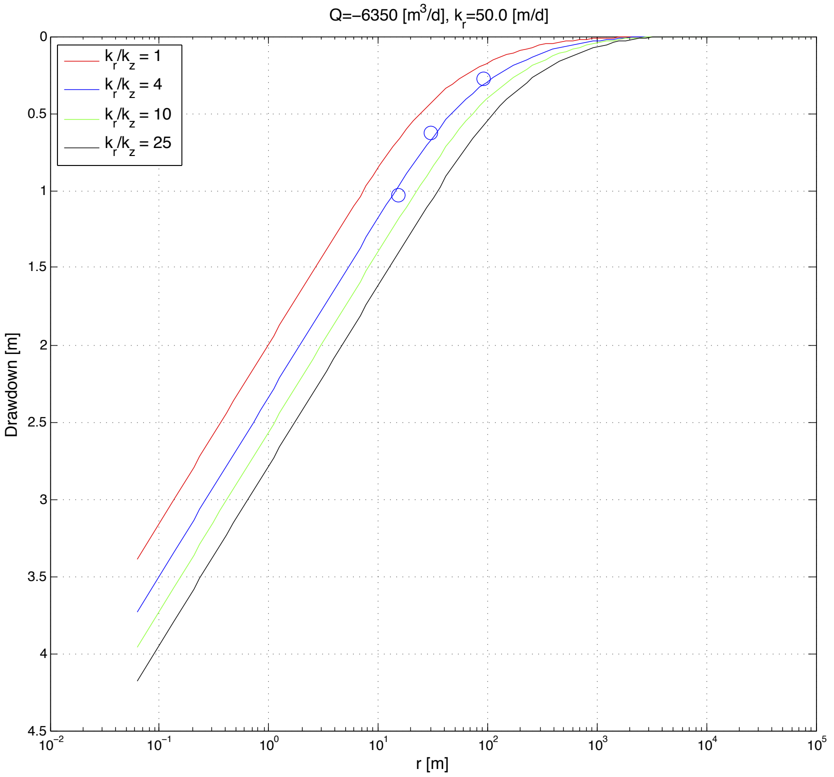

Figure 4.8: Distance-drawdown curves of the Janpur pumping test. *Blue bullets* represent the observed drawdown after 3,000 min of pumping ≅ (steady state). This is an independent check, using steady-state drawdown and assuming D = screen length. Parameters pertaining to Fig. 4.5 for the case of $k_r/k_z=4$ match with the corresponding model results and measured data. This shows that the USGS's (Bennett et al., 1967) distance-drawdown method gives reliable estimate for the k_r up to 90–120 m from the pumping well, which is very likely the case.

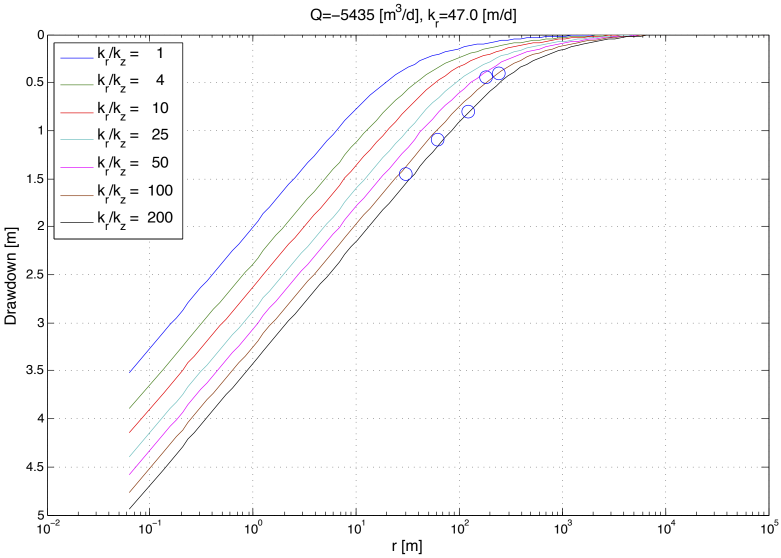

Figure 4.9: Distance-drawdown curves for different anisotropies at Chilian wala (C-21). *Blue bullets* represent the observed drawdown after 3,000 min of pumping ≅ (steady state). This is an independent check, using steady-state drawdown and assuming D = screen length. Parameters pertaining to Fig. 4.6 for the case of $k_r/k_z = 200$ match with the corresponding model results and measured data. This shows that the USGS's (Bennett et al., 1967) distance-drawdown method gives a reliable estimate for the k_r up to 90–120 m from the pumping well.

USGS pumping tests in Punjab

This study evaluates the USGS's (Bennett et al., 1967) interpretation by comparing their values with Hantush's modification of the Theis and Jacob methods. Table 4.7 shows the best parameter sets for five different anisotropies at the C-21 site. Since Bennett et al. (1967) in their technical paper did not publish the detailed pumping test data, this study had to refer to Birpinar (2003) and Chaudhari (1966) who included original data, but only for the wells they interpreted.

The data at site C-21 is compared with the different cases as shown in Fig. 4.6 and Table 4.7. The case with anisotropy factor of 200, matches the analytical and numerical solutions best (Fig. 4.6). Bennett et al. (1967) estimated the hydraulic conductivity at C-21 as 47.5 m/d (Fig. 4.9), which reasonably agrees with the fifth case in Table 4.7. The higher anisotropy of 200 indicates the presence of clay, which is also in accordance with geologic evidence given by Kidwai (1963) and with the findings of Bennett et al. (1967).

The streamlines at the end of the test are shown in Fig. 4.10 for different anisotropies. Fig. 4.10 shows that for anisotropies larger than about 25, the flow within about 120 m from the well is essentially horizontal. Fig. 4.10 also shows that the numerical model matches the analytic solution. The fraction of flow within the depth range of

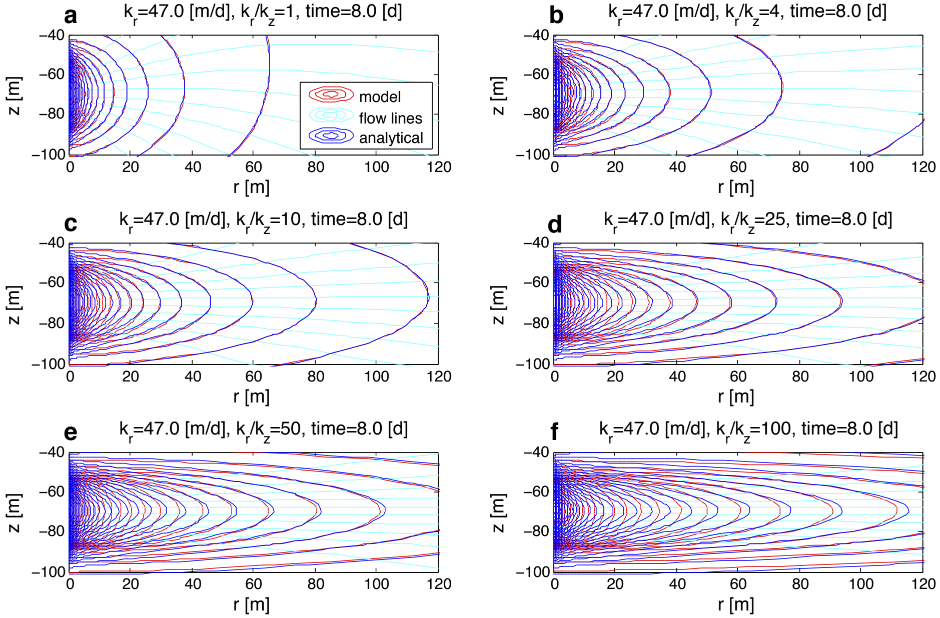

Figure 4.10: Hydraulic heads and streamlines at the end of the test for site Chilian wala (C-21). Anisotropy factors **a** 1, **b** 4, **c** 10, **d** 25, **e** 50 and **f** 100. The *red lines* represent the hydraulic heads of model (MODLOW) and the *blue lines* represent the analytical solution. The *cyan color* represents the streamlines.

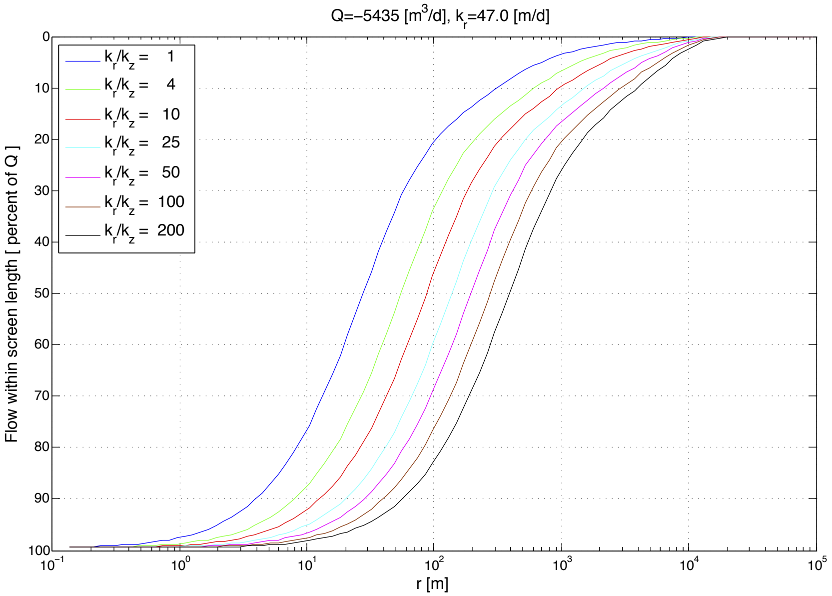

Figure 4.11: Percentage of flow within the depth range of the screen as a function of distance and for different anisotropies.

the screen as a function of distance from the well is shown in Fig. 4.11 for different vertical anisotropies. On perusal of Fig. 4.9, it is evident that the observed data up to 120 m are on the straight line and validate the Bennett's approach.

USGS special tests in Punjab

Bennett et al. (1967) re-analyzed their own aquifer tests of the Punjab to assert their distance-drawdown method. For this, they had a series of shallow and deep wells drilled to carry out so-called special tests in the Bari Doab that were designed to determine the vertical conductivity above the elevation of the center of the screen, as discussed in the section 'site description'. The outcome led Bennett et al. (1967) to confirm their selection of the Cooper and Jacob (1946) method using semilog distance-drawdown curves. Chaudhari (1966) also reanalyzed some of these tests using Hantush's modification of the Theis solution for the early-time data only, from which he drew the conclusions given in the '*Introduction*'.

Hantush's modifications for partially penetrating wells were applied, for different anisotropies, to compare the special pumping test near Harrapa (B-9) with Chaudhari (1966) and Bennett et al. (1967). Numerical and analytical results for k_r match Bennett et al. (1967) but not those of Chaudhari (1966) and reveal that the horizontal conductivity increases with anisotropy, while the vertical conductivity decreases (Table 4.9). The difference with the results of Chaudhari (1966), who did not scale for anisotropy, is 50% at least. This study thus concludes that with the characteristics of the aquifer in the Punjabi Indus Basin, the interpretation by Bennett et al. (1967) gives reliable results. Hantush's modification of the Theis solution leads to erroneous results without scaling. Table 4.9 shows the results of special pumping test B-9 that were evaluated using Hantush's modifications of the Theis method, while Table 4.8 shows the findings of Bennett et al. (1967) and of Chaudhari (1966). The aquifer thickness, determined by Chaudhari (1966) varies between 220 and 500 m, but this range matches neither analytical solutions nor existing geological evidence (Kidwai, 1963). The Punjab aquifer extends to depths of at least hundreds to probably thousands of meters over most of the area (Kidwai, 1963; Bennett et al., 1967); petroleum explorations mention depths between 1,500 and 4,500 m (Kidwai, 1963). It is not possible to determine the exact thickness of the aquifer, but its effective depth can be estimated, as it was done and has been shown in the tables.

This study also evaluated pumping test B-9, one of the USGS's (Bennett et al., 1967) so-called special tests, for which original data could be found. Table 4.8 reveals that the anisotropy, in the Punjab, or, more probably, in Bari Doab, varies between 4 and 40 with an average value of 15. In these tests, the vertical hydraulic conductivity is calculated by considering the vertical head difference between deep and shallow observation wells and, therefore, likely represents the true value of anisotropy at the

Table 4.8: Summary of four special tests in Punjab (Bennett et al., 1967; Chaudhari, 1966).

Special tests description			USGS (Bennett et al., 1967)				Chaudhari (1966)[a]			Chaudhari (1966)[b]	
Test ID	**Site**	**Q**	**k_r**	**k_z**	**k_r / k_z**	**S_y**	**k_r**	**S_s**	**D[c]**	**k_r**	**S_y**
		m^3/d	**m/d**	**m/d**	**–**	**–**	**m/d**	**m^{-1}**	**m**	**m/d**	**–**
B-5	Renala Khurd	4,280	39.5	1.0	40	–	–	–	–	–	–
B-8	Pakpattan L. R.	7,340	31.6	4.0	8	0.24	19.8	1.31×10^{-5}	305	17.4	0.20
B-9	Near Harrapa	6,679	36.9	11.0	4	0.04	19.0	2.61×10^{-5}	220	16.1	0.19
B-10	Arifwala	6,125	29.0	2.0	14	0.31	15.2	2.00×10^{-5}	500	15.2	0.18
Average		6,100	34.2	4.5	15	0.20	18.0	1.31×10^{-5}	340	16.2	0.19

Notes:

[a] Hantush's modification of Theis for early-time data ($k_r / k_z = 1$).

[b] Boulton (1963) method of delayed yield from distant wells ($k_r / k_z = 1$).

[c] Indicates approximate depth as derived by Hantush (1961a).

Table 4.9: Interpretation of special pumping test (B-9: observation well at r = 30.5 m and 45 m deep) for different anisotropic factors using Hantush's modifications of the Theis and Jacob methods (Fig. 4.7).

	Units	**$k_r / k_z = 1$**	**$k_r / k_z = 4$**	**$k_r / k_z = 10$[c]**	**$k_r / k_z = 25$**	**$k_r / k_z = 100$**
k_r (Type-curve)[a]	m/d	19.3	29.7	34.5	47.4	59.6
k_z (Type-curve)[a]	m/d	19.3	7.4	3.5	1.9	0.6
S_s (Type-curve)[a]	m^{-1}	2.35×10^{-5}	2.85×10^{-5}	4.20×10^{-5}	4.25×10^{-5}	5.28×10^{-5}
D[b]	m	–	–	–	–	–

Notes:

[a] Early-time drawdown by using Eq. (4.1).

[b] D cannot be determined in this case, because Chaudhari (1966) published time-drawdowns up to 600 min in his technical report, which are too short to conclude some plausible results for the effective aquifer depth.

[c] $k_r / k_z = 10$ is the final result.

point of investigation. The aforesaid three parameters (k_r, k_z, S_s) have been estimated using Hantush's modification of the Theis method by including vertical anisotropy.

The horizontal hydraulic conductivity of test B-9, as determined by Bennett et al. (1967) was 36.9 m/d (Table 4.8), whereas the average vertical conductivity of the USGS's (Bennett et al., 1967) four special tests was 4.5 m/d (above the screen center). Comparing these values with findings as shown in Table 4.9, it may be concluded that an anisotropy of 10 best matches the data of Bennett et al. (1967). This conclusion can further be strengthened by comparing the numerical and analytical models with the observed data as shown in Fig. 4.7. Numerical and analytical solutions are identical for all anisotropies, which verifies the correctness of numerical model. The solution with an anisotropy factor of 10, best matches with the observed data. This differs about 5% with those of Bennett et al. (1967) [Refer to Tables 4.8 and 4.9].

CONCLUSIONS

Representative hydraulic parameters necessary to evaluate groundwater use on a regional scale are impossible to obtain under the intense dynamics of area-wide irrigation and the millions of wells currently pumping groundwater in the Pakistani Punjab. To overcome this, the extended drilling and pumping test campaign carried out by the USGS for Pakistan between 1954 and 1963 (Bennett et al., 1967) is reevaluated to obtain hydraulic aquifer values (k_r, k_z, S_s) and the aquifer thickness suitable for future use in groundwater models. Other authors also reexamined these original tests using type curves for a single aquifer ignoring vertical anisotropy. Limiting the distance of the piezometers to 120 m from the pumping wells, Bennett et al. (1967) ensured that vertical anisotropy did not affect the results of their 141 pumping tests. Bennett et al. (1967) applied a simple distance-drawdown analysis, which gives results different from transient type curves.

This study reevaluated these tests by means of Hantush's modifications of the Theis and Jacob methods for partially-penetrating wells to determine (1) hydraulic conductivity, (2) specific storage, (3) vertical anisotropy, and (4) thickness of the aquifer. It is shown that the Hantush modifications of the Theis and Jacob methods give unrealistic results if coordinates are not scaled to compensate for vertical anisotropy. This study reinterpreted the original pumping tests to the extent that the original data are still available in the Pakistani archives. This was done with the mentioned analytical solutions and a numerical model. It is concluded that the original pumping tests, including their partially penetration effects, can successfully be interpreted with Hantush's modifications of the Theis and Jacob methods.

Streamlines show that the flow is essentially horizontal within 90–120 m from the pumping well, and steady-state distance-drawdown curves indicate that the influence of vertical flow components above and below the well screen may be neglected in the Punjab ($k_r/k_z \geq 25$) for piezometers less than 120 m from wells. Therefore, the distance-drawdown method by Bennett et al. (1967), which neglected vertical components for observation screens less than 120 m from the well, is correct, and so the hydraulic conductivities as determined by Bennett et al. (1967) are recommended for groundwater studies without correction, at least as a first estimate. Bennett et al. (1967) representative hydraulic parameter values are: average horizontal hydraulic conductivity 65 m/d, vertical conductivity 3 m/d, vertical anisotropy 25. This study adds specific storage between 2×10^{-5} and 5×10^{-5} m^{-1}, and effective thickness of the Punjabi aquifer between 500 and 1,500 m.

CHAPTER 5

Multidepth pumping tests in deep aquifers

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ABSTRACT

Multidepth pumping tests (MDPTs), in which different sections of a screen are pumped in sequence, are not being used by hydrogeologists, despite the capability of such tests to resolve uncertainties in the estimation of aquifer characteristics. MDPTs can be used to discern the effects of partial penetration and vertical anisotropy. This chapter demonstrates the use of MDPTs for a deep and vertically anisotropic aquifer, based on a real and unique series of pumping tests conducted in the Indus Basin. Traditional single-layer methods, which incorporate partial penetration and vertical scaling, were employed to evaluate these tests. However, the drawdowns of the 19 piezometers at different depths for which times series data were available could not be matched, presumably because of the layered structure of the aquifer. Numerical (MODFLOW) and multilayer analytical (Hemker and Maas, 1987; Hemker, 1999) approaches were used to assess the benefits of using MDPTs in the analysis of deep layered and anisotropic aquifers. The multilayer analytical solution results are consistent with the measured and numerically computed drawdowns. The original step-drawdown data were used to verify the model independently. The results of statistical analyses indicate that the parameters for a three-layer system are uniquely estimated. A sensitivity analysis showed that aquifer depths greater than 900 m do not affect the drawdown. The multilayer analytical solution was implemented in MATLAB and can be found in the online version of this article in *Groundwater*. This multilayer analytical approach was implemented in MLU by Hemker and Randall (2013) for up to 40 layers. The results of this study will be useful in groundwater management, exploration, and optimal well depth estimation for the Indus Basin aquifer and other vertically heterogeneous aquifers.

INTRODUCTION

The use of multidepth pumping tests (MDPTs) to determine the characteristics of deep aquifers is very rare, although they are very useful for this purpose. MDPTs offer the additional advantage over single-depth tests of being able to discern the effects of partial penetration and vertical anisotropy. MDPTs can be used to resolve uncertainties in the estimation of aquifer parameters that otherwise may not be possible to estimate, as demonstrated in this chapter by the example of the Indus Basin (Sayed, 1984).

In general, well screens tend to be located in coarse sand within available sandy layers. The screen length itself causes local flow to be horizontal, precluding to a large extent the extraction of aquifer information regarding vertical anisotropy and partial penetration within a certain radial distance, which, for the Punjab, is approximately 120 m, according to Bennett et al. (1967). However, the effects of partial penetration and vertical anisotropy are very important in deep aquifers, especially with respect to saltwater upconing (Bennett et al., 1967), which is a considerable problem in the Indus Basin aquifer (Asghar et al., 2002) and elsewhere.

Saltwater upconing is limited by vertical anisotropy in addition to density differences. The effect of density in counteracting saltwater upconing is proportional to the inclination of the freshwater–saltwater interface and therefore is significant only after the months or years of pumping necessary for the interface inclination to build up. However, saltwater upconing is directly affected by vertical anisotropy (Alam and Olsthoorn, 2014a). Once equilibrium has been reached, the water below the interface will be essentially stagnant, and therefore, no information with respect to its properties can then be extracted from that part of the aquifer. Vertical anisotropy thus determines the time scale at which salinization occurs (Alam and Olsthoorn, 2013).

To prevent saltwater upconing, MDPTs can be used to estimate the optimum depth of future wells in which we want to maximize the screen length and minimize saltwater upconing (Alam and Olsthoorn, 2014a).

Chen et al. (2003) analyzed the sensitivities of parameters for unconfined aquifers in an *r*–*z* coordinate space using the contours of the relative errors over a vertical profile to optimize the depth of the observation screens. They concluded that composite analyses of multiple observation wells can reduce the correlations between the aquifer parameters during the optimization process.

Hydrogeologists usually evaluate pumping tests using traditional methods such as Theis log–log curve-matching and the Cooper–Jacob semilog method. Such single-layer methods are not suitable for interpreting the hydraulic parameters of a stratified aquifer. The main reason for the dissimilarity of the results obtained from different standard pumping test analysis methods is the heterogeneous nature of the aquifer. A second choice often applied after the use of these traditional methods is parameter optimization, which has its own problems that cause additional uncertainty, such as the nonuniqueness of parameters. Traditional or conventional methods are only suitable in cases in which wells penetrate the aquifer completely and the flow is truly horizontal. However, Hantush (1961a,b) proposed modifications of the Theis and Jacob methods that can be used to estimate hydraulic parameters in cases in which wells partially penetrate isotropic aquifers. Hantush's early-time drawdown solution can even be used to estimate the hydraulic parameters of a deep aquifer because the solution does not depend on the depth of the aquifer, whereas Hantush's late-time drawdown solution can be used to estimate the depth of the aquifer, as it models the drawdown reflection that returns from the bottom of the aquifer (Alam and Olsthoorn, 2014b).

Coordinate transformation can be used to extend these analytical solutions to the case of an anisotropic but homogeneous aquifer. We show that this transformation yields unrealistic results for the present MDPTs as these analytical solutions only provide unique results for piezometers within a single layer. These analytical methods cannot optimize the hydraulic parameters uniquely, especially in case of MDPTs, which accentuate differences due to vertical anisotropy in different layers. Therefore, we conclude that traditional methods of interpretation and single-depth pumping tests are insufficient to accurately determine the effects of vertical flow. This also holds true for the advanced methods of aquifer interpretation proposed by Moench (1997), Barlow and Moench (1999) and Moench et al. (2001) because these were also developed for a single-layer homogeneous aquifer of a known depth.

The main objective of this study is to show that vertical flow is important and that traditional methods tend to mask its effects due to (1) dominant horizontal flow in the depth range of the screen within approximately 100 m from the well, and (2) the fact that most piezometers are installed in the same range. MDTPs can determine the layer structure using piezometers and pumping screens in different layers. The groundwater management of the Indus Basin is hampered by a lack of reliable information about its hydraulic parameters, especially with respect to its intrinsic layered structure and its vertical anisotropy. This study intends to fill this gap. The data made it possible to divide the groundwater system at the test location in the Indus Basin into three distinct layers. The optimized hydraulic parameters of this three-layered groundwater system are shown in Figure 5.8.

METHODS

Site description

The Indus Basin aquifer is of huge importance for agriculture. To determine its characteristics, the US Geological Survey (USGS) carried out 141 pumping tests in the 1960s and 1970s (Bennett et al., 1967). However, the aquifer is so large that even after these tests, its thickness remained a mystery. Based on some special tests, which were used to assess the vertical conductivity of the aquifer, the USGS concluded that the aquifer underlying Punjab is essentially unconfined and anisotropic (Bennett et al., 1967). Since that time, Arif (1966), Chaudhari (1966), Mundorff et al. (1972), Kruseman and de Ridder (1990) and Boonstra (1992) have tried to estimate the parameters of the aquifer by re-evaluating the USGS tests (Bennett et al., 1967), ignoring, however, the vertical components of flow. These authors concluded that the USGS had overestimated the horizontal hydraulic conductivity by 25–100%. However, geological evidence and the USGS tests had clearly shown that vertical anisotropy is important. The analyses of all the aforementioned authors, except Bennett et al. (1967), did not properly consider vertical hydraulic conductivity, which is the main reason for the discrepancies between their results and those of Bennett et al. (1967). Alam and Olsthoorn (2014b) have re-evaluated the USGS's pumping tests of the Punjab, and they concluded that the simple distance drawdown interpretation applied by the USGS is a valid means of excluding the influence of partial penetration on the results.

In 1965, a series of MDPTs was carried out in the Indus Basin near Kazi Ahmad (approximately 240 km northeast of Karachi, as shown in Fig. 5.1 to quantify both

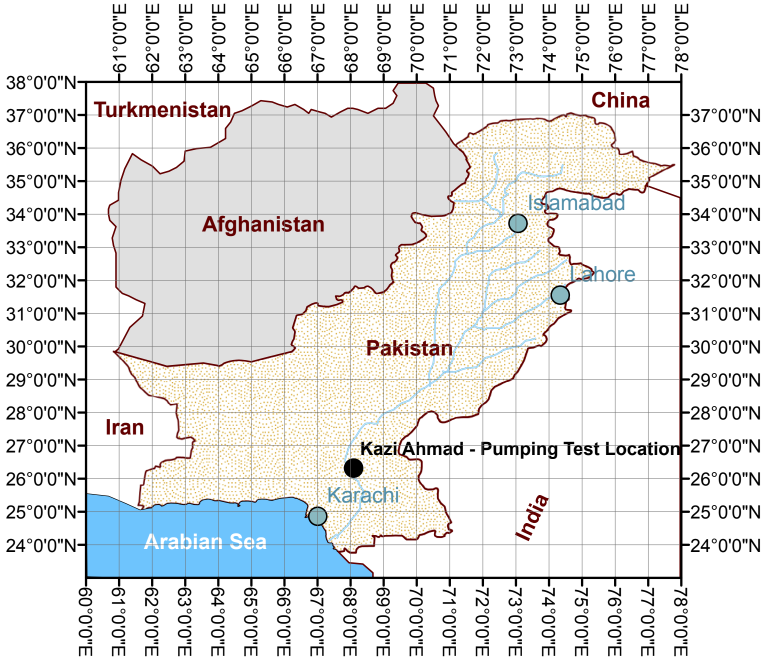

Figure 5.1: Location map showing the site of the MDPTs and step-drawdown test at Kazi Ahmad (Indus Basin, Pakistan). The black dot represents the testing location (after Sayed [1984]).

Table 5.1: Summary of piezometers used in calibration.

Nr.	Test nr.	Piezometer name	Included in calibration*	Distance r (m)	Depth z (m)
1	1	A8	1	15.2	−102.4
2	1	A7	1	15.2	−77.7
3	1	B5	1	15.2	−34.8
4	1	B6	0	15.2	−9.5
1	2	A8	1	15.2	−102.4
2	2	A7	1	15.2	−77.7
3	2	A6	1	15.2	−53.6
4	2	B5	1	15.2	−34.8
5	2	B6	0	15.2	−9.5
1	3	A1	0	4.6	−102.4
2	3	A2	0	4.9	−72.2
3	3	B2	1	4.9	−43.3
4	3	C2	1	4.9	−28.0
1	4	A8	1	15.2	−102.4
2	4	A7	1	15.2	−77.7
3	4	A6	1	15.2	−53.6
4	4	B5	1	15.2	−34.8
5	4	C4	1	15.2	−29.0
6	4	B6	0	15.2	−9.5

Note: * 1 means that the respective piezometer is included in the calibration, whereas 0 means that it is not included in the optimization process.
After Sayed (1984)

the vertical and horizontal conductivities of this aquifer (Sayed, 1984). This test was unique for (1) its use of a large number of piezometers (53) at different directions and depths (Figs. 5.2 and 5.3), and (2) the fact that after each test, approximately 25% of the screen, which was initially located 18.2 to 89.9 m below the ground surface

Table 5.2: Design parameters of MDPTs.

Test Nr.	Screen top (m)	Screen bottom (m)	Well discharge (m^3/d)	Well radius (mm)	Pumping duration (min)
1	−18.2	−89.9	7340	127	8,640
2	−18.2	−72.2	7340	127	5,760
3	−18.2	−45.7	4893	127	5,760
4	−18.2	−30.5	3670	127	5,760

After Sayed (1984)

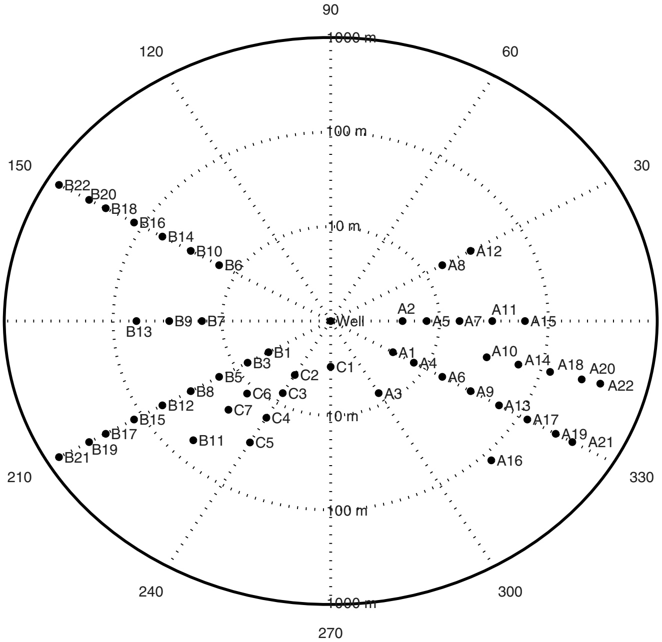

Figure 5.2: Areal locations of the piezometers (after Sayed [1984]). The radial distances are plotted on a log scale.

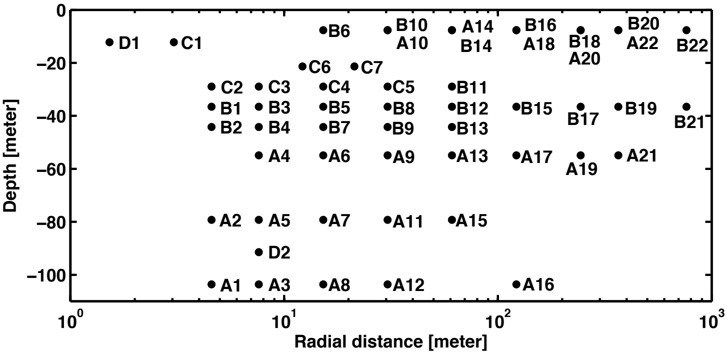

Figure 5.3: Spatial locations of the piezometers. The dots represent the centers of the piezometric screens (after Sayed [1984]).

(Table 5.2), was filled with grout to accentuate partial penetration effects in an attempt to obtain a clear view of the vertical conductivities. However, these tests have never been properly worked out. In his article in *Groundwater*, Sayed (1984) published final drawdowns graphically and showed the time-drawdown graphs of only 19 of the 53 piezometers. He made some comments on these graphs, but he did not analyze the results quantitatively. Our study describes for the first time the only full analysis of these tests that has been done and shows the differences between various approaches. The data used for our analysis are, however, limited to the information provided by Sayed (1984) because, despite our efforts, the original data could not be traced, even within the relevant governmental and academic institutions in Pakistan. Sayed, however, has provided us with the original data from his step-drawdown tests, which he carried out before test number 1, i.e., with the full screen being pumped. This original step-drawdown data have never been analyzed or published before. The data are given in Table 5.3.

Sayed (1984) describes the top 12 m at the site as silty clay, followed by medium to fine sand, with the water table at a depth of 4.5 m. The depth of the aquifer, however,

Table 5.3: Step-drawdown test data and comparison with the computed drawdowns.

Step[1]	**1**	**2**	**3**	**4**	**5**
Discharge (m^3/d)	**2,447**	**4,893**	**7,340**	**9,786**	**12,233**
Piezometers	**Drawdown in meters[3]**				
Well	1.10/1.17	2.04/2.36	3.34/3.57	4.69/4.79	5.94/6.01
P-1(E)[2]	0.02/–	0.05/–	0.05/–	0.05/–	0.09/–
P-2(E)[2]	1.07/–	1.91/–	3.01/–	4.14/–	5.17/–
P-3(E)[2]	1.06/–	1.87/–	2.99/–	4.12/–	5.14/–
P-1(W)[2]	1.09/–	1.98/–	3.18/–	4.42/–	5.63/–
P-2(W)[2]	1.11/–	2.03/–	3.30/–	4.67/–	4.76/–
P-3(W)[2]	1.08/–	1.99/–	3.18/–	4.43/–	5.66/–
A1	0.29/0.22	0.52/0.46	0.83/0.72	1.13/0.98	1.43/1.25
A2	0.58/0.53	0.99/1.07	1.57/1.63	2.13/2.21	2.68/2.78
A3	0.29/0.21	0.51/0.45	0.82/0.70	1.12/0.96	1.41/1.23
A4	0.55/0.47	0.97/0.95	1.53/1.46	2.10/1.97	2.60/2.48
A5	0.50/0.41	0.88/0.85	1.36/1.30	1.87/1.75	2.32/2.22
A6	0.42/0.35	0.74/0.72	1.34/1.11	1.62/1.50	2.02/1.90
A7	0.41/0.30	0.72/0.63	1.13/0.97	1.55/1.31	2.28/1.67
A8	0.28/0.20	0.50/0.42	0.79/0.65	1.12/0.89	1.40/1.14
A9	0.33/0.24	0.58/0.50	0.92/0.78	1.28/1.06	1.61/1.35
A10	0.15/0.11	0.26/0.26	0.40/0.42	0.62/0.60	0.98/0.78
A11	0.32/0.21	0.58/0.44	0.89/0.69	1.23/0.94	1.54/1.20
A12	0.27/0.17	0.48/0.35	0.78/0.55	1.03/0.76	1.30/0.98
A13	0.24/0.15	0.43/0.32	0.69/0.50	0.96/0.70	1.23/0.89
A14	0.20/0.09	0.38/0.21	0.65/0.35	0.91/0.50	1.18/0.65
A15	0.23/0.14	0.42/0.30	0.67/0.47	0.93/0.65	1.21/0.84
A16	0.16/0.07	0.30/0.17	0.46/0.28	0.65/0.40	0.86/0.51

Table 5.3: Step-drawdown test data and comparison with the computed drawdowns (continued)

Step[1]	**1**	**2**	**3**	**4**	**5**
A17	0.16/0.08	0.30/0.18	0.47/0.29	0.66/0.42	0.86/0.54
A18	0.05/0.05	0.09/0.13	0.13/0.22	0.21/0.33	0.29/0.45
A19	0.08/0.03	0.16/0.08	0.27/0.14	0.38/0.21	0.49/0.28
A21	0.04/0.01	0.10/0.04	0.16/0.08	0.24/0.12	0.32/0.17
B1	0.72/0.57	1.21/1.17	1.87/1.78	2.55/2.40	3.19/3.02
B2	0.60/0.55	1.04/1.11	1.66/1.69	2.29/2.28	2.87/2.88
B3	0.56/0.50	0.98/1.02	1.56/1.56	2.16/2.10	2.69/2.65
B4	0.53/0.46	0.93/0.95	1.48/1.45	2.04/1.96	2.58/2.47
B5	0.44/0.35	0.77/0.72	1.23/1.10	1.70/1.50	2.13/1.90
B6	0.47/0.12	0.40/0.28	0.69/0.46	1.04/0.65	1.42/0.84
B7	0.41/0.35	0.74/0.73	1.19/1.11	1.65/1.51	2.07/1.91
B8	0.35/0.25	0.60/0.52	0.96/0.80	1.34/1.09	1.70/1.39
B9	0.33/0.25	0.60/0.51	0.96/0.79	1.32/1.08	1.66/1.38
B10	0.10/0.11	0.24/0.25	0.51/0.42	0.81/0.60	1.13/0.78
B11	0.24/0.15	0.43/0.33	0.70/0.52	0.98/0.72	1.25/0.93
B12	0.24/0.15	0.43/0.33	0.70/0.52	0.98/0.72	1.25/0.92
B13	0.24/0.15	0.43/0.33	0.69/0.52	0.97/0.72	1.20/0.92
B14	0.24/0.09	0.43/0.21	0.69/0.35	0.99/0.50	1.26/0.66
B15	0.16/0.08	0.28/0.18	0.48/0.30	0.65/0.42	0.82/0.55
B16	0.09/0.05	0.19/0.13	0.34/0.23	0.52/0.34	0.66/0.45
B17	0.05/0.03	0.14/0.08	0.25/0.14	0.34/0.21	0.45/0.28
B18	0.08/0.02	0.16/0.05	0.26/0.10	0.35/0.16	0.46/0.23
B19	0.05/0.01	0.08/0.04	0.16/0.07	0.25/0.11	0.30/0.16
B20	0.03/0.01	0.06/0.02	0.11/0.05	0.18/0.09	0.25/0.13
B21	0.01/0.00	0.01/0.00	0.02/0.01	0.02/0.02	0.06/0.03
B22	0.00/0.00	0.01/0.00	0.02/0.01	0.02/0.01	0.06/0.02
C1	0.58/0.43	1.00/0.88	1.63/1.35	2.21/1.83	2.76/2.31
C2	0.70/0.53	1.13/1.08	1.81/1.65	2.45/2.22	3.06/2.80
C3	0.54/0.45	0.97/0.92	1.56/1.41	2.15/1.90	2.74/2.40
C4	0.14/0.34	0.79/0.71	1.38/1.10	1.74/1.49	2.15/1.89
C5	0.34/0.25	0.60/0.52	0.97/0.80	1.34/1.09	1.72/1.39
C6	0.50/0.38	0.87/0.78	1.40/1.20	1.96/1.62	2.49/2.05
C7	0.38/0.29	0.69/0.60	1.12/0.93	1.55/1.26	1.96/1.61

Notes: [1] Each step consisted of 100 minutes each.

[2] Six piezometers of 12.5 mm radius were installed within the gravel pack to study the well losses.

[3] Drawdowns are expressed as "Measured / Computed" values. The computed drawdowns were obtained using the multilayer analytical solution of Hemker and Maas (1987), Hemker (1999) and Hemker and Randall (2013).

is unknown. Sayed (1984) described the depth of the aquifer as practically infinite. By the very nature of the alluvial aquifer and from "other tests in the region" there can be no doubt that the aquifer is vertically anisotropic (Bennett et al., 1967). Sayed (1984) described the Indus Basin aquifer in this region as "well sorted, fine to medium micaceous sands, with bands and lenses of silt and silty clay. The surface layers contain more clay than the rest of the formation. These layers are thin and ranged within 15 m. In the lower layers, sand predominates; and the largest sand percentage occurs between 15 m and 60 m. The aquifer becomes more clayey below 60 m."

Test description

The pumping test was conducted in four parts, each of which was in itself a test conducted over the course of several days. The length of the screen was reduced with grout from 71.7 m to 54 m after the first test, then to 27.5 m after the second test, and finally to 12.3 m after the third (Table 5.2). Sayed (1984) showed the "final" drawdown of these tests in four charts in which all 53 piezometers are projected onto the *r*–*z* coordinate space, without regard to their orientation with respect to the well. The fact that these charts show reasonably consistent iso-drawdown lines implies that horizontal anisotropy does not play an important role. Instead of the absolute drawdowns, Sayed (1984) presented the drawdowns as percentages of the maximum drawdown inside the well. We translated these back into absolute drawdowns based on the time-drawdown graphs given in Sayed's article, taking the values near the end of each test as the absolute final drawdown. However, these graphs only represent at most 19 piezometers of the 53 during any of the tests at distances of 4.9 m or 15.2 m from the well. This matching resulted in a reengineered maximum drawdown at the well as 3.6, 3.9, 3.6 and 4.5 m for the four tests.

Sayed (1984) also presents a time-drawdown graph for each of the tests, in which he shows the course of the drawdown in 4, 5, 4, and 6 piezometers. It should be noted that the vertical logarithmic axis of his time-drawdown curves for test 4 is wrong by a factor of 10, as follows from his Figure 12.

Interpretation

Interpretations of these unique pumping tests have been unresolved since Sayed (1984). Our first attempt at resolution was to apply single-layer analytical methods, based on Hantush's modifications of the Theis solution for early-time drawdowns and Jacob's solution for late-time drawdowns (Hantush, 1961a,b). Both of these modifications are suitable for the interpretation of pumping tests with partially penetrating wells in a single aquifer. We applied these methods to all four tests separately, scaling the coordinates to address vertical anisotropy, as explained by Alam and Olsthoorn (2014b). The early-time drawdown solution does not depend on the aquifer depth, but it is highly sensitive to partial penetration and vertical anisotropy (Alam and Olsthoorn, 2014b). This should allow us to determine k_r (the horizontal hydraulic conductivity), k_z (the vertical hydraulic conductivity) and S_s (the specific storage) for a number of vertical anisotropies, after which the optimal anisotropy could be selected by matching the type curves with the actual drawdown measurements.

In a second step, the effective thickness of the aquifer could then be determined using Hantush's modification of the Jacob method, which is valid for late-time drawdowns and does depend on depth. This should provide the most appropriate value of the effective depth. Unfortunately, however, these analytical interpretations gave inconsistent results between the four tests. We conclude that this interpretation is not unique.

Next, we mimicked the analytical solutions using MODFLOW (Harbaugh et al., 2000) and PEST (Doherty, 2013), which made it possible to optimize the same parameters for all available time-drawdowns for all four tests jointly. The MATLAB-based MODFLOW model (mfLab; Olsthoorn, 2013) is axially symmetric and has a radius of 100,000 m and cell widths that increase logarithmically from 0.1 m to 13,110 m in 98 steps. Vertically, the 93 model layers vary in thickness from 1.8 m to 3.5 m and are refined gradually down to 7 cm toward the top and bottom of the screen. Uniform extraction along the screen is assumed as a boundary condition. There are no fixed head boundaries; all extracted water comes from storage. However, the size of the model is so large that the lack of head boundaries does not influence the drawdown during the tests. The numerical interpretations are explained in the following section.

The discussion of the numerical interpretations concludes with the vertical anisotropy of the sandy screen layer, the determined value of which is 1, which is unexpected in a layered aquifer. To find its cause, the multilayer analytical solution of Hemker and Maas (1987), Maas (1987) and Hemker (1999) was used to discern the effects of partial penetration and vertical anisotropy. This advanced analytical approach assumes the presence of a resistance layer (aquitard) between each pair of conductive layers (aquifers). The resistance layers control the vertical flow. The advanced analytical multilayer solution takes the transient release of water from the aquitards into account, whereas a simple numerical approach in which an aquitard is modeled by means of a single model layer cannot simulate this effect. The numerical model would require many resistant layers between two aquifers to model this effect. However, with the analytical multilayer solution, there is also no parameter combination that would allow the extraction of a vertical anisotropy above 1 from the data. In conclusion, the system has to be multilayered, which precludes the use of single-layer solutions for its interpretation.

RESULTS

Numerical interpretations

A single vertical anisotropy cannot represent the entire aquifer from the ground surface to a great depth because it would be inconsistent with the high clay content in the first 12 m mentioned by Sayed (1984) and the higher clay content detected in the region at greater depths.

To analyze the aquifer in a way that matches its geological description while keeping its representation as simple as possible, it had to be divided into three vertical zones: (1) from the ground surface to a depth of 12 m, (2) from a depth of 12 m to some distance below the screen to be determined by optimization, and (3) the zone below the second zone, which extends to a great depths (we chose a depth of 5,000 m). This third zone, however, has no piezometers. Further subdivision does not make sense as it leads to nonunique parameters. The analysis has, therefore, been performed numerically (for an analytical interpretation, see the next section). MODFLOW and PEST (Doherty, 2013) were used as implemented in the MATLAB code (mfLab; Olsthoorn, 2013). Sensitivity analysis shows that a depth greater than approximately 900 m has no affect on the drawdown (Fig. 5.4). Therefore, our a priori chosen model depth of 5,000 m is more than that required.

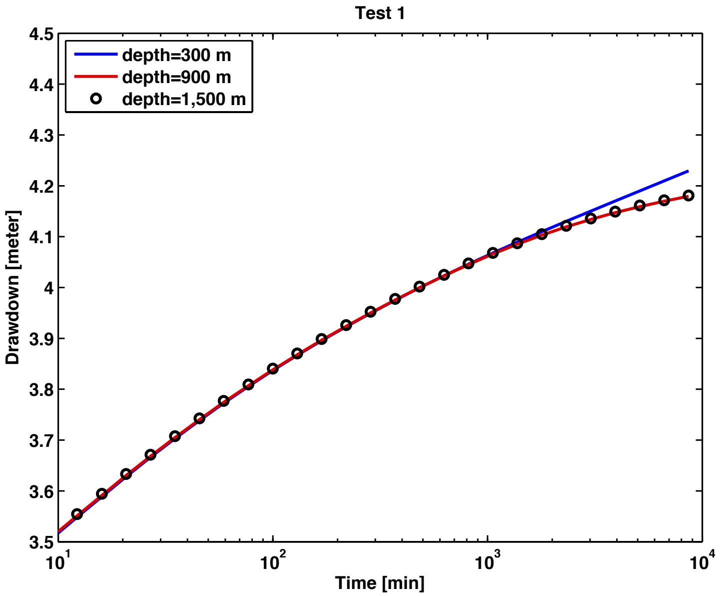

Figure 5.4: Sensitivity analysis of aquifer depth. The drawdown in the pumping well for three different depths in the case of Test 1 is shown. The blue line is almost hidden by red line; it is only visible at the end of the curve.

The parameters to be optimized are k_r, k_z and S_s for the aforementioned three zones and the specific yield S_y for the top layer. This set of parameters does not yield a unique result directly; prior information is necessary, for which we chose the following: (1) vertical anisotropy of 25 with a log standard deviation of 1.26 for the deepest zone, and (2) the top of zone 3 at 200 m below the ground surface with limits at 100 and 300 m and a log standard deviation of 2 to set their presumed uncertainty.

To weigh the early and distant drawdowns equally with late drawdowns, the log difference between the computed and measured drawdowns was used instead of the absolute difference.

Some piezometers did not perform well. In fact, measured drawdowns of these piezometers were physically impossible. One of these was the shallow piezometer B6 at a depth of 9.5 m and a distance of 15.2 m from the well. This piezometer sits in the first zone, far above the screen, yet it has a "measured" drawdown greater than those of the piezometers opposite the screen in zone 2, which is impossible. Assuming an error of a factor of 0.1 for the drawdowns of this piezometer, as in Figure 11 of Sayed (1984), did not yield realistic results. Therefore, the data from this piezometer had to be discarded (Table 5.1).

Piezometers A1 and A2 in test 3 also posed problems. Their drawdowns were greater than those of the model if run with vertical anisotropy 1 in zone 2. This implies that the vertical conductivity in this zone should be much higher than the horizontal conductivity, which is physically and geologically impossible. Perhaps, the legends for these piezometers in Figure 10 of Sayed (1984) are wrong. Figures 3 and 10 of Sayed (1984) also show inconsistent depths for piezometer A2. The data for these two piezometers therefore had to be discarded as well (Table 5.1).

The parameter optimization was performed for all the remaining piezometers of the four tests simultaneously. As the thickness of the shallow zone is only approximately 10% of the second, its transmissivity has hardly any effect on the drawdown. Therefore, without a piezometer in this zone (because we had to discard piezometer B6), its calibration was not possible.

On the basis of hundreds of bore logs made during their campaign in the Punjab, Bennett et al. (1967) estimated that clay layers made up 20% of the aquifer thickness. Assuming this is also true here, and assuming the average conductivity of the sand is the same throughout the aquifer, while that of the clay is negligible horizontally, a 20% presence of clay in the vertical profile can reduce the transmissivity of the aquifer and therefore its average horizontal conductivity by at most 20%. The three zones were considered to consist of alternating layers of sand and clay, with the conductivity of the sand always being the same. However, the percentages of sand were taken to be 50%, 100% and 80% in the three zones. The 80% estimate is based on Bennett et al. (1967), the 100% estimate is based on the fact that zone 2 consists entirely of sand,

and the 50% estimate is based on the fact that Sayed (1984) described the upper layer as silty clay. In any case, the horizontal conductivity of the first zone does not count much in the overall result. However, the presence of clay makes a large difference in the vertical conductivity. Therefore, vertical anisotropy has to be a separate calibration parameter for zones 1, 2 and 3. This resulted in a unique solution.

We have thus determined that a vertical anisotropy of approximately 25 for zone 3 could be considered representative to a depth of approximately 900 m. We found a vertical anisotropy of 1 to be optimal for the sand layer with the well screens and all the piezometers. The optimal value for the elevation of the bottom of the sand layer (zone 2) is approximately 130 m, 40 m below the screen, as it was in test 1. The optimal horizontal conductivity of the sand was found to be 30 m/d, and the optimal specific storage coefficient was found to be $4.13 \times 10^{-5}\ \mathrm{m}^{-1}$. The specific yield used for zone 1 was 14%, as suggested by Bennett et al. (1967), reflecting the fact that the system has essentially a free water table. This water table functions as a time-dependent top boundary for the fast elastic system below. Therefore, the vertical anisotropy of the top zone is an essential parameter governing the overall long-term drawdown of all deeper piezometers. To match at least the early behavior of the discarded shallow piezometer, we calibrated the vertical anisotropy of zone 1, together with its elastic storage coefficient, but keeping its specific yield at 14%. This resulted in $S_s = 2.00 \times 10^{-4}\ \mathrm{m}^{-1}$ and a vertical anisotropy of approximately 225. The early drawdown in the shallow but discarded piezometer B6 now matches the model; however, it does not match the late portion of this drawdown. Given that the evaluation of this late portion was neither physically nor geologically feasible, we consider only the time at which the shallow piezometer starts reacting rather than its absolute drawdown.

This final solution is shown in Figure 5.5, which contains all the measured drawdown time series in Sayed (1984) and the curves of our best model. For reference, the figure also contains the information from the discarded piezometers, but this information was not used in the optimization and should be ignored in the comparison.

In test 3, the early drawdowns in piezometers B2 and C2 deviate from the model, possibly owing to skin effects of the piezometer screens during the fast initial drawdown of these piezometers that were within 4.9 m of the pumped screen. Because data on the drawdown in the well during the pumping test were not available, the skin effect cannot be evaluated. These early drawdowns have, however, been included in the optimization and may thus have some effect on the result, which was not further analyzed. The optimized parameters are listed in Figure 5.8. The optimal elevation of the bottom of zone 2 is 130 m, 40 m below the initial screen bottom. The optimized vertical anisotropy of zone 1 is 225, and that of the deep zone is 25.

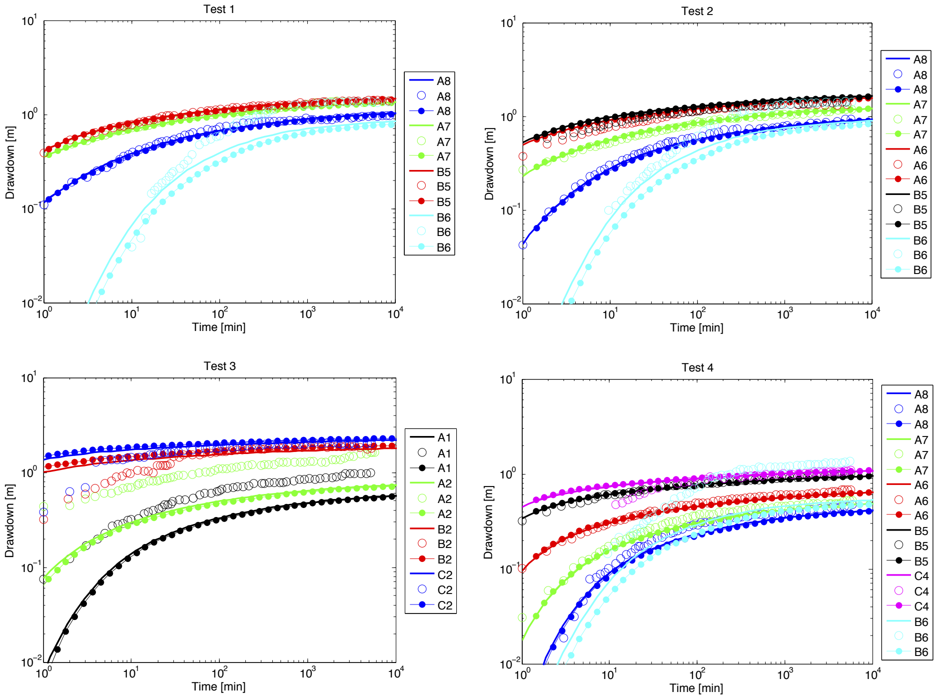

Figure 5.5: Measured and computed drawdowns with respect to time. The *hollow dots* represent the measured drawdowns, the *thick curves* represent the numerically computed drawdowns (MODFLOW), and the *solid dots* with lines represent the drawdowns computed analytically using the multilayer analytical solution (Hemker and Maas, 1987; Hemker, 1999). The piezometers “A1” and “A2” in Test 3 were not included in the optimization, as explained in the text. The shallow piezometer “B6”, represented by the *cyan color*, was also excluded, as discussed in the text. Refer to Table 5.1 for the depths and radial distances of the piezometers.

We verified the calibration results by comparing the model-computed final drawdowns with all 53 final drawdowns that Sayed (1984) presented. To accomplish this, we converted the relative drawdowns of Sayed (1984) to absolute ones using the previously mentioned maximum drawdowns that we reengineered for each test. The results are shown in Fig. 5.6. In this figure, the lines are the contours of the drawdown computed by the model, and the red crosshairs are the drawdown locations, along with the drawdown values of Sayed (1984), after our conversion. In general, the overall match is good for all four tests, as shown in Figure 5.6. This is also true for test 3, for which we had to discard two piezometers.

Multilayer analytical solution

Because using a single-model layer to represent an aquitard in a numerical model is sometimes insufficient to discern the effects of vertical flow in its entirety, MDPTs

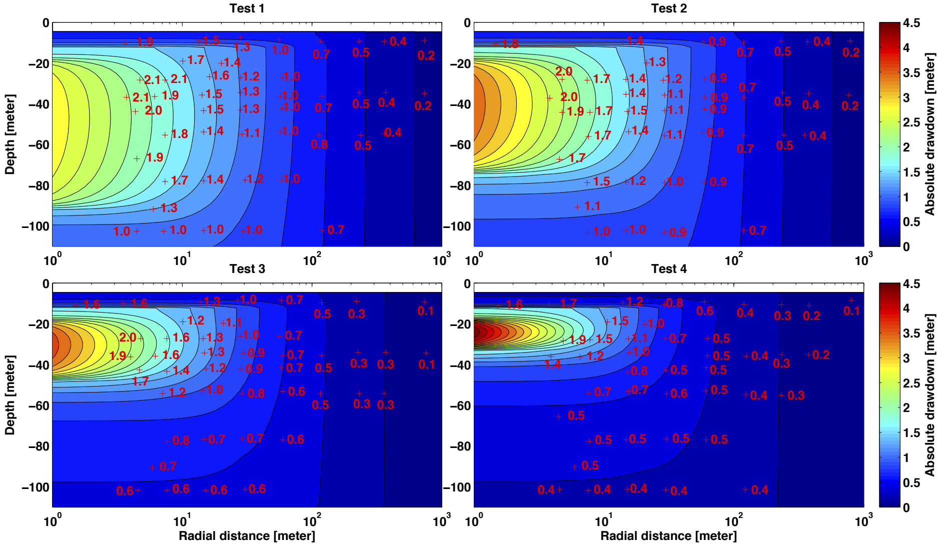

Figure 5.6: Spatial distributions of the final absolute drawdowns. The *color bar* represents the numerical scale of the results of the model, and the *red cross-hairs* represent the drawdown measurements (the converted values from Figures 4–7 of Sayed [1984]).

were also analyzed using the multilayer analytical solution of Hemker and Randall (2013). MDPTs may encounter vertical flow due to (1) partially penetrating wells or (2) a stratified aquifer. In such situations, the drawdown varies along the vertical profile and can be matched only if the aquifer is subdivided into a number of layers. Therefore, to accurately simulate the vertical flow, each zone of the aforementioned three-zone aquifer was further subdivided into many sublayers between 0.5 and 220 m thick. Each pair of sublayers was separated by a resistance layer. This subdivision was made keeping in mind the depths of the 53 piezometers and the 4 pumping screens to ensure sufficient detail regarding the vertical flow components. The total number of sublayers was 38, which were separated by 37 resistance layers of zero thickness. The parameters, optimized with the numerical model as described in the previous section, were supplied as initial estimates to optimize the MDPTs simultaneously using the analytical multilayer solution. To make the results compatible with the previous optimization, the hydraulic parameters were optimized in three groups corresponding to the original three-layered aquifer. This resulted in values for three parameters for each of the three zones, i.e., the transmissivity of each zone, its vertical resistance and its specific storativity. This subdivision was made only to estimate the vertical flow and hydraulic parameters uniquely given the situation that none of piezometers fall in the third zone.

This multilayer analytical solution takes into account the internal dynamics of the resistance layers (aquitards), but for this case, these dynamics did not make a difference, and could make a difference only in early drawdowns. The time required for the release of water from an aquitard may be estimated from the following equation

$$t = \frac{D^2 S_S{}'}{4k'} = \frac{Sc}{4} \tag{5.1}$$

This time estimate is independent of the thickness of the aquitard *D*, or rather, the dependence on the thickness of the aquitard is fully incorporated in its total storage coefficient *S* and its total hydraulic vertical resistance *c*. The delay caused by gradual release of water by resistant layers is here on the order of a maximum of 5 minutes and is hence negligible.

The multilayer analytical approach optimized the hydraulic parameters in such a way that the optimization trials tended to decrease the vertical anisotropic ratio of the sandy screen layer by approximately 20–30% below our physical lower limit of 1. If we fix the vertical anisotropy of the second zone at 1, we obtain the same results as those obtained from the numerical optimization. The match between the measurements and the analytical results is almost perfect, with somewhat reduced values for zone 2, but they are still very good if the vertical anisotropy of zone 2 is limited to 1 (Fig. 5.5).

The equivalent multilayer analytical solution of the aforementioned numerical model was obtained for the following layer values: (1) transmissivities (m^2/d) of the 38 aquifer sublayers, T = [1.5; 33; 33; 15; 33; 60; 60; 60; 114; 120; 120; 120; 60; 120; 120; 120; 120; 120; 120; 120; 120; 120; 120; 60; 120; 120; 117; 123; 120; 120; 30; 120; 90; 300; 378; 441.6; 1176; 6000], (2) resistance (days) of the 37 aquitards, c = [17.06; 32.63; 23.73; 23.73; 31.15; 0.07; 0.07; 0.10; 0.13; 0.13; 0.13; 0.10; 0.10; 0.13; 0.13; 0.13; 0.13; 0.13; 0.13; 0.13; 0.13; 0.13; 0.10; 0.10; 0.13; 0.13; 0.13; 0.14; 0.13; 0.08; 0.08; 0.12; 0.22; 0.38; 0.52; 35.10; 155.73], (3) storativities of the aquifer sublayers, S = [0.2; 4.4; 4.4; 2; 4.4; 0.83; 0.83; 0.83; 1.57; 1.65; 1.65; 1.65; 0.83; 1.65; 1.65; 1.65; 1.65; 1.65; 1.65; 1.65; 1.65; 1.65; 1.65; 0.83; 1.65; 1.65; 1.61; 1.69; 1.65; 1.65; 0.41; 1.65; 1.24; 4.13; 5.2; 7.6; 20.2; 103] $\times 10^{-4}$, and (4) the storativities of the resistance layers (*S*′), which were all set to zero or very low values (1×10^{-8}).

Notice that the analytical multilayer model does not require thicknesses; they are implicit in the transmissivities and resistances. The piezometers B6, C2, C4, B5, B2, A6, A2, A7, A8 and A1 are located in layers 4, 11, 11, 13, 15, 18, 23, 24, 31 and 31, respectively, of the equivalent multilayer model. MODFLOW or other numerical implementations should have all the aforementioned aquifer and aquitard sublayers and an extra aquifer on the top and the bottom to allow fixing of the head. The aquifers should have $k_z = 1 \times 10^6$, $k_r = D/T$ and $S_s = S/D$, and the aquitards should have $k_z = d/c$, $k_r = 0$ and $S_s = S'/D$, where D and d are the thicknesses of the aquifer and aquitard sublayers, respectively, which are taken as unity with their transmissivities and resistances as given above. The head is fixed on top of the top aquitard and at the bottom of the lowest aquitard, as mentioned earlier. The radial extent of the model should be sufficiently large to match the results with the analytical solution. This equivalent system can readily be used to reproduce the numerical model without knowing any other information regarding the numerical model.

Step-drawdown test

Step-drawdown tests can be used to determine aquifer characteristics (Clark, 1977) and well losses. Sayed (1984) mentioned step-drawdown tests that were performed at the same location (Fig. 5.1) before each constant-rate pumping test. We greatly appreciate his willingness to send us the data for the original step-drawdown test conducted before the pumping test Nr 1. The screen top and bottom and the other design parameters are therefore equal to those of test 1 (Table 5.2). These original step-drawdown data are shown in Table 5.3, with one column per step, along with the drawdown values computed using the multilayer analytical solution as implemented in the MLU software (Hemker and Randell, 2013). The results form an independent check of our previous optimizations. The results shown in Table 5.3 indicate that the

Table 5.4: Statistical summary of parameter optimization.

Statistical measure	**Performance indicator**	
	Multidepth pumping tests	**Step-drawdown test**
Mean of residuals (m)	0.301	0.137
Standard variance of residuals (m^2)	0.112	0.018
Standard deviation / standard error of residuals (m)	0.334	0.134
Root-mean-square (m)	0.335	0.134
Correlation coefficient	0.998	0.987

Table 5.5: Parameter correlation coefficient matrix.

	k_r	$(k_r/k_z)_2$	$(k_r/k_z)_3$	S_s	D
k_r	**1.000**	5.830×10^{-1}	3.476×10^{-2}	-6.740×10^{-1}	-2.660×10^{-1}
$(k_r/k_z)_2$	5.830×10^{-1}	**1.000**	2.072×10^{-2}	-8.060×10^{-1}	-1.360×10^{-1}
$(k_r/k_z)_3$	3.476×10^{-2}	2.072×10^{-2}	**1.000**	-1.749×10^{-2}	3.513×10^{-3}
S_s	-6.740×10^{-1}	-8.060×10^{-1}	-1.749×10^{-2}	**1.000**	7.037×10^{-2}
D	-2.660×10^{-1}	-1.360×10^{-1}	3.513×10^{-3}	7.037×10^{-2}	**1.000**

Note: $(k_r/k_z)_2$ is the vertical anisotropy in zone 2 and $(k_r/k_z)_3$ is the vertical anisotropy in zone 3.

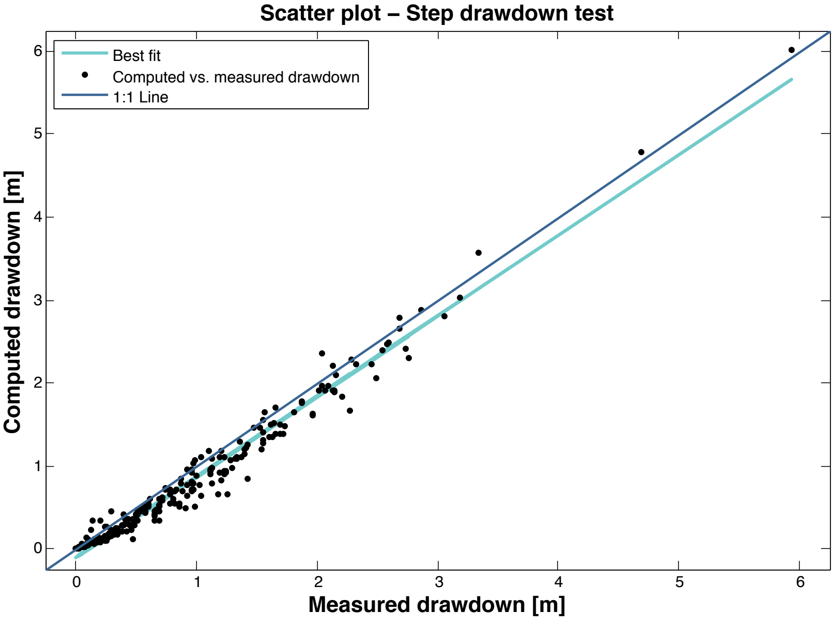

Figure 5.7: Scatter plot of the measured and computed drawdowns (from the multilayer analytical solution) from the step-drawdown test.

computed drawdowns are reasonably accurate; their root-mean-square error (RMS) is 0.134 m, which is much less than the value of 0.335 obtained from the MDPTs (Table 5.4).

A scatter plot of the measured versus computed drawdowns is shown in Figure 5.7. The graph suggests a strong relationship between the computed and measured values.

The difference in the drawdown between the average of the five working piezometers in the gravel pack and that in the well (Table 5.3) reveals that the well losses range between 0.02 m in step 1, with a flow of 30 lps, to 0.67 m in step 5, with flow of 140 lps.

Statistics

Doherty (2013) concluded that the correlation coefficient between the measured and computed drawdowns should be greater than 0.9 to be considered acceptable (Hill et al., 1998). We obtained coefficients of 0.998 and 0.987 for the MDPTs and the step-drawdown test, respectively (Table 5.4). The summary of the statistical measures (Table 5.4) indicates that the optimized parameters are within the specified limits and represent the real system well. The RMS scores are excellent, according to the ranking system developed by Henriksen et al. (2003).

Table 5.6: Parameter covariance matrix.

	k_r	$(k_r/k_z)_2$	$(k_r/k_z)_3$	S_s	D
k_r	5.854×10^{-5}	1.576×10^{-4}	1.059×10^{-6}	-2.011×10^{-4}	-1.776×10^{-5}
$(k_r/k_z)_2$	1.576×10^{-4}	1.249×10^{-3}	2.914×10^{-6}	-1.111×10^{-3}	-4.206×10^{-5}
$(k_r/k_z)_3$	1.059×10^{-6}	2.914×10^{-6}	1.584×10^{-5}	-2.715×10^{-6}	1.220×10^{-7}
S_s	-2.011×10^{-4}	-1.111×10^{-3}	-2.714×10^{-6}	1.521×10^{-3}	2.394×10^{-5}
D	-1.776×10^{-5}	-4.206×10^{-5}	1.220×10^{-7}	2.394×10^{-5}	7.607×10^{-5}

Note: $(k_r/k_z)_2$ is the vertical anisotropy in zone 2 and $(k_r/k_z)_3$ is the vertical anisotropy in zone 3.

Table 5.7: Normalized eigenvectors of parameter covariance matrix.

	Vector_1	Vector_2	Vector_3	Vector_4	Vector_5
k_r	-5.904×10^{-2}	-9.490×10^{-1}	-2.850×10^{-1}	5.958×10^{-2}	-0.103
$(k_r/k_z)_2$	-1.945×10^{-3}	2.121×10^{-3}	7.420×10^{-2}	-7.490×10^{-1}	-0.659
$(k_r/k_z)_3$	9.980×10^{-1}	-6.211×10^{-2}	4.298×10^{-4}	-1.310×10^{-3}	-1.609×10^{-3}
S_s	-7.239×10^{-3}	-1.220×10^{-1}	1.550×10^{-3}	-6.560×10^{-1}	0.745
D	-1.790×10^{-2}	-2.830×10^{-1}	9.560×10^{-1}	7.698×10^{-2}	1.929×10^{-2}
Eigenvalues	-1.579×10^{-5}	2.715×10^{-5}	7.814×10^{-5}	2.676×10^{-4}	2.531×10^{-3}

Note: $(k_r/k_z)_2$ is the vertical anisotropy in zone 2 and $(k_r/k_z)_3$ is the vertical anisotropy in zone 3.

The parameter correlation coefficient (PCC) was calculated for each possible pair of model parameters. If the PCC for a pair of parameters is close to 1, the parameters cannot be estimated uniquely. The absolute values of the correlation coefficients between the different parameters are shown in Table 5.5. The values are much less than 1, which implies that the optimized parameters have been estimated uniquely.

Tables 5.6 and 5.7 present the parameter covariance values between different parameters and their normalized eigenvectors and eigenvalues. The values in these tables are expressed in terms of log values. We have converted these matrices back to their real-world values and found that the standard deviations of the estimated parameters range between ±1% and ±9%, which suggests that the parameters are uniquely estimated.

CONCLUSIONS

Food production in Pakistan relies heavily on the Indus valley, which is densely populated and has been intensively irrigated, originally by surface water but since the 1960s increasingly by groundwater. Currently, millions of wells are simultaneously pumping groundwater from the Indus Basin. The groundwater away from the rivers of the Indus Basin is naturally salty as a result of the infiltration of these rivers

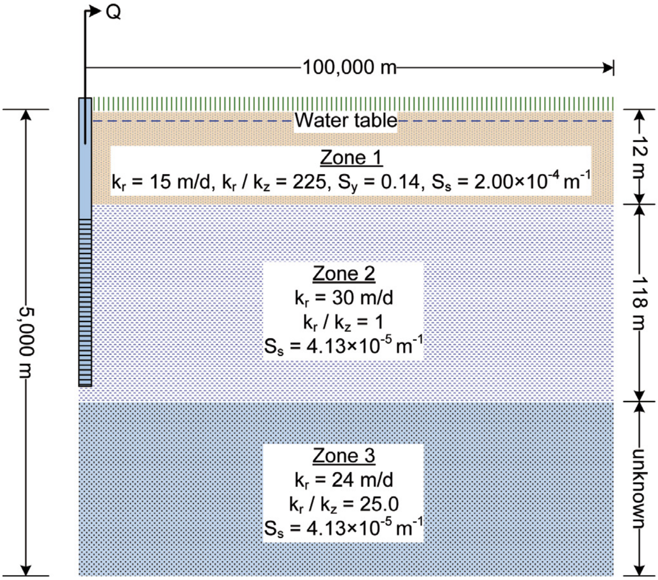

Figure 5.8: Three-layered groundwater system in the Pakistani Indus Basin, with optimal values.

and the evaporation, which caused salt water to accumulate away from the rivers. Large-scale surface water irrigation schemes in place since the early 1900s have over time leaked so much water that this water, together with irrigation return flow, has become a source of fresh water for famers. Due to the irregular availability of canal water, farmers have come to rely more on groundwater. This increasing groundwater usage causes wide-scale salinity problems due to salt upconing, which endangers food security and livelihoods in the long run. The salt upconing itself is affected by vertical anisotropy. To prevent salt upconing, MDPTs can be used to estimate the optimum depths of future wells. MDPTs can also be used to resolve uncertainties in the estimation of aquifer parameters and aquifer layering that otherwise may not be possible to resolve (Figure 5.8).

The subsurface of the area consists of unconsolidated sediments of the Indus river branches in alternating layers of sands and clays, several hundred to a thousand meters deep or more. The exact depth of the aquifer is unknown, as no test well has ever been drilled deeper than 450 m — no one has reached the bedrock. However, petroleum explorations mention depths between 1,500 and 4,500 m (Kidwai, 1963). The groundwater system is essentially a single unconfined aquifer that is highly vertically heterogeneous owing to the nature of the fluvial deposits, with an average overall vertical anisotropy factor on the order of 25 (Bennett et al., 1967).

Alam and Olsthoorn (2014b) have reevaluated the USGS pumping tests and recommended hydraulic parameters to be used in groundwater studies, at least as initial estimate. On the basis of single-layer early-time drawdown and late-time drawdown analytical methods, they reevaluated the single-depth pumping tests to reach their conclusions. The piezometers in these single-depth pumping tests were only screened in the sandy layer and mostly at the center of the screen interval. Therefore, their characterization of the aquifer does not provide reliable information regarding the layered groundwater system.

In this study, the MDPTs were interpreted on the basis of data from a network of 53 piezometers in different layers. The results of these four full-scale tests provide detailed information on vertical and horizontal conductivities in the important Indus Basin aquifer, obtained by reducing the screen length after each test through grouting the lower 25% of the screen. This, together with the large number of piezometers, makes the tests unique. Traditional methods of interpretation and single-depth pumping tests are insufficient to accurately determine the effects of vertical flow, especially in the case of MDPTs and a layered groundwater system.

Parameter optimization with PEST using MODFLOW uniquely estimated the hydraulic parameters for a three-layer system corresponding to the geology of the aquifer. However, simultaneous optimization of the four MDPTs yields a vertical anisotropy of the sandy screen layer of 1, which is unexpectedly low. To determine the reason for this low value, the MDPTs were analyzed using the multilayer analytical solution of Hemker and Maas (1987), Maas (1987) and Hemker (1999), in which resistance layers (aquitards) between aquifers control the vertical flow. This analytical solution takes into account the internal dynamics within resistance layers, causing them to gradually release their water, which results in a delay in the drawdown compared to that predicted by more simplistic methods such as the representation of the aquitard as a single layer in a numerical model. This delay may affect early drawdowns and was therefore considered important. Efforts were made to explore parameter combinations that would increase the vertical anisotropy of the sandy screen layer above the seemingly unrealistic value of 1, but the multilayer analytical solution showed that this is impossible. Geologically, a vertical anisotropy of 1 may be possible for sandy layers but definitely not for the entire aquifer. The multilayer analytical solution yields results that are consistent with the measured and numerically computed drawdowns when we use the optimized hydraulic parameters.

A step-drawdown test was used to check the correctness of our model. The original data from the step-drawdown test were collected using 56 piezometers, including 6 piezometers in the gravel pack, which can be used to analyze the well losses. This data set was never published or analyzed, and we are taking the opportunity to make it available to the groundwater community along with our analysis.

The optimized hydraulic parameters for the layered groundwater system are shown in Figure 5.8. The optimization statistics show that these parameters were estimated uniquely and that their standard deviations range from ±1% to ±9%. A sensitivity analysis concludes that an aquifer depth greater than approximately 900 m does not affect the drawdowns. The Indus Basin aquifer is very likely to be well over 500 m deep. The results of this study show that vertical flow is important in vertically heterogeneous aquifers and that its effects are masked by traditional methods for conducting and analyzing pumping tests because of the dominance of horizontal flow in the depth range of the screen and the fact that most piezometers are installed in the same range. We hope that the results of this study will be useful in groundwater management, exploration, and optimal well depth estimation for the Indus Basin aquifer and other vertically heterogeneous aquifers.

CHAPTER 6

Sustainable conjunctive use of groundwater for additional irrigation

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ABSTRACT

The key to 'sustainable conjunctive use of groundwater for additional irrigation' is the salt balance of groundwater below an irrigated field. This chapter aims to develop a mathematical tool to study the accumulation of salt in the groundwater below an irrigated field as caused by irrigation recirculation. This study derives a salt balance of groundwater to ensure that the additional irrigation from groundwater remains possible in the future. The water and salt budgets by themselves do neither provide information concerning farmers' options nor on the limits of the individual terms in the budget equations. It is presumed that farmers will intuitively aim for (1) an optimal value of the actual evapotranspiration, and (2) a return flow as a feasible low fraction of the available water. We, therefore, derive the irrigation from groundwater Q as a consequence of the predefined farmers' aims to achieve a high actual evapotranspiration in combination with a given optimally used irrigation system. Our model concludes that the required amount of drainage is only dependent on the ratio of the salinity in the surface irrigation water and the acceptable salinity of the groundwater. The final salinity in the saturated zone only depends on salt-carrying inflows and outflows. From the aforesaid model, it is further concluded that sustainable conjunctive use of groundwater for additional irrigation requires long-term salt management, which should be founded on the essential controlling factors as derived in this study.

INTRODUCTION

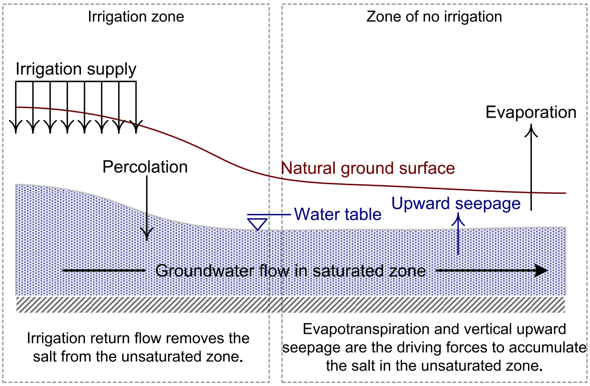
The major cause of salinity in the groundwater system is the irrigation return flow. Canal water and groundwater contain salts that remain behind after the water has evaporated. The most important way to control salt is drainage. A sufficient amount of drainage could be between 10% and 20% of the irrigation water, which should be discharged through an appropriate drainage system. The salt concentration in the drainage water should normally be 5–10 times higher than that of the irrigation water (Wikipedia, 2013b). This condition ensures a long-term salt balance, and, therefore, salt will not accumulate in the saturated zone (Ritzema, 1994).

Salinity is a common environmental problem in arid and semi-arid irrigated lands as it lowers the crop yield. The problems are associated with high water tables, which are often caused by a lack of subsurface drainage. Poor subsurface drainage may be attributed to (1) an insufficient transport capacity of the aquifer, and (2) a situation where water cannot exit from the aquifer, for instance, a topographical depression or when an area is enclosed by inflow boundaries such as different doabs in the Punjab (a doab is an area enclosed between two adjacent rivers, refer to Wikipedia, 2013a). The major factor in the accumulation of salt in soils is a lack of net recharge (Wikipedia, 2013b; Ritzema, 1994).

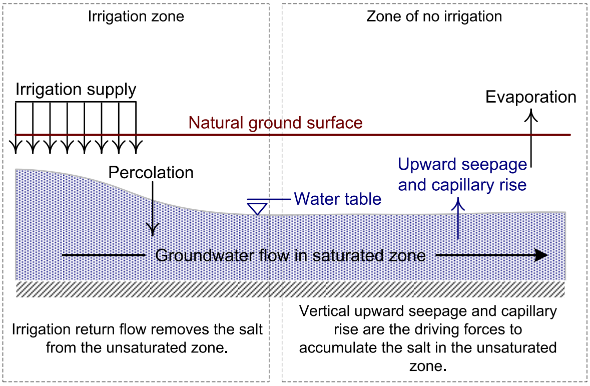
The second cause of salinity in irrigated lands is waterlogging, which may be the result of changes of the natural water balance after the introduction of irrigation. Plants often do not completely consume irrigation water. It is not possible to attain 100% irrigation efficiency in most irrigation systems. The maximum feasible irrigation efficiency is almost 90%, but usually, it is less than 60%. It depends upon the irrigation method and the farmers' discipline (Brouwer et al., 1989). This means that a minimum of 10% but usually more than 40% of the irrigation water is not evaporated and transpired. The water returns to the saturated zone as irrigation return flow. The return flow, more than the expectations, significantly changes the natural hydrology of aquifers. Many aquifers can neither absorb nor transport these quantities of irrigation return flow, and as a consequence, the water table rises and finally leads to waterlogging and salinity (Ritzema, 1994; Wikipedia, 2013b).

The significance of the salt balance of groundwater is frequently underrated, whereas the information from such analysis is of huge importance (Kijne, 1996). The water resources managers seldom pay proper attention to analyze the water and salt balance before designing, rehabilitating and managing the water resources (Kijne, 1996). Hoorn and Alphen (1994) and Ridder and Boonstra (1994) have given an overview of the various techniques and models to determine water and salt balances of saturated and unsaturated zones. Ridder and Boonstra (1994) stressed to estimate the drainage requirement of an irrigated field, which prevents waterlogging and crop damage due to high concentration in the unsaturated zone. Thayalakumaran et al. (2007) have discussed the application of the salt balance phenomenon at different scales. They concluded that a favourable salt balance is achievable at a root-zone scale, although it is often neither practical nor necessarily beneficial for scales larger than the root-zone. Zhou (2009) has clarified the water budget controversy and uses the water balance to analyze the concepts of safe yield and sustainable yield. Marlet et al. (2009) presented a simple salt balance model suitable for irrigation schemes. Their analyses enabled the magnitude of the salinization process to be foreseen as a function of hydrological changes linked to irrigation, drainage, groundwater flow and extension of the irrigated area. They successfully applied their approach in Fatnassa oasis. Their approach could be generalized to other situations with some limitations.

The water and salt budgets do not provide information on farmers' options though these are very useful. These budgets do not provide limits on the individual



(a) Salt accumulation in the lower part of undulating land due to evapotranspiration and vertical upward seepage.



(b) Salt accumulation in the lower part of flat land due to vertical upward seepage and capillary rise.

Figure 6.1: Influence of aquifer conditions on salt accumulation below an irrigated field (after Oosterbaan [2003]).

terms in the budget equations; however, it can be presumed that farmers will aim for an optimal value for the actual evapotranspiration. It can further be assumed that the farmer will intuitively aim for a return flow as a feasible low fraction of the available water. Too high a return flow implies a loss of irrigation water and too low a value will cause elevated salinities that would lower crop production. Therefore, this study derives Q, irrigation from groundwater, as a consequence of the defined farmers' aims. To make sure that additional irrigation from groundwater remains possible in the future, the concentration in the saturated zone, c_2, can be limited to a maximum allowable concentration. This can be achieved by draining a sufficient amount of water.

Aquifer conditions below an irrigated field and the groundwater flow play an important role in groundwater salinity (Fig. 6.1). This chapter quantifies long-term accumulation of salt and recirculation below a typical irrigated field. This chapter also derives the salt balance of groundwater below an irrigated field due to irrigation recirculation. The derived salt balance of groundwater can be used to design additional sustainable irrigation from groundwater. To achieve this aim, long-term development of subsurface salinity is investigated in relation to drainage and additional irrigation from groundwater.

IRRIGATION RECIRCULATION

This study considers a soil column divided into two distinct reservoirs (Fig. 6.2). Reservoir 1 is the unsaturated zone; it is the zone from which evapotranspiration takes place. Reservoir 2, is the saturated zone, Punjab aquifer. Each reservoir has incoming and outgoing fluxes (Fig. 6.2). The water balance is based on the principle of conservation of mass for boundaries defined in space and time and can be written as

$$\text{In} - \text{Out} = \text{rate of change of storage}$$

The additional irrigation from groundwater is necessary in Punjab because transient supply of surface irrigation water is not enough to meet the irrigation demand of farmers. Moreover, the onfarm availability of groundwater immediately fulfills the crop water requirements, and therefore, groundwater irrigation has emerged spontaneously from the need of farmers in the Punjab. The aim of this study is to investigate long-term development of subsurface salinity in relation to drainage and additional irrigation from groundwater. This can be investigated by considering the long-term water budget of the subsurface in equilibrium. The rationale behind this is that min-

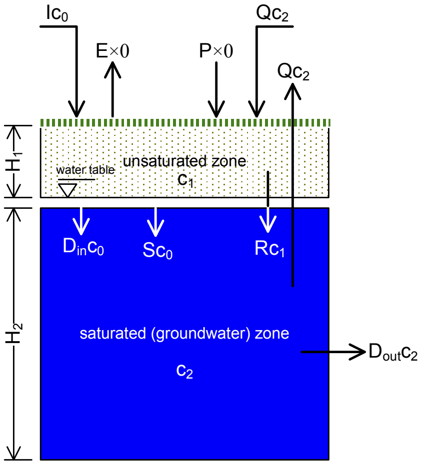


Figure 6.2: Salt balance conceptual model to study the irrigation recirculation.

ing by over extraction is impossible in the Punjabi doabs, because it would lead to salt concentrations beyond the point that is not supportable for farming. The surplus of the groundwater budget is not possible on the long term, as this would lead to waterlogging, and therefore, to prevent permanent loss of food production capacity generally implies increase of drainage. Variations of the water budget within a year or between years are of less importance to the long-term development of the overall salinity of the currently fresh groundwater. The long-term analysis is not affected by the fact that irrigation from surface water and additional irrigation from groundwater are more or less mutually exclusive at any one time, because groundwater extraction means an extra cost to the farmer and, generally, also a higher salinity than the surface water that is supplied through the irrigation system, when it is available.

The water budget is, therefore, considered steady state or long term. It can be drawn up for the unsaturated and saturated zones separately. A combined water budget is also possible with minor or no differences with respect to the final conclusions. With this steady water budget in mind, this study considers the transient development of the salinity in the subsurface, which is a slow process and may take hundreds of years to reach equilibrium. The water budget can be expressed as

$$I + P + Q - E = R \tag{6.1}$$

$$S + R - Q + D_{in} - D_{out} = 0 \tag{6.2}$$

where Eq. (6.1) represents the unsaturated zone and Eq. (6.2) the saturated zone, with all water fluxes in L/T; I is irrigation surface water delivered via the irrigation system; P is precipitation; Q is irrigation from groundwater; E is actual evapotranspiration including interception; R is irrigation return flow for the water budget of the unsaturated zone (Eq. 6.1). S is the leakage (seepage) from surface irrigation canals, R is the incoming irrigation return which includes I, P and Q (Eq. 6.4), Q is the extraction by irrigation wells, D_{in} is water infiltrating from bounding rivers into the saturated zone and D_{out} is groundwater discharging to the bounding rivers for the water budget of saturated zone (Eq. 6.2). Drainage generally consists of (1) natural drainage along with natural groundwater head gradients, and (2) artificial drainage to the dedicated drainage infrastructure including possibly drainage wells. Away from the rivers in the Punjab, most of the doabs currently have a water table not far below ground surface. It has risen by sometimes more than 20 m since the onset of irrigation by the end of the 19th century (Greenman et al., 1967). Currently, doab-wide groundwater gradients are small, so that natural drainage is also small. Therefore, required drainage is mainly artificial through drainage canals and vertical drainage wells. Figures for the average rates of the different terms for the situation in the Punjab are given in Table 6.1.

Table 6.1: Representative values of Punjab for salt and water balance model.

Terms	Description	Value	Unit	References
P	Precipitation	0.21	mm/d	Ahmad (1972); Arcadis-Euroconsult et al. (1999)
S	Canal seepage	0.58	mm/d	Ahmad and Ahmed (1985); Arcadis-Euroconsult et al. (1998a)
Q	Groundwater extraction	1.52	mm/d	Shah et al. (2003a)
E_0	Potential evapotranspiration	4.71	mm/d	Arcadis-Euroconsult et al. (1998b)
E	Actual evapotranspiration	1.63	mm/d	Arcadis-Euroconsult et al. (1998b)
I	Surface water irrigation	1.51	mm/d	Ahmad and Ahmed (1985)
θ	Field capacity	0.1	–	Brouwer et al. (1985)
ϵ	Total porosity	0.35	–	Greenman et al. (1967)
H_1	Thickness (zone 1)	10	m	Representative thickness of unsaturated zone[a]
H_2	Thickness (zone 2)	20	m	Representative thickness of saturated zone[b]
c_0	Surface water concentration	500	mg/L	Greenman et al. (1967)[c]
r	Irrigation efficiency	0.2	–	Arcadis-Euroconsult et al. (1998c,d, 1999)[d]
e	Crop factor	0.75	–	Arcadis-Euroconsult et al. (1998b)

[a] Based on the data collected during field measurements (Alam, 2011; WAPDA, 2012). It is the representative value in the central part of doabs in the Punjab.

[b] Based on recent transient electromagnetics (TDEM) measurements in the Punjab (Alam, 2011). The thickness of the saturated zone, containing freshwater, is variable in space. We have taken the representative value of the central part of doabs, which is highly vulnerable to salinity due to irrigation recirculation.

[c] $c_0 = 500$ mg/L is the average salinity of Punjabi river irrigation water (Greenman et al., 1967).

[d] In general, r can be taken as 40% for flood irrigation, 25% for sprinkler irrigation and 10% for drip irrigation (Brouwer et al., 1989).

The water budgets by themselves do neither provide information on farmer options nor on limits of the individual terms in the budget equations. The presumption is that farmers will aim for an optimal value for the actual evapotranspiration equal to eE_0 where e is a crop factor, which is 0.75 on average in the Punjab (Arcadis-Euroconsult et al., 1998b), and E_0 is the potential evapotranspiration, which is determined by the local climate. Therefore, we have

$$E \leq eE_0 \tag{6.3}$$

However, this condition is still subject to the requirements as specified in Eqs. (6.5) and (6.6), so that the actual e may have to be reduced below the desired value. This condition has to be checked in the water balance.

It is also assumed that the farmer will intuitively aim for a return flow as a feasible low fraction of the available water, i.e.,

$$R = r(I + P + Q) \tag{6.4}$$

where r is specific for a given irrigation method. For instance, r will be lower for drip irrigation than for flood irrigation (Brouwer et al., 1989). Too high a return flow implies a loss of irrigation water, and too low a value will cause elevated salinities that would lower crop yield and crop value.

Because the only way in which salt can be discharged from the saturated zone is through the term $c_2 D_{out}$, a further condition is that the farmers maintain a net groundwater drainage:

$$c_2 D_{out} - c_0 D_{in} > 0 \tag{6.5}$$

Hence, a precondition to a sustainable salt concentration is

$$D_{out} > 0 \tag{6.6}$$

From Eqs. (6.1) – (6.4), we have

$$\begin{gathered} Q \leq eE_0 - (I + P) + R(I + P + Q) \\ Q \leq \frac{e}{1-r} E_0 - (I + P) \end{gathered} \tag{6.7}$$

where Q now is a consequence of the defined farmers' aims.

With regard to the salt budget of the two layers, the salt balance of the two zones is as follows

$$\theta H_1 \frac{dc_1}{dt} = Ic_0 + P \times 0 + Qc_2 - E \times 0 - Rc_1 \\ = Ic_0 + Qc_2 - Rc_1 \tag{6.8}$$

$$\epsilon H_2 \frac{dc_2}{dt} = (S + D_{in})c_0 - Qc_2 + Rc_1 - D_{out}c_2 \tag{6.9}$$

where c_0 is the salt concentration of the recharged surface water, c_1 the salt concentration of the unsaturated layer and c_2 that of the saturated layer. The salt concentration in the precipitation is neglected as is the salt concentration of the evaporated and transpired water. H_1 and H_2 are the effective thicknesses of the two layers with moisture contents θ and ϵ respectively, where θ can be regarded equal to field capacity and ϵ equal to total porosity of the saturated zone.

Equilibrium concentrations for the two layers follow from Eqs. (6.8) and (6.9)

$$0 = Ic_o + Qc_2 - Rc_1 \\ 0 = (S + D_{in})c_0 - Qc_2 + Rc_1 - D_{out}c_2$$

Therefore, the equilibrium salinities of the unsaturated and saturated zones are respectively

$$c_1 = \frac{Ic_0 + Qc_2}{R} \tag{6.10}$$

$$c_2 = \frac{I + S + D_{in}}{D_{out}} c_0 \tag{6.11}$$

where R will be according to Eq. (6.4). R is likely to be in the order of 40% of $(I+P+Q)$ for flood irrigation (Fig. 6.4), but may be in the order of 20% for more efficient irrigation systems (Brouwer et al., 1989). This means that high concentrations will occur in the unsaturated zone, which should also be managed to prevent crop damage. The only option for the farmer to do that is by guaranteeing sufficient return flow.

To make sure that additional irrigation from groundwater remains possible in the future, the concentration in the saturated zone, c_2, has to be limited to a maximum allowable value. The only option to do this is by draining a sufficient amount of water, according to:

$$D_{out} = \frac{c_0}{c_2}(I + S + D_{in}) \tag{6.12}$$

From this equation, it is concluded that only when there is sufficient drainage, the final salinity can be limited to a preset value, which, perhaps counter intuitively, is independent of the return flow and the amount of recharge from groundwater. Without drainage, the groundwater will become too saline over time. The reason is, of course, that the net supply of salt, $c_2(I+S+D_{in})$ must balance the net discharge of salt, c_2D_{out}. This immediately has consequences for the salinity downstream. If all available river water would be used for irrigation, the required drainage would be according to Eq. (6.12). The salt concentration for downstream users would eventually be equal c_2 in Eq. (6.10). The actual drainage should be more than that of Eq. (6.12) to prevent unacceptable salt concentrations downstream. Drainage, therefore, requires planning in order to make irrigation sustainable, also for downstream agricultural users.

The transient increase of the average salinity in the unsaturated and saturated zones leads to a coupled set of ordinary differential equations that can be written in matrix form

$$\frac{dC}{dt} = -AC + B \tag{6.13}$$

where

$$A = \begin{bmatrix} \frac{R}{\theta H_1} & -\frac{Q}{\theta H_1} \\ -\frac{R}{\epsilon H_2} & \frac{Q+D_{out}}{\epsilon H_2} \end{bmatrix} \tag{6.14}$$

$$B = \begin{bmatrix} \frac{I}{\theta H_1} c_0 \\ \frac{S+D_{in}}{\epsilon H_2} c_0 \end{bmatrix} \tag{6.15}$$

The solution of this system is

$$\begin{gathered} \frac{d(C-A^{-1}B)}{dt} = -A(C - A^{-1}B) \\ C_{t=t} - A^{-1}B = \exp\big(-A(t-t_0)\big)\big(C_{t=t_0} - A^{-1}B\big) \\ C_t = \Big(1 - \exp\big(-A(t-t_0)\big)\Big) A^{-1}B + \exp\big(-A(t-t_0)\big)C_{t_0} \end{gathered} \tag{6.16}$$

For a steady state, we get

$$C = A^{-1} B \tag{6.17}$$

For a single saturated reservoir, we get

$$I + S - E + Q - Q + D_{in} - D_{out} = 0$$

$$D_{out} = (I + S + D_{in}) - E$$

Q drops out because the extracted water is completely reused for irrigation (Fig. 6.2). Therefore,

$$
\begin{aligned}
\epsilon H_2 \frac{dc_2}{dt} &= -D_{out}\left(c_2 - \frac{I+S+D_{in}}{D_{out}} c_0\right) \\
\frac{dc_2}{dt} &= -\frac{D_{out}}{\epsilon H_2}\left(c_2 - \frac{I+S+D_{in}}{D_{out}} c_0\right) \\
c_2 - \frac{I+S+D_{in}}{D_{out}} c_0 &= \left(c_{2,t=0} - \frac{I+S+D_{in}}{D_{out}} c_0\right) \exp\left(-\frac{D_{out}}{\epsilon H}(t-t_0)\right) \\
c_2 &= \left(1 - \exp\left(-\frac{t-t_0}{T}\right)\right)\frac{I+S+D_{in}}{D_{out}} c_0 + \exp\left(-\frac{t-t_0}{T}\right) c_{2,t=0} \\
T &= \frac{\epsilon H}{D_{out}}
\end{aligned}
$$

For a steady state, we get, as before

$$c_2 = \frac{I+S+D_{in}}{D_{out}} c_0 \qquad (6.18)$$

Development of salinity

Equation (6.7), which represents the farmers' aims, can be used to further analyze the development of the salinity of the groundwater. Salinity can be computed using Eq. (6.16) for arbitrarily long times, as long as the fluxes and the concentration in the river water are considered to remain constant. The elements within the matrices in Eqs. (6.14) and (6.15) can be replaced by Eqs. (6.4), (6.7) and (6.12). This implies that irrigation from groundwater, Q, is now a consequence of the aim of the farmer to achieve a high actual evapotranspiration in combination with a given optimally used irrigation system.

With $c_0 = 500$ mg/L and, for instance, $c_2 = 3000$ mg/L, drainage must be $\geq (I + S + D_{in})/6$ to limit the final salinity in the aquifer to 3000 mg/L. In Eq. (6.7), the first term on the right hand side is the net evapotranspiration of the irrigation water that was pumped from the aquifer, and the second term is the return flow due to $I + P$. This implies that to maintain the groundwater level, less water has to be drained when groundwater is used for irrigation, as some groundwater is evaporated. However, there is a consequence for the salinity, which increases faster when groundwater is used for irrigation than when it is not, at least if the salinity of the groundwater exceeds that of the irrigation water received from barrages. This can be simulated by using the following set of equations (results in Fig. 6.3)

$$
\begin{aligned}
D_{out} &= (I + S + D_{in})c_0/c_{\mathrm{Inf}} \\
Q &= \max\left(0, \frac{e}{1-r}E_0 - (I + P)\right) \\
R &= (I + P + Q)r \\
A &= \begin{bmatrix} \frac{R}{\theta H_1} & -\frac{Q}{\theta H_1} \\ -\frac{R}{\epsilon H_2} & \frac{Q + D_{out}}{\epsilon H_2} \end{bmatrix} \\
B &= \begin{bmatrix} \frac{I}{\theta H_1}c_0 \\ \frac{S + D_{in}}{\epsilon H_2}c_0 \end{bmatrix}
\end{aligned}
$$

$$C_t = \left(1 - \exp\left(-A(t - t_0)\right)\right)A^{-1}B + \exp\left(-A(t - t_0)\right)C_{t_0}$$

For this, figures that are representative of the Punjab are used (Table 6.1). It is assumed that all fluxes are constant in time, even though the model has the capability to compute it with varying fluxes. All fluxes are considered for a unit surface area, so that space is excluded.

RESULTS AND DISCUSSION

Sustainable conjunctive use of groundwater for additional irrigation requires long-term salt management. This sustainable management should be founded on the essential controlling factors as derived previously. Four different cases (Table 6.2) are presented hereunder to highlight the importance of different management options for sustainable additional irrigation from groundwater. In these cases (Figs. 6.3–6.5), the blue curve represents the salinity of the unsaturated zone in the two-reservoir system. The green curve represents the salinity of the groundwater in the two-reservoir system, and red circles represent the salinity of the groundwater in the one-reservoir system. The latter matches with the groundwater of two-reservoir system. Table 6.2 shows that the water budgets for the unsaturated and saturated layers (Eqs. 6.1 and 6.2) are balanced.

Farmers' aim for long-term sustainable irrigation

Sustainable additional irrigation from groundwater can be maintained by limiting the concentration in the saturated zone, c_2, to a maximum allowable value. This can be achieved by draining a sufficient amount of water, according to Eq. (6.12). Fig. 6.3 represents two different cases of preset allowable salinity. Fig. 6.3(a) depicts that additional irrigation from groundwater to the maximum of 0.72 mm/d of acceptable

Table 6.2: Water budget components and water balance.

Budget terms	**Case 1**	**Case 2**	**Case 3**	**Case 4**	
	Fig. 6.3(a)	**Fig. 6.3(b)**	**Fig. 6.4**	**Fig. 6.5**	
e	0.415	0.34	0.415	0.415	–
r	0.20	0.20	0.40	0.20	–
E_0	4.71	4.71	4.71	4.71	mm/d
$E = eE_0$	1.95	1.60	1.95	1.95	mm/d
I	1.51	1.51	1.51	1.51	mm/d
P	0.21	0.21	0.21	0.21	mm/d
S	0.58	0.58	0.58	0.58	mm/d
Q	0.72	0.28	1.54	0.72	mm/d
$I + P + Q$	2.44	2.00	3.26	2.44	mm/d
R	0.49	0.40	1.31	0.49	mm/d
D_{in}[a]	0	0	0	0	
D_{out}	0.35	0.70	0.35	0.35	mm/d
$E + R$	2.44	2.00	3.26	2.44	mm/d
$S + R + D_{in}$	1.07	0.98	1.88	1.07	mm/d
$Q + D_{out}$	1.07	0.98	1.88	1.07	mm/d
$I + P + Q - E - R$	0	0	0	0	Eq. (6.1)
$S + R - Q + D_{in} - D_{out}$	0	0	0	0	Eq. (6.2)

[a] It is the river leakage and just adds a given value to the canal seepage without any mathematical consequences.

quality (3,000 mg/L) remains possible in the future. Farmers can set a predefined allowable concentration limit by draining a sufficient amount of groundwater from the saturated zone. In order to maintain a preset value of 1,500 mg/L [Case 2, Fig. 6.3(b)] in the saturated zone instead of 3,000 mg/L [Case 1, Fig. 6.3(a)], we have to increase drainage to twice that of case 1 (Eq. 6.12). In these scenarios, the river inflow (D_{in}) is assumed zero because it just adds a given value to the leakage from the irrigation system (S) with the same concentration, c_0, without any mathematical consequences.

An optimally designed irrigation system to prevent crop damage

More efficient irrigation systems will cause high concentrations in the unsaturated zone [Fig. 6.3(a)], which should be managed to prevent crop damage. Farmers can achieve this option by guaranteeing sufficient return flow. Such a return flow is only possible in a less efficient irrigation systems. Fig. 6.4 shows that the concentration in the unsaturated zone is almost two-third than that of Fig. 6.3(a). This low concentration is achieved by increasing return flow fraction of (I+P+Q) from 20% to 40%. Brouwer et al. (1989) have defined the efficiencies of different irrigation methods and the level of farmers' discipline. These efficiencies can be used to design an appropriate

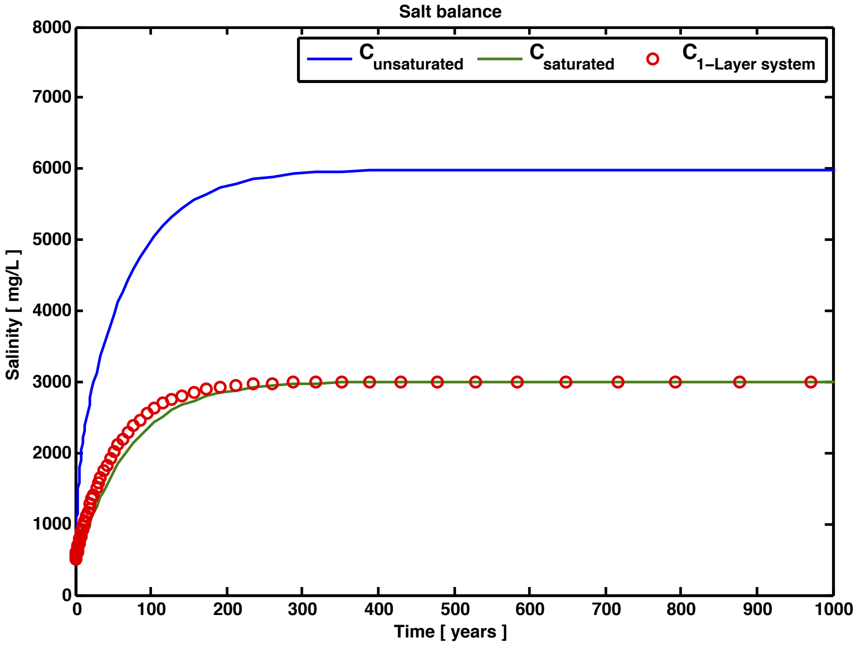


Figure 6.3: (a) Long-term sustainable additional irrigation from groundwater with predefined salt concentration, $c_2 = 3{,}000$ mg/L, in the groundwater (Case 1, Table 6.2).

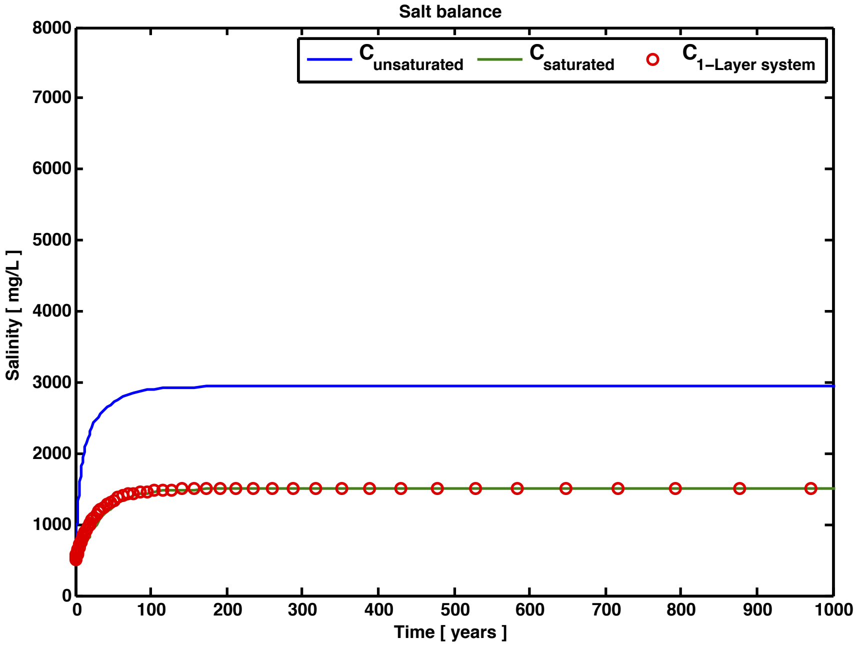


Figure 6.3: (b) Long-term sustainable additional irrigation from groundwater with predefined salt concentration, $c_2 = 1{,}500$ mg/L, in the groundwater (Case 2, Table 6.2).

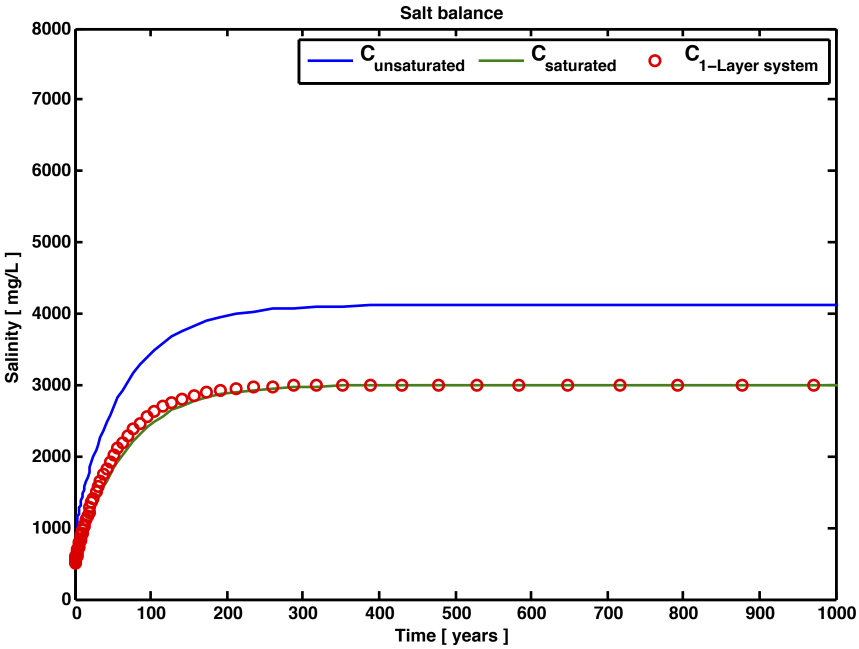


Figure 6.4: Optimal irrigation system to prevent crop damage (Case 3, Table 6.2).

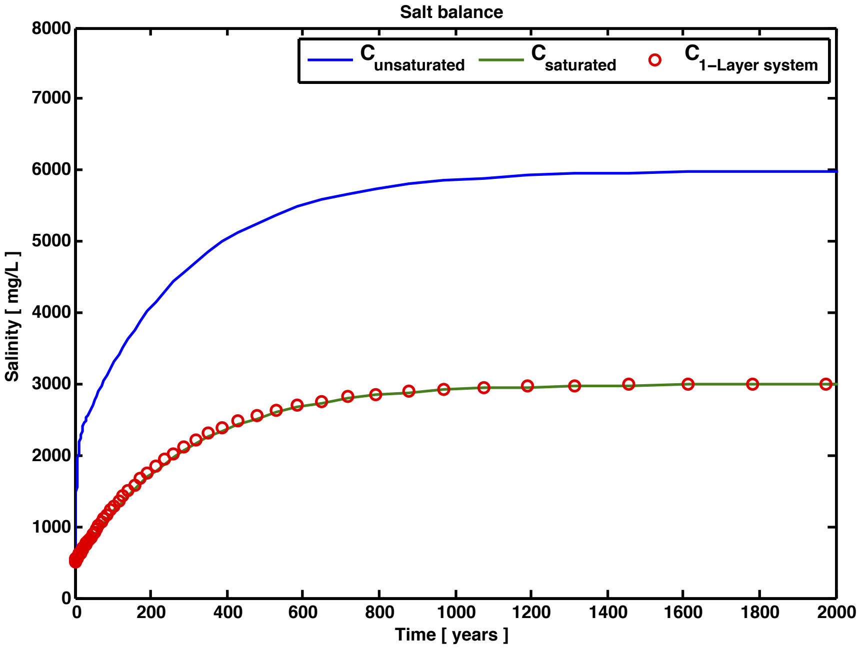


Figure 6.5: The time to achieve the salt equilibrium is a function of layer thickness (Case 4, Table 6.2).

irrigation system that prevents crop damage by ascertaining the essential controlling factors, as derived previously. Keeping the present farmer's practices and the future requirements in Punjab, this optimal design is recommended for widespread adoption in Punjab (Table 6.2).

Layer thickness determines the time to reach salt equilibrium

The time, in which salt equilibrium is achieved, depends upon the thickness of the unsaturated and saturated zones. In Fig. 6.5, we have increased the thickness of saturated zone from 20 to 100 m, and therefore, salt equilibrium is attained in 1,600 years as compared to 350 years. This can clearly be observed on inspection of Figs. 6.3(a) and 6.5.

CONCLUSIONS

Food production in the Punjab depends essentially on irrigation from surface water, which is distributed by an extended system of canals. Since about four decades, groundwater has gradually become a vital additional source of irrigation water, owned and managed by individual farmers. This currently intense and unregulated use of groundwater is not sustainable, because of increasing salinities.

To achieve sustainable additional irrigation from groundwater, its salinity has to be managed. This can only be done by sufficient drainage, which can be estimated from the actual supply of surface water including seepage times the ratio of the salinity in the surface irrigation water and the acceptable salinity of the groundwater. Therefore, the final salinity in the saturated zone only depends on salt carrying inflows and outflows, i.e., import from surface water and export through groundwater drainage. Groundwater drainage should be regarded as independent variable. It can be fixed through the farmer adjustable crop factor e and irrigation efficiency r. From these, groundwater irrigation and irrigation return flow follow. The literature figures of the actual situation in the Punjab as presented in Table 6.1, required a crop factor less than the desired value of 0.75; however, the computed sustainable actual evapotranspiration, E, still matches approximately the given literature value (Table 6.2). Where the actual availability of irrigation water is higher, the crop factor and, hence, E can also be sustainably increased.

The salinity in the unsaturated zone depends on the supply of surface water and its salinity, on the amount of irrigation from groundwater and its salinity, and on the amount of irrigation return flow. The only way for a farmer, who uses groundwater as an additional source, to limit the salinity at the roots of his crops is by maintaining sufficient return flow, which depends on the efficiency of the irrigation method.

The thickness of the unsaturated and saturated zones determines only the time in which salt equilibrium is attained. This may be tens to several hundreds of years. Sustainable conjunctive use of groundwater for additional irrigation requires long-term salt management that is founded on the essential controlling factors as derived in the aforementioned texts.

CHAPTER 7

Punjab scavenger wells for sustainable additional groundwater irrigation

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ABSTRACT

We aim to solve the longstanding problem of sustainable groundwater extraction in the Pakistani Punjab (Indus Basin). Since public scavenging wells were abandoned in the 1990s, farmers have largely embraced the practice of skimming wells to prevent or reduce salinity in their abstracted water. Although this may be an effective short-term solution, salinity levels will continue to rise over time, rendering groundwater unsuitable for irrigation. We investigate the creation of balanced scavenging wells to reduce salinization so that sustainable groundwater use is possible as an additional source for irrigation. To achieve such sustainability, a certain amount of brackish water must be discharged, and this amount is determined by assessing the combined salt and water budgets. MATLAB-based SEAWAT models were used to show that (1) recirculation wells can substantially delay (but not prevent) salinization as a mid-term solution and (2) scavenging is the only long-term option to solve the salinization problem. Final (i.e., long-term) salinity does not depend on hydraulic parameters or initial groundwater salinity, which can only delay or speed up the process of salinization. A sensitivity analysis showed that vertical anisotropy (ratio of horizontal to vertical hydraulic conductivity) is the most important hydraulic variable for reducing the depth reached by streamlines, which reduces the time required to reach the equilibrium salinity. We conclude: (1) the extraction of freshwater can be determined from leakage, return flow and saltwater extraction; (2) the required saltwater extraction does not depend on freshwater extraction, although for recirculation, saltwater extraction does depend on saltwater injection; and (3) the final salinity in the saturated zone only depends on the salinity of the irrigation water, saltwater extraction, leakage from the irrigation canal system and, in the case of recirculation, the saltwater injection.

INTRODUCTION

The Punjab is characterized by its doabs: elongated islands surrounded by the five great rivers of the Indus Basin. These doabs have been almost 100% irrigated for more than a century. River water held up behind dams and barrages is distributed through an extended network of large to small irrigation canals over virtually the entire region. This irrigation turned the once desert conditions into the breadbasket of Pakistan.

An irregular irrigation supply has caused the widespread introduction of private tube wells that allow individual farmers to provide additional water exactly when their crops need it. However, fresh groundwater is limited because it has largely originated from canal leakage and irrigation return flow since irrigation was introduced before the end of the 19th century (Greenman et al., 1967; Asghar et al., 2002). The overexploitation of this valuable "new" resource has led to high salinity because of the upconing of underlying naturally saline groundwater (Asghar et al., 2002; Shah et al., 2003).

A solution to the problem has been sought by public scavenging wells and private skimming wells since the 1970s (Ahmad and Ahmed, 1985; Ahmad, 1994). Scavenger wells have a lower and an upper screen; where the lower (scavenging) screen is meant to extract and discharge the saltwater, and the upper screen extracts and discharges the freshwater. Skimming wells, however, are shallow and partially penetrate the upper zone of the fresh-saline aquifer to minimize the extraction of saltier water. They often have more screens (up to 26) that are arranged around a central point to spread out the extraction and thus skim off the fresh water. The discharge rates, penetration depth, number of screens, distance between screens, etc. are designed to either prevent or at least substantially reduce the extraction of brackish and salt water from the aquifer below the shallow screen (Saeed and Ashraf, 2005; Saeed et al., 2002a,b).

The use of skimming wells or similar techniques by farmers in the Punjab is ubiquitous. These farmers are facing the following long-term problems: (1) shallow wells falling dry; (2) salinity gradually rising to levels that are unacceptable for irrigation; and (3) the high cost of drilling, maintenance, and replacement (Saeed et al., 2002b). Still, these (skimming) wells are being promoted locally by institutions to farmers and in publications. Among these promoters are research organizations such as the International Water Management Institute, the International Waterlogging and Salinity Research Institute, the Center of Excellence in Water Resources Engineering, the Pakistan Council of Research in Water Resources, and water resources groups of Harvard University and Colorado State University. These institutes have conducted many studies to evaluate the performance of skimming wells and have played a key role in the rapid diffusion of skimming technology throughout the Pakistani Punjab

(Wang, 1965; Sahni, 1972, 1973; Zuberi and McWhorter, 1973; McWhorter, 1980; Chandio and Larock, 1984; Sufi et al., 1998; Saeed et al., 2002a,b,c; Asghar et al., 2002; Saeed et al., 2003; Ali et al., 2004; Saeed and Bruen, 2004; Saeed and Ashraf, 2005; Ashraf et al., 2011).

Asghar et al. (2002) provided design rules for skimming wells based on the calibration of a 16-day pumping trial on a single-strainer skimming well in the Punjab. They used a MODFLOW and MT3D model of 89 × 89 × 100 m with minimum layer thickness of 12 m, and the upconing of the 3,000 mg/L plane was 10 m during the trial. However, design values cannot be founded on a model of this small extent, large layer thickness, and limited test duration. Saeed and Bruen (2004) measured and simulated groundwater salinity from three skimming wells in the Punjab that were pumped for 10, 12 and 16 days. Although the rate of salinization varied with the hydraulic parameters in their sensitivity analysis, the pumping and simulation period were too short to reach a definitive conclusion on the pumped water salinity after long periods of use because the results were too dependent on the initial conditions. Kelleners (2001) evaluated the different designs of skimming wells and concluded that the maximum discharge of skimming wells mainly depends on the thickness of the fresh-groundwater lens and the hydraulic parameters of the aquifer, whereas Alam and Olsthoorn (2013) concluded that the layer thickness was only able to determine the time in which the salt equilibrium is attained.

The 3-hour duration 4.7 × 0.3 × 0.8 m sand tank experiment and the 16- and 32-day field experiments by Sufi et al. (1998) were too short to allow for general conclusions because the salinity continued to rise at the end of their two field tests. Ashraf et al. (2011) provided operational rules for skimming wells based on three 3-day pumping tests, which were too short to recommend limiting the maximum discharge for wells less than 350 m apart to 2,400 m^3/d. Our analytical and numerical 300 year simulations show that wells cannot sustainably extract more than 1,000 m^3/d under the prevailing situation of the Punjab, where the average well distance is about 500 m. Skimming wells can only delay the process of upconing, but are unable to prevent it as is evident from long-term (years) simulation, contrary to the very short simulation (days) in the previously cited papers and reports, on which different design and operational rules are based.

McWhorter (1980) is a primary promoter of the widespread diffusion of skimming well technology in the Punjab and summarized the Pakistani skimming well investigations that were designed and carried out by Colorado State University during the 1970s. In addition to the previously cited authors, he highlighted that the performance of skimming wells depends on parameters such as strainer diameter, penetration depth ratio, distance between strainers, and the thickness of the freshwater layer below the strainers. Studies carried out in different areas of the Indus

Basin concluded that skimming wells are a suitable technology if certain guidelines and operational schedules are kept. However, these studies failed to address the long-term subsurface salinity distribution, which is also the result of spatial and temporal pumping dynamics that are subject to varying economies and crop types.

The pertinent longstanding question is whether the sustainable use of groundwater is possible in the given situation and if it is possible to prevent the ongoing accumulation of salt as a result of the repeated recirculation of irrigation return flow. The sustainable use of groundwater requires the discharge of saltwater and a supply of freshwater. While the supply of freshwater is guaranteed by the (leaking) irrigation network, the discharge of brackish water may be achieved by scavenger wells or similar techniques. Since the early 1970s, the Pakistani government has made several attempts to perform such operations with negative results (Ahmad, 1994). For instance, wells have been used to extract the freshwater that had previously leaked, but these wells eventually salinized (Ahmad, 1994). Some wells were specifically designed for the central saline areas of the Punjabi doabs to dispose of saltwater (Ahmad, 1994). These wells are now totally abandoned because they gradually moved the salt water from the greater depths to the more shallow zones (Ahmad, 1994). Currently, farmers use skimming wells on a private basis; however, despite using an often extended number of strainers (screens), farmers are experiencing difficulty in preventing or reducing the salinity caused by upconing from below.

Scavenging on a scientific basis may still be an effective way to mitigate and/or prevent the upconing of saline groundwater into the fresh screen, but only if the saltwater is discharged and the volumetric flows and salt loads balance at the farm scale. A second condition is that the streamlines that are caused by the well must remain shallow. However, this is a consequence of the "cells" formed by a large number of wells extracting simultaneously, as explained in the following sections.

The results of the present study show that long-term sustainable groundwater extraction in the Punjab is possible. MATLAB-based SEAWAT models (Olsthoorn, 2013) were used to show the results of the analysis. This chapter explores the use of, what we call, "Balanced" scavenger wells to ameliorate the salinization problem so that sustainable groundwater use is possible as an additional source for irrigation. First, the water and salt budgets will be considered to determine the sustainable extraction rates. Next, these rates will be translated to the scale of a farm for onward use in groundwater flow and salt transport models.

WATER AND SALT BUDGETS TO DETERMINE RECOVERABLE GROUNDWATER

In this section, the assessment of water and salt budgets for determining recoverable groundwater is reported. Recirculation, in which the saltwater is disposed from the scavenging screen into the aquifer at a deeper depth to either reduce or delay the salt burden on the downstream users, is also considered. Both are derived independently of space (i.e., per m^2). Wells are considered in the following section. The budget analysis demonstrates the necessity of discharging saltwater to make sustainable extraction possible. Two systems are considered: a top system, which is essentially in the unsaturated zone from which all evapotranspiration occurs, as well as a saturated bottom system with groundwater extraction. The return flow connects both systems. The upward seepage from the bottom system to the top system was ignored. The terms of the water budget and concentrations are shown in Fig. 7.1.

The water budget equation for the top system can be written as follows

$$P_a + I + Q_f = E + R + S_r \tag{7.1}$$

where P_a is the actual amount of precipitation, I the surface water irrigation supply, Q_f the irrigation from groundwater, E the evapotranspiration, R the irrigation return

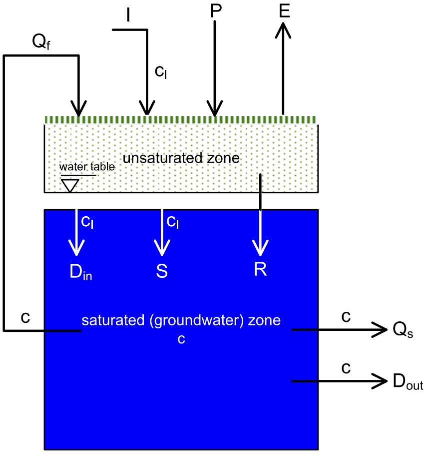

Figure 7.1: Salt balance conceptual model to study the recoverable groundwater. P is the effective precipitation; I is the surface irrigation supply; E is the evapotranspiration; R is the irrigation return flow; Q_f is the irrigation from groundwater; Q_s is the extraction by scavenging screens; S is the seepage from the canal irrigation system; D_{in} is the water infiltrating from bounding rivers into the saturated zone; D_{out} is the groundwater that discharges to the bounding rivers or natural groundwater drainage; c_I is the TDS concentration in the surface irrigation water; and c is the TDS concentration in the aquifer.

flow or recharge from the unsaturated zone to groundwater and S_r is the surface runoff, which is essentially negligible in the Punjab except during the monsoon months of July and August (Hassan and Bhutta, 1996). Surface runoff is not significant in the presence of ubiquitous "bunds" around the irrigated fields in the Punjab (Hassan and Bhutta, 1996); bunds are small earth embankments that contain irrigation water within basins (Brouwer et al., 1990). The surface runoff effect has been included in the effective precipitation term P, the actual precipitation P_a minus surface runoff and interception (Hassan and Bhutta, 1996; Arcadis-Euroconsult et al., 1999; Sarwar and Eggers, 2006):

$$P = P_a - S_r \tag{7.2}$$

Therefore, the water budget for the top system is

$$P + I + Q_f = E + R \tag{7.3}$$

All fluxes are in L/T, for example, in mm/d. The water budget for the bottom groundwater extraction system reads

$$Q_f + Q_s + D_{out} = S + R + D_{in} \tag{7.4}$$

where Q_s is the extraction by scavenging screens, i.e., water to be discharged, S the seepage (leakage) from the canal irrigation system, and D_{in} is the water infiltrating from bounding rivers into the saturated zone. Both S and D_{in} inadvertently originate from the river water. D_{in} is insignificant in most of the Punjab, i.e., $D_{in} < S$ and essentially zero toward the center of the doab where salt water is naturally prominent. In this study, the use of scavenging wells that balance the water budget was investigated. Hence, D_{in} is also assumed to be negligible. Therefore, in this analysis, both S and D_{in} are combined into S. D_{out} is the groundwater that discharges to the bounding rivers or natural groundwater drainage. The small hydraulic gradients and presence of a sub-alluvial ridge in all of the doabs of the Punjab are the main barriers that lead to poor subsurface drainage (Greenman et al., 1967). The inadequate subsurface drainage further increases the salinization in the Punjab (Greenman et al., 1967). Based on this finding, the subsurface drainage is essentially negligible:

$$D_{out} \approx 0$$

Therefore, the water budget for the bottom system (Eq. 7.4) results in

$$Q_f + Q_s = S + R \tag{7.5}$$

For the recirculation case, the water budget equation (7.5) can be written as

$$Q_f + Q_s = S + R + Q_{inj} \tag{7.6}$$

where Q_{inj} is the injection of brackish water or saltwater back into the aquifer at a greater depth.

Based on the concentration (total dissolved solids [TDS]) in the long-run, i.e., after the salt equilibrium has been reached in both systems and assuming the salinity of the precipitation and evaporation are zero, the top (unsaturated zone) system can be expressed as

$$Ic_I + Q_f c = Rc_R \tag{7.7}$$

and the bottom (groundwater) system can be expressed as

$$(Q_f + Q_s)c - Sc_I = Rc_R \tag{7.8}$$

where c_I is the TDS concentration in the surface irrigation water, c the TDS concentration in the aquifer and c_R is the TDS concentration in the irrigation return flow.

However, because of Eq. (7.5), the salt equilibrium is

$$c_R = \frac{S(c-c_I)+Rc}{R} \tag{7.9}$$

Therefore, Eqs. (7.7) and (7.8) become

$$Ic_I + Q_f c = S(c - c_I) + Rc \tag{7.10}$$

$$(Q_f + Q_s)c - Sc_I = S(c - c_I) + Rc \tag{7.11}$$

From Eq. (7.10) and Eq. (7.11),

$$Ic_I - Q_s c + Sc_I = 0 \tag{7.12}$$

$$Q_s = \frac{c_I}{c}(I + S) \tag{7.13}$$

Therefore,

$$a = \frac{c}{c_I} = \frac{I+S}{Q_S} \quad (7.14)$$

or

$$Q_s = \frac{1}{a}(I + S) \quad (7.15)$$

where a is the factor by which the irrigation water salinity is multiplied to obtain the equilibrium concentration in the aquifer.

For the recirculation case, Eq. (7.15) can be expressed as

$$Q_s = \frac{1}{a}(I + S) + Q_{inj} \quad (7.16)$$

Both Eqs. (7.15) and (7.16) show that the saltwater discharge Q_s is a fixed quantity that is independent of the freshwater extraction; however, Q_s depends on the amount of brackish or saltwater injection Q_{inj} into the aquifer, as shown in Case 4 (refer to Table 7.1). Therefore, to maintain an equilibrium concentration at a factor a times that of the surface irrigation water, there must be a discharge as large as the total net recharge, i.e., the return flow R plus seepage S; and recirculation also includes Q_{inj}, as shown in Eqs. (7.5) and (7.6). Under natural circumstances, Q_s is the drainage of the groundwater system. However, the salt and water budgets are considered without drainage to distant surface waters, and therefore, Q_s is the scavenging well extraction.

In these scenarios, the equation $R = \frac{b}{a}I + \frac{b-a}{a}S$ was selected; it is subject to $b = \frac{Q_f+Q_s}{Q_s}$ to relate the return flow R to both extractions (Table 7.1). In fact, the return flow is enhanced by Q_f, the value of which can be selected arbitrarily while keeping the necessary saltwater extraction at $Q_s = (I + S) / a$. The required surface water irrigation I follows from inserting Eq. (7.15) and Eq. (7.5) into Eq. (7.3); I is entirely dependent on the evapotranspiration, precipitation, seepage and permissible concentration factor a:

$$I = \frac{a}{a-1}(E - P) - S \quad (7.17)$$

with P, I, S and E remain constant, the return flow directly follows the groundwater irrigation Q_f (Eq. 7.3):

$$\partial R = \partial Q_f \quad (7.18)$$

and may be regulated by the groundwater irrigation, for instance, to flush out salts.

From Eq. (7.5) and Eq. (7.15),

$$Q_f = \frac{b-1}{a}(I + S) \tag{7.19}$$

For recirculation,

$$Q_f = \frac{b-1}{a}(I + S) + (b - 1)Q_{inj} \tag{7.20}$$

From Eq. (7.14), the equilibrium concentration (Alam and Olsthoorn, 2013) is

$$c = c_I \frac{(I+S)}{Q_s} \tag{7.21}$$

For recirculation, the equilibrium concentration is

$$c = c_I \frac{(I+S)}{(Q_s - Q_{inj})} \tag{7.22}$$

If seepage depends on the canal construction and maintenance, then the final (i.e., long-term) groundwater salinity does not depend on any of the hydraulic parameters of the groundwater system, wells, or initial groundwater salinity, as shown in Eqs. (7.21) and (7.22). Both the hydraulic parameters and initial groundwater salinity may only delay or speed up the process of salinization in the groundwater system (refer to Figs. 7.11-7.14).

MATERIALS AND METHODS

Hydrogeology of the Punjab

Food production in Pakistan is largely dependent on the Punjab Plain, where large rivers split the region into islands called doabs that are densely populated and intensively irrigated, originally by surface water. But since the 1960s, irrigation has been increasingly supplied by groundwater (Alam and Olsthoorn, 2014c). The doabs have an almost similar geology that can be described as unconsolidated sediments of the Indus River branches and consists of an alternation of sands and clays to a depth of hundreds of meters. The groundwater system is essentially a single unconfined aquifer that is highly heterogeneous vertically as a result of the nature of the fluvial deposits (Bennett et al., 1967). Currently, millions of wells are concurrently pumping groundwater from the Punjab (Alam and Olsthoorn, 2014c). The Punjab consists of five rivers; the Thal, Chaj, Rechna and Bari Doabs; and adjacent narrow strips of land on the right bank of the Indus River and left bank of the Sutlej River (Fig. 7.2).

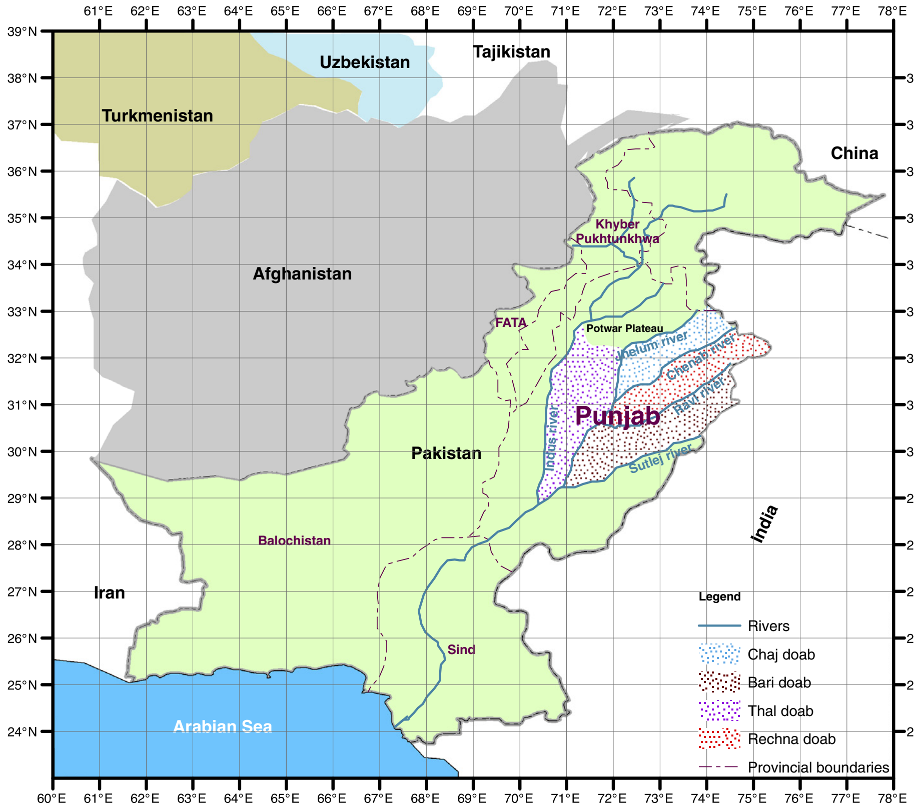

Figure 7.2: Location, rivers and doabs of the Punjab (after Bennett et al., 1967; Alam and Olsthoorn, 2014b).

The Punjab Plain is a vast alluvial plain traversed by the Indus River and its tributaries, the Jhelum, Chenab, Ravi and Sutlej Rivers. The alluvial plain extends from the Himalayan foothills, salt range and Potwar Plateau in the north to the Arabian Sea in the south. The alluvial complex consists of predominantly fine-to-medium grained sand, silt and clay. The slope of the land in most of the Punjab is toward the southwest and ranges from approximately 0.4 m/km in the northern part of the area to less than 0.2 m/km at the southern end. The area is both drained and fed by its five rivers. The climate of the Punjab ranges from semi-humid in the northeast to arid in the southwest and is characterized by a large seasonal variation in temperature and rainfall (Greenman et al., 1967).

Balanced scavenging wells

The groundwater flow and salt transport in four cases were simulated to demonstrate the relevant phenomena. The first case is simply an extraction of saltwater without irrigation from the groundwater and shows that a preset limit of salinity of the recoverable groundwater can be achieved. The other three cases show that sustainable additional irrigation from groundwater is possible. In the second case, the freshwater and saltwater extractions are equal. In the third case, freshwater extraction is twice that of saltwater. In the fourth case, the amount of saltwater to be discharged is reduced by injecting one-third of it in a third screen at a greater depth. The fourth case represents a method of reducing or delaying the salt burden on downstream users.

Translating the concept to the scale of the farm

In this section, the concepts outlined in the previous section are translated to the scale of individual farms. Table 7.1 displays a referenced overview of the data used in the four simulation cases announced in the previous subsection. To demonstrate the conceptual ideas in terms of groundwater flow and transport of salinity, a farm was considered as a circular area with a radius of 500 m that represents with a single well in the center. This radius is representative of the size of the "cells" that are formed by the water divides between adjacent wells that pump simultaneously; currently, farmers in the Punjab extract groundwater using wells having discharge rates between 1,950 and 2,600 m^3/d (Saeed et al., 2002b), which are equivalent to an area with a radius of 500 m served by one well.

A reasonable supply of groundwater irrigation amounts to three times the fixed saltwater extraction, which is demonstrated by the three cases presented below. All have the same E, P, I, S and a values as shown in Table 7.1. The groundwater irrigation amount is determined by the factor b, which is the ratio between the total extraction from all screens (i.e., net extraction) and the saltwater screen. In case 1, $b = 1$; in case 2, $b = 2$; and in case 3, $b = 3$. In Case 4, the recirculation of brackish water injected back into the deeper aquifer is considered. In all cases, the limit of the groundwater salinity is set at $a = 6$ times the TDS of the surface irrigation water. The salinity of the precipitation is neglected. As Table 7.1 shows, the return flow increases to 0.81 mm/d along with the groundwater irrigation amount, Q_f.

The environment mfLab (Olsthoorn, 2013) was used to generate complex inputs for the SEAWAT models (Weixing and Langevin, 2002; Langevin et al., 2003, 2008) and to analyze and visualize its output. The model simulated the flow in an axially symmetric fashion. The two required screens were placed between −5 and −30 m and between −50 and −80 m relative to the ground surface (Table 7.2). The initial TDS distribution is listed in Table 7.3 and based on the recent time-domain electromagnetic (TDEM) measurements in the Punjab (Alam, 2011).

The TDEM investigations were conducted using a TEM-FAST 48 HPC (a portable geophysical system, http://www.aemr.net). The field procedures involved placing a square loop of wire or antenna (typically 25 × 25 m) at the ground surface. A steady current in the transmitter loop was abruptly turned off to create a magnetic pulse or

Table 7.1: Overview of the four cases.

Description		CASE				
		1	**2**	**3**	**4**	
Evaporation [a]	E	1.95	1.95	1.95	1.95	mm/d
Precipitation [b]	P	0.21	0.21	0.21	0.21	mm/d
Seepage [c]	S	0.58	0.58	0.58	0.58	mm/d
Return flow	R	−0.23	0.12	0.47	0.81 [d]	mm/d
Canal supply [e]	I	1.51	1.51	1.51	1.51	mm/d
Groundwater irrigation	Q_f	0.00	0.35	0.70	1.04 [f]	mm/d
Extraction by scavenging screen	Q_s	0.35	0.35	0.35	0.52 [g]	mm/d
Deep groundwater injection	Q_{inj}	–	–	–	0.17	mm/d
$P + I + Q_f - E - R$		0	0	0	0	Eq. (7.3)
$Q_f + Q_s - S - R$ [h]		0	0	0	0	Eq. (7.5)
Surface water concentration	c_I	100	100	100	100	mg/L
Salinity of evaporated water		0	0	0	0	mg/L
Salinity in precipitation		0	0	0	0	mg/L
cLimit		600	600	600	600	mg/L
a	a	6	6	6	6	–
b	b	1	2	3	3	–
cReturn	c	600	600	600	600 [i]	mg/L
Concentration in fresh well	c_{fresh}	600	600	600	600	mg/L
Well area of influence	r	500	500	500	500	m
$Ic_I - Q_s c + Sc_I$ [j]		0	0	0	0	Eq. (7.12)

[a] In the Punjab, the potential evapotranspiration is 4.71 mm/d (Arcadis-Euroconsult et al., 1998b), and the prevailing crop factor is 0.415 (Alam and Olsthoorn, 2013).

[b] Ahmad (1972); Arcadis-Euroconsult et al. (1999).

[c] Ahmad and Ahmed (1985); Arcadis-Euroconsult et al. (1998a).

[d] $R = Q_f + Q_s - Q_{inj} - S$, Eq. (7.6) in Case 4 for the recirculation well.

[e] Ahmad and Ahmed (1985).

[f] $Q_f = \frac{b-1}{a}(I + S) + (b - 1)Q_{inj}$, Eq. (7.20) in Case 4 for the recirculation well.

[g] $Q_s = \frac{1}{a}(I + S) + Q_{inj}$, Eq. (7.16) in Case 4 for the recirculation well.

[h] $Q_f + Q_s - S - R - Q_{inj} = 0$, Eq. (7.6) in Case 4. This is the groundwater budget equation in the case of the recirculation well when saltwater is injected back into a deeper aquifer.

[i] $c = c_I \frac{(I+S)}{(Q_s - Q_{inj})}$, Eq. (7.22) in Case 4 for the recirculation well.

[j] $Ic_I - (Q_s - Q_{inj})\, c + Sc_I = 0$, in Case 4. This is the salt budget equation in the case of the recirculation well, when saltwater is injected back into a deeper aquifer.

transient in the ground. The measurements were recorded with the same transmitter loop, and the TEM-RES program (http://www.aemr.net) conducted the inversion of the TDEM sounding data. The TDEM measurements resulted in the vertical profile of the electric resistivity of the subsurface, which indicated the depth of the water

Table 7.2: Detail of the screens used in simulations.

Screen ID	Description	Screen top (m)	Screen bottom (m)
Well-01	Freshwater extraction screen	−5	−30
Well-02	Saltwater extraction screen	−50	−80
Well-03	Brackish or saltwater injection screen	−200	−250

Table 7.3: TDEM-based TDS profiles in the Punjab.

Elevation [m]	TDS [mg/L] [a]	TDS [mg/L] [b]
0	600	2,000
−15	960	4,000
−25	1,920	6,000
−450	20,000	20,000

[a] Average salinity profile in the Punjab, which is based on approximately 600 recent TDEM measurements (Alam [2011]).

[b] Assumed initial salinity of groundwater in the Punjab. This is considered the worst-case scenario.

table and thickness of the fresh and brackish groundwater layers. These vertical profiles were also matched with available geological and borehole data, groundwater samples and *EC*-logger registrations.

The initial distribution (refer to Table 7.3) was based on approximately 600 TDEM measurements, especially in the center of the Chaj Doab, which was prominently known for salt upconing. Because of the similarity of the Punjabi doabs, this initial salinity condition was assumed to be generally representative of the Punjab. Mostly, skimming wells were used to extract the groundwater in the center of the Punjabi doabs. Farmers are currently facing problems finding freshwater through their single- or multi-strainer skimming wells. Farmers are constantly relocating their skimming wells to find freshwater (verbal communication during the field visit in the Punjab, 2010–11).

Kelleners (2001) calibrated a skimming well test performed in the Punjab during the 1970s and further validated his 16-day skimming well model by using a 23-day scavenger well experiment at the same location, i.e., Phularwan farm. He has also performed a sensitivity analysis and concluded that vertical anisotropy is the most sensitive parameter. His calibrated and validated parameters are shown in Table 7.4, and these calibrated parameters were used in our model. The vertical anisotropy can range between 15 and 90 (Bennett et al., 1967) on the regional scale. Kelleners (2001) concluded that "SURTRA predictions for the skimming well and the scavenger well are of sufficient quality to use the model for scenario analysis," whereas the results of this study indicate that 16-day and 23-day simulations or tests are not sufficient to predict the long-term groundwater salinity. In the absence of long-term salinity

Table 7.4: Calibrated parameters of the skimming wells and scavenger wells in the Punjab (Kelleners, 2001).

Parameter	Description	Unit	Value
k_r	Horizontal hydraulic conductivity	m/d	35
k_r / k_z	Vertical anisotropy	–	4 [a]
ϵ	Total porosity	–	0.35
α_L	Longitudinal dispersivity	m	0.1
α_T	Transverse dispersivity	m	0.005
D_m	Porous medium diffusion coefficient	m^2/d	0

[a] Kelleners (2001) considered anisotropy 4 based on core samples by Smith and Wheatcraft (1992). His sensitivity analysis clearly shows that the change in the salinity beyond $k_r / k_z \geq 10$ is almost negligible. Our sensitivity analysis is consistent with this result (Fig. 7.12).

observations in the Punjab, Kellener's calibrated parameters (Kelleners, 2001) were used to demonstrate our conceptual model. As shown in the previous section and demonstrated in the following section, the hydraulic parameters do not affect the final salinity in the groundwater system and can only delay or speed up the process of salinization.

RESULTS AND DISCUSSION

All simulations were over 300 years, and the flow fields at the end of the simulations are shown in Figs. 7.3, 7.5, 7.7, 7.9, 7.11 and 7.13. These figures represent the stream lines with the flow between each pair, i.e., $\Delta\psi$, which is shown in the title of each figure. The density flow is included in the simulation as it is shown in the respective figures. The final TDS distribution is shown in color, and its values are denoted according to the color bar to the right of the figures. The distance x [m] has been calculated with respect to the heart of the well. The outer boundary is closed and assumes that the well is surrounded by other similar wells to form a mosaic of individual cells that each has a well at its center. All inflows and outflows of the water budget are expressed in terms of the rates listed in Table 7.1. The water budget equations (7.3) and (7.5) of the top and bottom systems, respectively, have been balanced and are shown in Table 7.1. The brackish water disposal rates Q_s required to guarantee sustainability are listed in the seventh row of Table 7.1.

The four cases, three of which demonstrate freshwater extraction, are presented and discussed below; animations of these cases can be found in the online version of this article in *Agricultural Water Management* (Alam and Olsthoorn, 2014a).

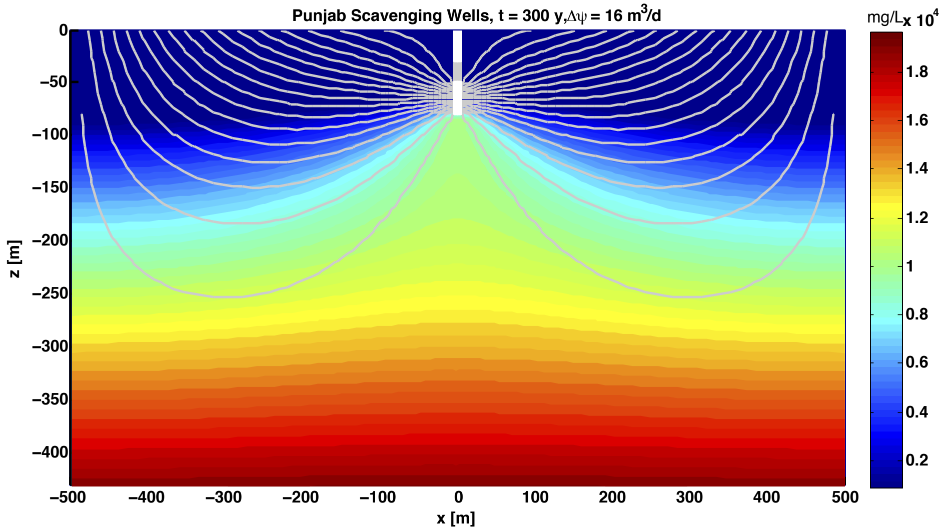

Figure 7.3: Cross-sectional view of the flow field after 300 years in Case 1. Refer to Table 7.1 for the data. $\Delta\psi$ is the flow between each pair of streamlines.

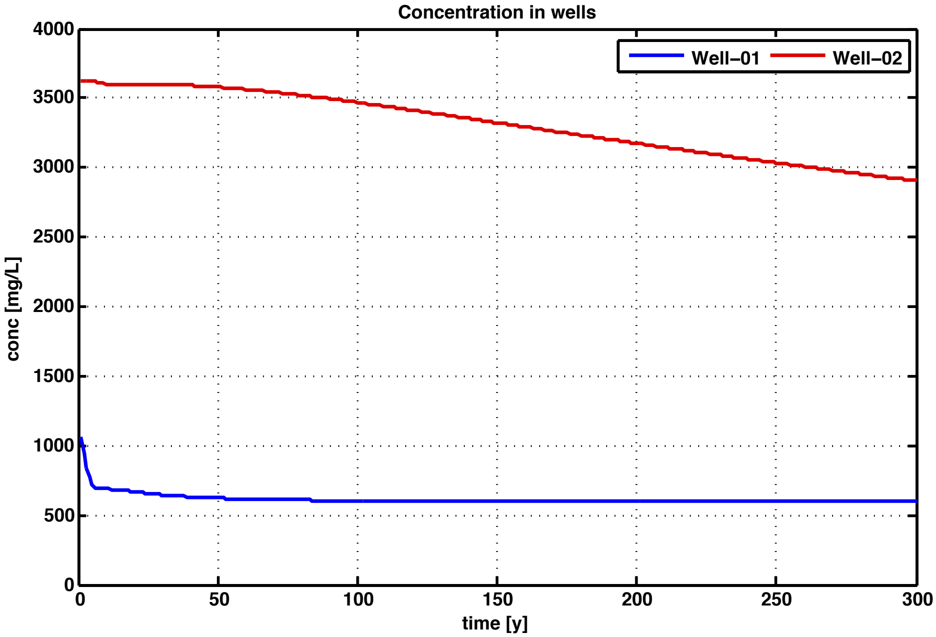

Figure 7.4: Concentration of TDS in both the fresh and salt screens for Well-01 and Well-02, respectively, in Case 1. The *blue line* is the salinity of the freshwater screen despite its flow being zero.

Groundwater drainage by only extracting saltwater [Case 1]

This case corresponds to the data in the first column of Table 7.1. Fig. 7.3 shows the flow field and Fig. 7.4 depicts the resulting concentrations extracted by the well screens over time. In this case, the freshwater screen is not extracting (Table 7.1); therefore, its concentration represents the transmissivity-averaged value of the screen-intersected model layers. The TDS concentration of the freshwater gradually approaches the equilibrium value of the return flow, which is 600 mg TDS/L in this case and reached in approximately 50 years. The lower screen approaches a quasi equilibrium, which is a mixture of shallow and saltwater as it arrives to the face of the screen from above as well as from below. From the stream lines, it can be concluded that it may take thousands of years until the saltwater above the lowest drawn stream line has been removed by the well. Thus, a section of the aquifer is effectively cleaned of its natural salt.

Freshwater extraction is equal to the saltwater removal by scavenging [Case 2]

In this case, the upper and lower screen extract the same amount of water. The resulting flow field after 300 years is shown in Fig. 7.5, and the TDS concentrations extracted from the screens are shown in Fig. 7.6. A somewhat longer time period is required to reach the equilibrium concentration of 600 mg/L in the top screen compared to the first case, whereas the salinity in the water extracted by the lower screen is also higher than in the previous case.

Freshwater extraction = 2 × Case 2, or $Q_f = 2Q_s$ [Case 3]

In this case, the extraction from the fresh screen (0.7 mm/d) is twice that of the scavenging screen (0.35 mm/d), which is below the freshwater screen. The flow field after 300 years is shown in Fig. 7.7, and the concentrations in the previous two screens are shown in Fig. 7.8. As a result of the larger overall extraction (1.05 mm/d, see Table 7.1), the salt screen reaches a maximum TDS after approximately 70 years, i.e., earlier than in Case 2. The maximum TDS is also higher than that of Case 2 and then starts declining as natural saltwater continues to be flushed out of the aquifer. This process will eventually take place in Case 2, starting essentially at a later time. Over longer time periods, additional salt will be removed in this case because the overall extraction is higher and causes the deepest stream lines to reach greater depths (Fig. 7.7). Therefore, this case may be referred to as the most efficient system and can provide the highest sustainable amount of freshwater compared to the previous cases.

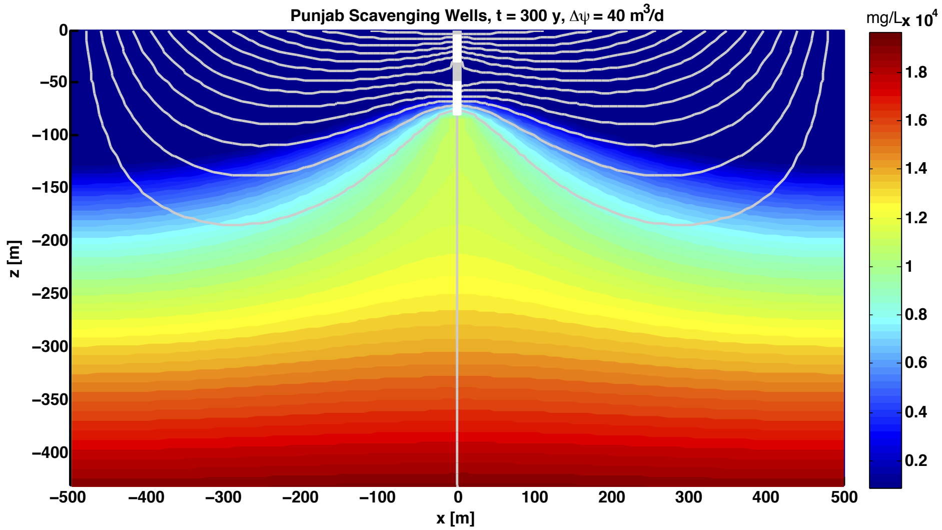

Figure 7.5: Flow field with $Q_f = Q_s$ after 300 years in Case 2 (refer to Table 7.1) where Q_f is the extraction by freshwater screen and Q_s is the extraction by scavenging screen. $\Delta\psi$ is the flow between each pair of streamlines.

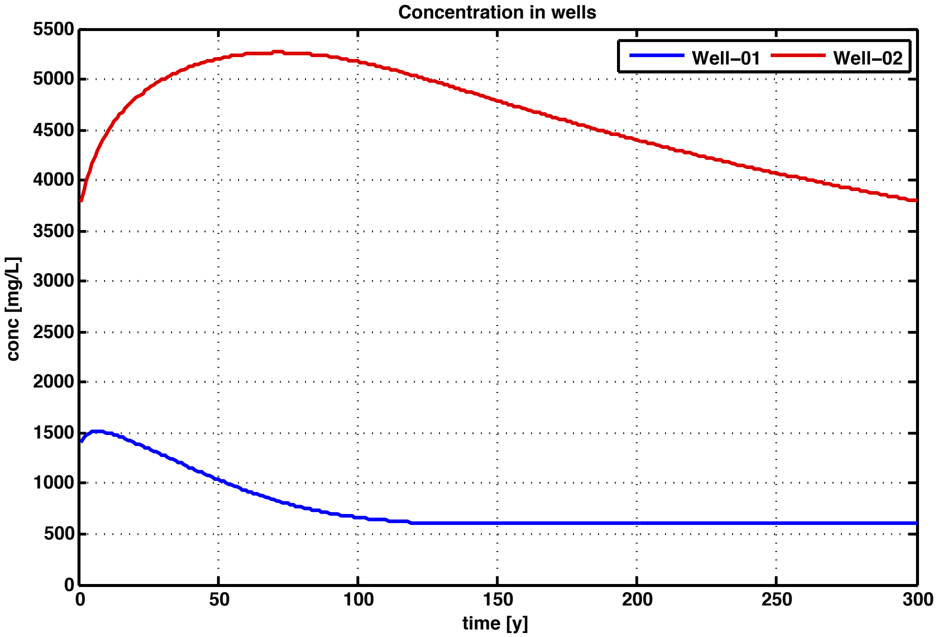

Figure 7.6: Concentration of TDS in both the fresh and salt screens in Well-01 and Well-02, respectively, for Case 2, where $Q_f = Q_s$. Q_f is the extraction by freshwater screen and Q_s is the extraction by scavenging screen.

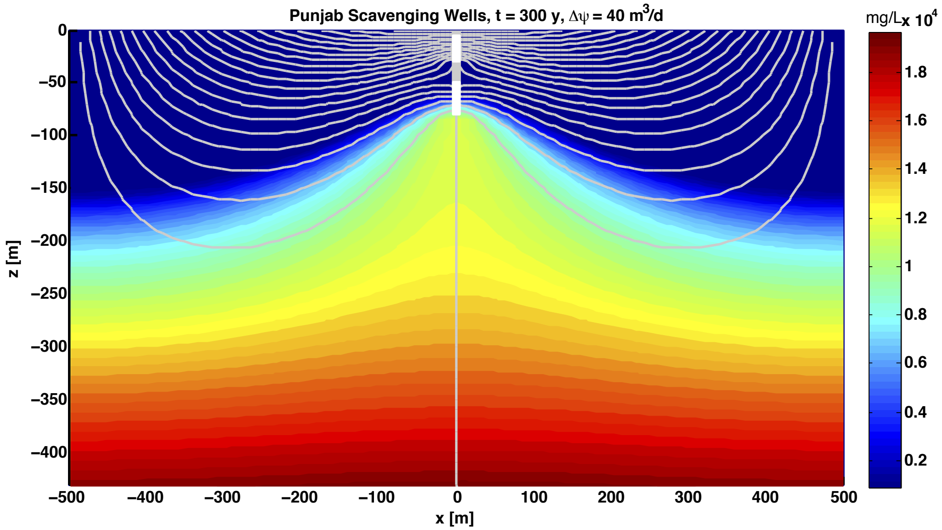

Figure 7.7: Flow field with $Q_f = 2Q_s$ after 300 years in Case 3 (refer to Table 7.1) where Q_f is the extraction by freshwater screen and Q_s is the extraction by scavenging screen. $\Delta\psi$ is the flow between each pair of streamlines.

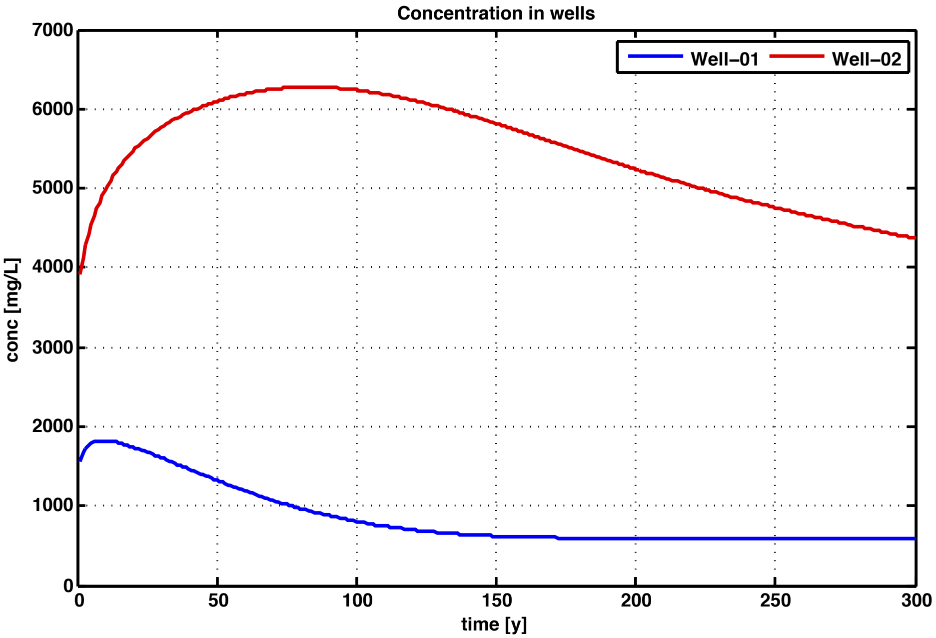

Figure 7.8: Concentration of TDS in both the freshwater and saltwater (scavenging) screens in Well-01 and Well-02, respectively, for Case 3 (refer to Table 7.1), where $Q_f = 2Q_s$. Q_f is the extraction by freshwater screen and Q_s is the extraction by scavenging screen.

Injection of the most saline water at greater depths (recirculation) [Case 4]

Case 4 demonstrates an option to discharge the most saline water from the second scavenging screen into a deeper third screen. This is the case of partial recirculation and may reduce the salinity in the water discharged into the irrigation system in cases where no drainage infrastructure is present. It leaves as much highly mineralized natural water in the aquifer as possible. The settings are the same as in Case 3; however, the saltwater extraction is multiplied by 3/2, i.e., increased from 0.35 to 0.52 mm/d, and one-third of the Q_s is injected into the deeper third screen. The injection water is taken from the bottom of the second screen where the water with the highest salt concentration enters. The flow field after 300 years of simulation is shown in Fig. 7.9, and the concentrations are shown in Fig. 7.10. From these figures, it can be concluded that there is no real benefit to be expected from this complicated and expensive system except for a delay in the increase of salinity in the shallow screen for the first 50 years. The total volume of brackish water in the subsurface will grow by such recirculation (Fig. 7.9) and eventually affect the salinity in the freshwater screen.

Sensitivity analysis of the hydraulic parameters

A sensitivity analysis was conducted by assuming different values of the vertical anisotropy (k_r / k_z) in Case 3; the other hydraulic parameters and initial salinity remained the same. The results of this analysis are shown in Figs. 7.11 and 7.12 and analysis revealed that the vertical anisotropy was the most important hydraulic variable, and it either delayed or accelerated the process of salinization. The higher values of the vertical anisotropy reduced the depth reached by the streamlines, which in turn reduced the time required to reach the equilibrium salinity in the cases of skimming or shallow screens. The depth of the streamlines was reduced by a factor of 2 when the flow field of the vertical anisotropy of 25 (Fig. 7.11) was compared to Case 3 (Fig. 7.7) where the vertical anisotropy was 4. Fig. 7.12 shows that the salinities in the shallow and scavenging screens decreased with the increasing vertical anisotropy. The blue lines in Fig. 7.12 further show that the final groundwater salinity did not depend on the hydraulic parameters of the groundwater system. The vertical anisotropy was the only important hydraulic variable that could at most shorten or lengthen the time to reach the equilibrium salinity. The high values of the vertical anisotropy, i.e., $k_r / k_z \geq 10$ in the Punjab, could only shorten the process of salinization to the final (long-term) salinity. Fig. 7.12 reveals that the time required to reach the predefined equilibrium concentration, i.e., 600 mg/L, is 100 years in case of $k_r / k_z \geq 10$, whereas it may take up to 150 years in Case 3, where $k_r / k_z = 4$.

Fig. 7.12 further shows that the final salinity, i.e., 600 mg/L, in all 4 cases of the different vertical anisotropy for shallow screens reaches equilibrium after 250 years, whereas the salinity in the scavenging screen may take at least a thousand years or

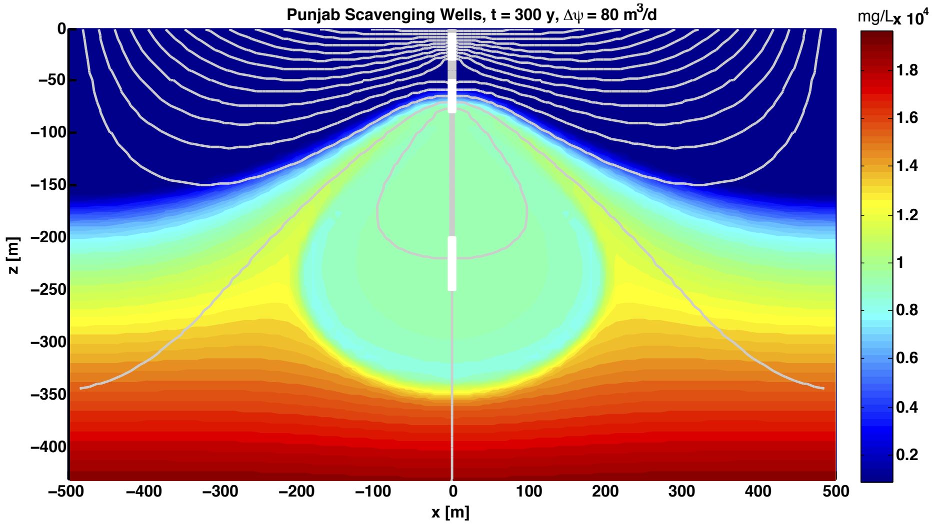

Figure 7.9: Flow field in Case 4 with extractions $Q_f = -815\ \text{m}^3/\text{d}$, $Q_s = -405\text{m}^3/\text{d}$, $Q_{inj} = +135\text{m}^3/\text{d}$, where Q_f is the extraction by fresh screen, Q_s is the extraction by scavenging screen and Q_{inj} is the injection of the saltwater back into the aquifer at a deeper depth. $\Delta\psi$ is the flow between each pair of stream lines.

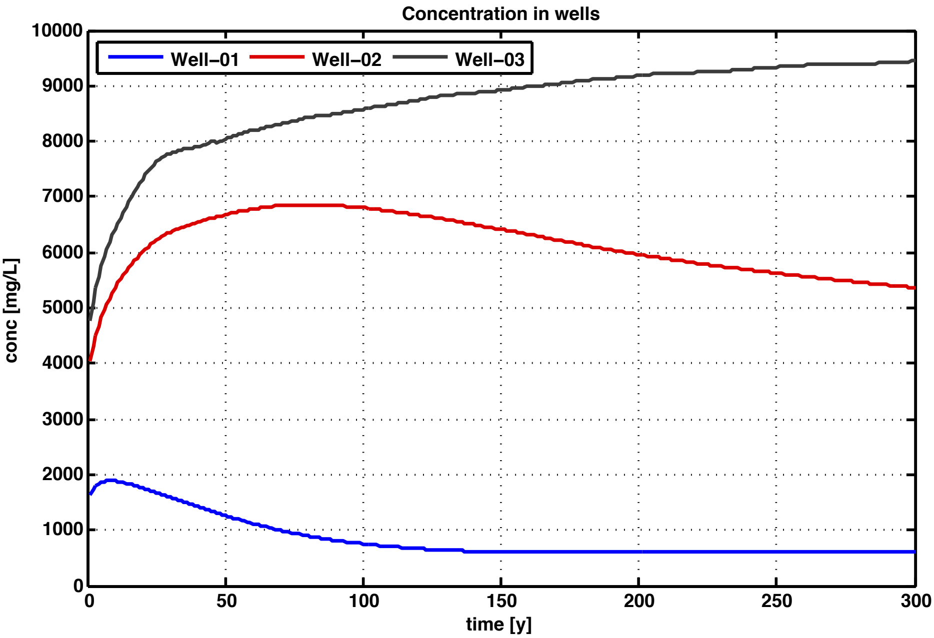

Figure 7.10: TDS concentration in the three screens of Case 4: $Q_f = -815\ \text{m}^3/\text{d}$ (Well-01 represented with *blue line*), $Q_s = -405\ \text{m}^3/\text{d}$ (Well-02 represented with *red line*), $Q_{inj} = +135\ \text{m}^3/\text{d}$ (Well-03 represented with *grey line*), where Q_f is the extraction by fresh screen, Q_s is the extraction by scavenging screen and Q_{inj} is the injection of saltwater back into the aquifer at a deeper depth.

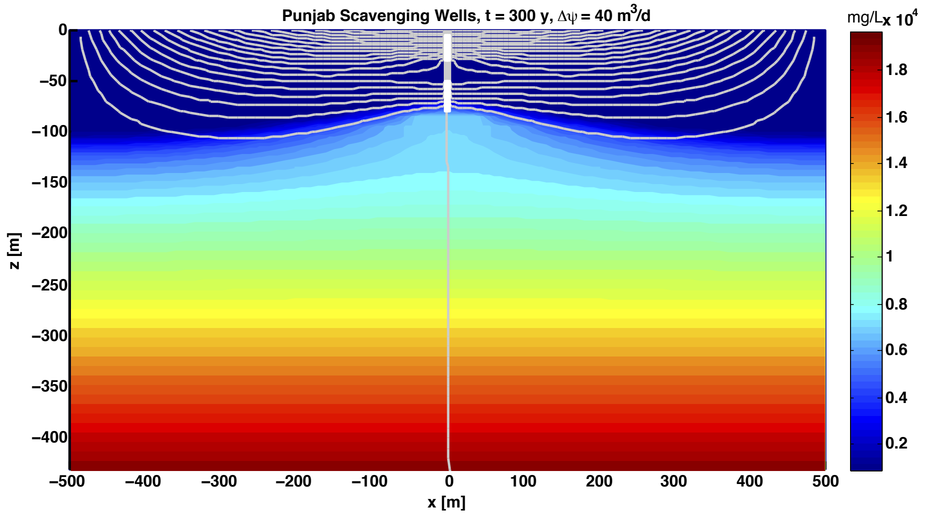

Figure 7.11: Flow field with $\frac{k_r}{k_z}=25$; other hydraulic parameters and initial salinity conditions are the same as in Case 3. $\Delta\psi$ is the flow between each pair of streamlines.

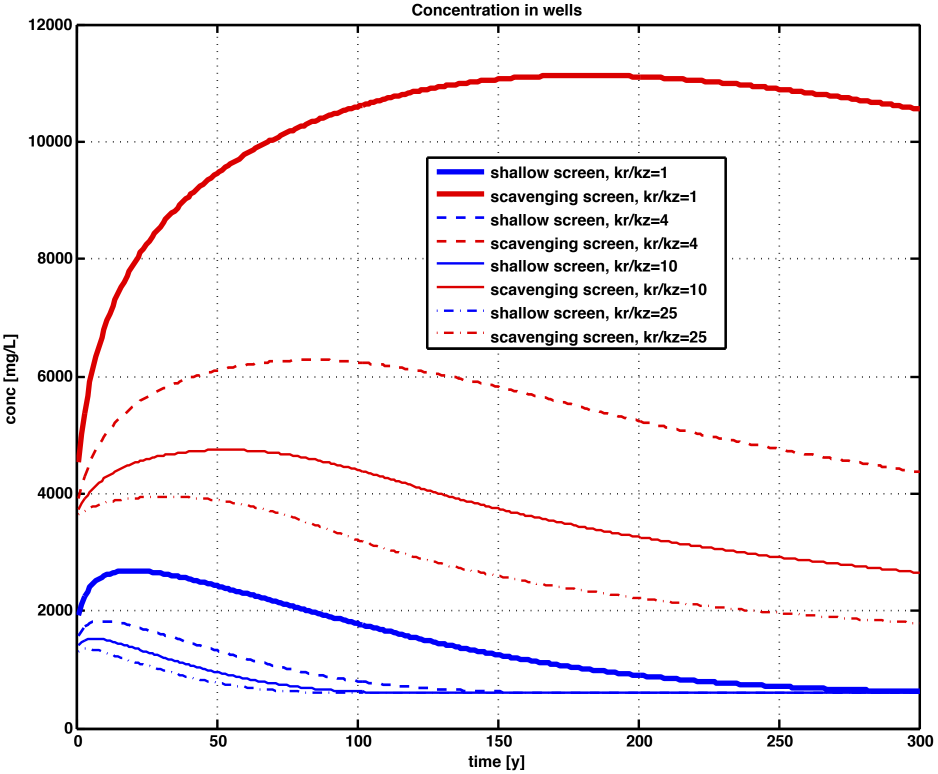

Figure 7.12: Sensitivity analysis of the hydraulic parameters.

more to reduce it within the limits that would be acceptable for the downstream users.

Initial salinity conditions determine the time to reach the equilibrium

Case 3 is again simulated by considering the worst salinity distribution scenario in the Punjab as shown in Table 7.3 that is hardly possible to exist; in which all of the hydraulic parameters remain the same. The results of this worst-case scenario are presented in Figs. 7.13 and 7.14. The flow field in Fig. 7.13 shows that the depth of the streamlines remained the same as in Case 3 (Fig. 7.7) where the average salinity profile in the Punjab was considered. The depth reached by the streamlines was dependent on the vertical anisotropy. However, these streamlines did not depend on any other hydraulic parameters or the initial salinity in the groundwater system.

A comparison of the graphs in Fig. 7.8 for Case 3 and Fig. 7.14 for this worst-case scenario, clearly reveal that the equilibrium in the fresh (upper) screen at the predefined limit of 600 mg/L is attained in approximately 180 years (Fig. 7.14), whereas it takes approximately 150 years in Case 3 (Fig. 7.8). Therefore, it is concluded that the initial salinity conditions may only delay or speed up the process of salinization to reach the equilibrium salinity. The salinity in the scavenging screen (Fig. 7.14) is reduced from the maximum value of 9,500 mg/L to 6,000 mg/L in approximately 200 years, whereas in Case 3 (Fig. 7.8), the maximum value of 6,200 mg/L decreases to 4,300 mg/L in approximately 225 years. Hence, it is further concluded that the initial high salinity in the groundwater system may require much larger time periods to reduce the extracted salinity from the scavenging screen to the acceptable limits for the downstream users.

CONCLUSIONS

The results of our analysis and the four presented cases show that a long-term equilibrium can be reached in which the TDS concentration of the extracted fresh groundwater does not exceed a preset limit for which a value is chosen that is acceptable for irrigation. These cases essentially cover the range of possibilities, and the most probable set of hydraulic parameters for the Punjab was used. However, the different sets of parameters and initial salinity did not change the final (i.e., long-term) salinity of the extracted groundwater used for irrigation, and other parameter values can at most shorten or lengthen the time in which a preset equilibrium salinity is reached. Therefore, to achieve sustainability, a certain amount of brackish water has to be discharged. This can be performed by scavenging, a method in which an extra screen is installed below the regular freshwater screen. In all cases, the required

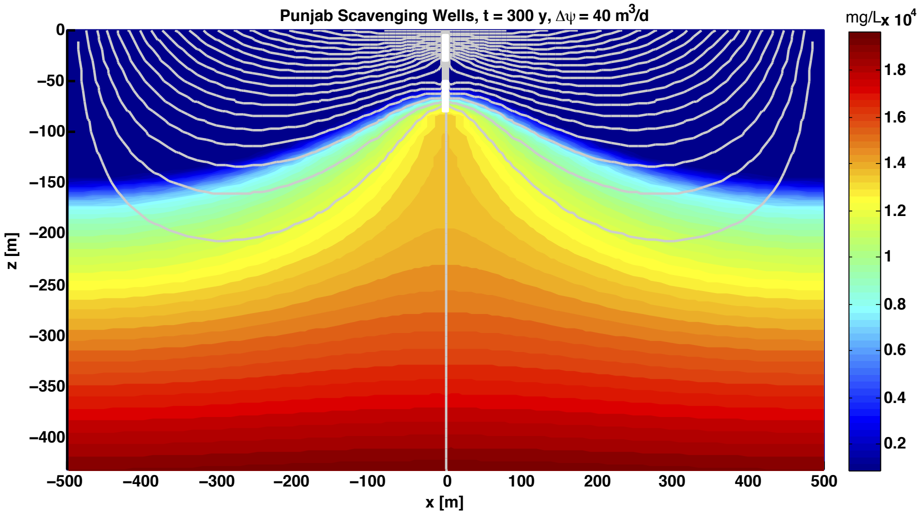

Figure 7.13: Flow field in the worst-case scenario of the initial groundwater salinity (refer to Table 7.3); all hydraulic parameters are the same as in Case 3. $\Delta\psi$ is the flow between each pair of streamlines.

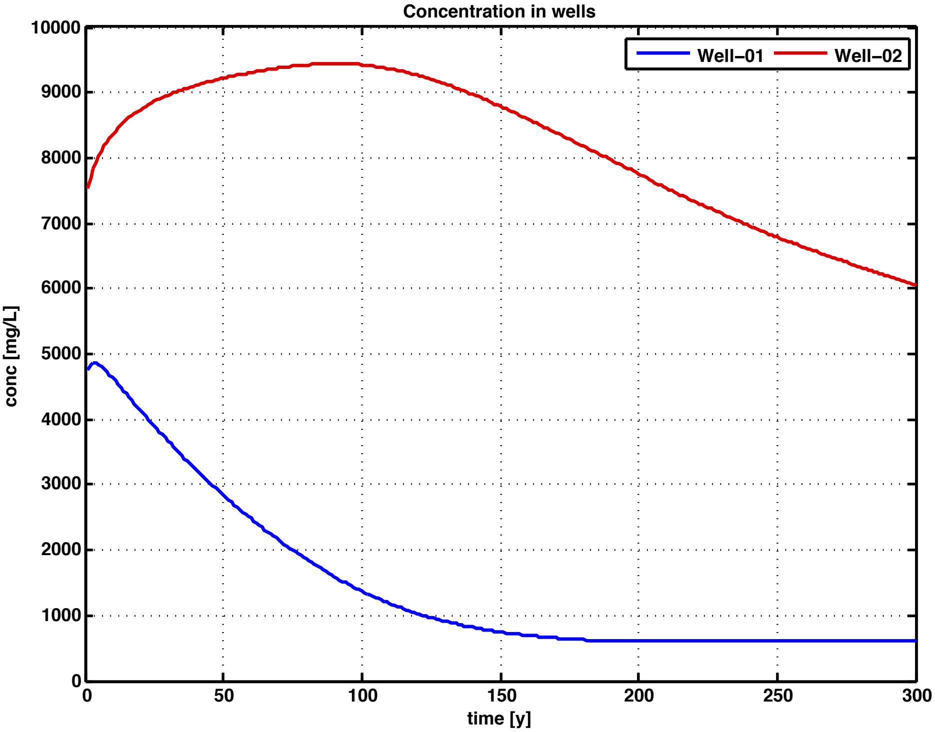

Figure 7.14: TDS concentration of the freshwater and scavenging screens represented by Well-01 and Well-02, respectively, in the worst-case scenario of the initial groundwater salinity (refer to Table 7.3).

extraction from such a deeper screen is determined by the derived salt and water budgets. The only free variable is the extraction of the freshwater screen Q_f.

To prevent both water logging and depletion, the volume in the aquifer was maintained at constant level over time. This implies that in all cases, both the freshwater and scavenging screens extract the entire recharge, i.e., $(S + R)$ in the case of a scavenger well or $(S + R + Q_{inj})$ in the case of a recirculation well.

The seepage from the unsaturated zone is called the return flow (R) and is the deciding factor, as it must be maintained to reduce the salt of the infiltrating water to the maximum permissible concentration for irrigation. Maintaining the balance of both the volume in the aquifer and its salinity requires that the terms of the water budget are quantified in the field and extraction limits are adapted accordingly. Of course, the infrastructure required to reject the extracted saltwater is essential to prevent discharge into the irrigation canals. Ultimately, all salt will end up in the Indus River and may burden the downstream users, which requires national planning with respect to agricultural production. Whether such required drainage is acceptable must be investigated on an expanded national scale.

A clear disadvantage of scavenging wells is that much of the natural saltwater is unnecessarily discharged. Only the saltwater increase in the fresh aquifer caused by mixing, i.e., dispersion, must be discharged over time. The discharge of highly mineralized native groundwater is a consequence of upconing into the lower screen, as shown in the figures. The re-injection of saltwater into the aquifer at a proper depth might be a mid-term solution to delay the discharge of salt. The total volume of brackish water in the subsurface will grow by such recirculation and eventually affect the salinity in the freshwater screen (Fig. 7.9). Fig. 7.10 shows that for the recirculation case, i.e., Well-03, the extracted salinity continuously increases, whereas in the other cases, a maximum concentration is reached at some point in the future.

These findings have led to three main conclusions: (1) skimming wells cannot prevent long-term salinization; (2) recirculation wells can substantially delay salinization as a mid-term solution but will not prevent it; and (3) scavenging may be the only option to solve the long-term salinization problem. The issue of salinization in skimming wells that is currently affecting farmers is a result of saltwater not being removed from the groundwater system; viable solutions require the removal of a certain amount of saltwater, which can most effectively be performed by scavenging.

We have shown that, in the Punjab, additional irrigation from the groundwater is sustainable if the groundwater is discharged at a rate equal to a fraction of the irrigated surface water.

A sensitivity analysis showed that vertical anisotropy is the most important hydraulic variable because it reduces the depth reached by the streamlines. Therefore, vertical anisotropy reduces the time in which the preset equilibrium salinization is reached.

The final salinity in the saturated zone reached by the streamlines can only be influenced by the inflows and outflows that carry salt, which are the irrigation water, seepage from canals, and discharged water. Long-term salinity depends to some extent on leakage from irrigation canals, which can only be influenced by construction and maintenance. However, long-term salinity does not depend on any of the hydraulic parameters of the groundwater system and wells. The maximum average extraction of freshwater Q_f is determined from $(S + R - Q_s)$, i.e., the leakage, return flow and saltwater extraction. The required saltwater extraction Q_s does not depend on freshwater extraction. In the recirculation case, it depends on the saltwater injection Q_{inj}. The final salinity, i.e., long-term salinity, does not depend on the hydraulic parameters or initial groundwater salinity; it only depends on the salinity of the irrigation water c_I, saltwater extraction Q_s, leakage from the irrigation canal system and in the recirculation case, on the saltwater injection Q_{inj}, as shown in equations 7.21 and 7.22.

CHAPTER 8

Synthesis and discussion

In the Punjab, the groundwater away from the rivers of the Indus Basin is naturally salty as a result of the infiltration of these rivers and the accumulation of saltwater caused by evaporation. The unconsolidated fluvial Punjabi aquifer is essentially unconfined, highly vertically anisotropic and of unknown depth with large quantities of native saltwater.

After re-evaluation of literature on hydraulic parameters of the Punjabi aquifer, it was concluded that the values obtained in the drilling and pumping test campaign carried out by US Geological Survey in the 1960s still provides the best initial data for regional modeling. Multidepth pumping tests prove both practical and suitable to determine essential vertical anisotropy values of the aquifer system.

Because sedimentation is a continuing process in surface water reservoirs, and because development of new dams is very difficult, the availability of surface irrigation water is expected to become more irregular in the future, which will increase the need of additional irrigation from groundwater. Therefore, groundwater management requires more emphases, with focus on conjunctive use. In this context, leakage of freshwater into the natural salt aquifer in much of the center of the doabs, which has gone on for more than a century, is essential to replenish and maintain this new groundwater as a resource.

The fresh groundwater throughout the Punjab is to large extent new as it resulted from irrigation canal leakage since the late 1800s. Since the 1980s, million of farmers installed tube-wells to compensate for irregular availability of surface irrigation water. This new fresh groundwater is of a great value and needs careful management, because it is limited in quantity and because food production has become highly dependent on it.

The skimming technology introduced in 1980s and now used by millions of private wells in the Punjab aims at reducing or preventing saltwater upconing into the well strainers. Contrary to what many studies on the subject suggest, skimming technology cannot prevent salinization, it may only delay it.

Sustainable extractions from groundwater for additional irrigation are possible, and achieved by balancing the water and salt on the scale of the field or farm. Water balancing is required to prevent waterlogging and over-exploitation; salt balancing is required to maintain salinity, which can only be realized by managing salt-carrying inflows and outflows, i.e., surface water irrigation, canal leakage and groundwater discharge to drainage.

The salinity of the groundwater can be maintained below a preset acceptable maximum by sufficient drainage. The required amount of drainage can be estimated from the actual supply of surface water, including canal seepage, times the ratio of the salinity in surface irrigation water and the acceptable salinity in the groundwater. The final salinity in the saturated zone can only depend on the salt-carrying inflows and outflows, i.e., the import of surface water and the export through groundwater drainage as independent variables that can be fixed through farmer adjustable crop factor and irrigation efficiency. From these, groundwater irrigation and irrigation return flow follow. The thickness of the unsaturated and saturated zones only determines the time in which salt equilibrium is attained. This may be tens to hundreds of years.

These conclusions are independent of the actual values of the hydraulic parameters of the aquifer system; the most important of which is the vertical anisotropy; low values of vertical anisotropy can only delay the time in which salt equilibrium is reached: neither low salinity in the irrigation canal water nor an initial low salinity of the groundwater can prevent salinization due to recirculation of salt; only drainage can prevent it in the long run.

Such drainage is best realized by scavenging wells that dispose of the more saline water from their deep screen through the regional drainage system. Adding a deeper screen to skimming wells should, therefore, be a feasible solution if placed just below the freshwater screen to prevent natural salt groundwater to be unnecessarily discharged.

Re-injection of saltwater into a deeper screen is sometimes mentioned as an alternative for disposal of saltwater to the drainage system. However, such reinjection can only be a temporary solution; it can only delay salinization of the shallow groundwater.

The salinization, which farmers are facing with their skimming wells, is because they do not remove any saltwater from the groundwater system: there can be no solution without removal of some saltwater, which can most effectively be performed by scavenging.

The required saltwater extraction does not depend on the hydraulic parameters of the groundwater system or amount of freshwater extraction used for additional irrigation.

It is evident that large-scale disposal of saltwater may affect downstream usage in Sind province, which requires national planning with respect to agricultural production. Whether such required drainage is acceptable must be investigated on an expanded national scale (refer to GOP, 2005; Schultz et al., 2003, 2005).

A geophysical measurements campaign in the Punjab has revealed that brackish and saline groundwater generally occurs at depths that are few to perhaps tens of meters below the screen of skimming wells, which make them very vulnerable to salinization. The freshwater depth observed in this campaign is consistent with the findings of Greenman et al. (1967), which were concluded half a century ago.

Sustainable conjunctive use of groundwater for additional irrigation requires long-term salt management that is founded on the essential controlling factors as derived in this thesis.

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About the author

Naveed Alam was born on May 25, 1974 in Faisalabad, Pakistan. After completion of his graduation in Civil Engineering, Naveed started his career in 1999 as a Consulting Engineer with NESPAK – a leading engineering consultancy firm, which is operating in South Asia and Middle East. He has also served in Punjab Irrigation Department as an Assistant Executive Engineer. He has an extensive and diversified experience, including working experience with a consortium of international consulting firms like Binnie & Partners of UK and Harza Engineering Company of USA, which broadened his vision to explore new horizons in providing sustainable solutions. He has acquired a diversified experience of more than 15 years in the field of engineering consultancy, research and feasibility studies, groundwater modeling, geotechnical and hydrogeological investigations, drilling and logging, field measurements, writing technical and review reports, planning and management of water resources, etc.

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Publications

PEER-REVIEWED JOURNAL ARTICLES

Alam, N. and Olsthoorn, T. N. (2014). Punjab scavenger wells for sustainable additional groundwater irrigation. Agricultural Water Management, 138: 55–67, http://dx.doi.org/10.1016/j.agwat.2014.03.001.

Alam, N. and Olsthoorn, T. N. (2014). Multidepth pumping tests in deep aquifers. Groundwater, http://dx.doi.org/10.1111/gwat.12155.

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Alam, N. and Olsthoorn, T. N. (2013). Sustainable conjunctive use of groundwater for additional irrigation. Hydrological Processes, http://dx.doi.org/10.1002/hyp.10049.

Alam, N. and Olsthoorn, T. N. (2011). Sustainable conjunctive use of surface and ground water: Modeling on the basin scale. International Journal of Natural Resources and Marine Sciences, 1(1): 1–12, http://ecopersia.modares.ac.ir/article_1_0.html.

PEER-REVIEWED CONFERENCES

Alam, N. and Olsthoorn, T. N. (2013). Comprehensive evaluation of farmers' practices in Indus Basin and solutions to control salt upconing. MODFLOW and More 2013: Translating science into practice, June 2–5, 2013, IGWMC, Denver, Colorado, USA.

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Alam, N. and Olsthoorn, T. N. (2011). We develop our understanding of Indus Basin by calibrating the predevelopment situation. We show that by doing this, we will end up with a more reliable model than otherwise possible. IUGG 2011 — Earth on the edge: Science for a sustainable planet, June 28 – July 7, 2011, Melbourne, Australia.

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Alam, N. and Olsthoorn, T. N. (2008). Comprehensive evaluation of skimming wells — An alternate technology for environmentally sustainable irrigation in the Indus Basin of Pakistan. EGU General Assembly 2008, April 13–18, 2008, Vienna, Austria.

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REPORT

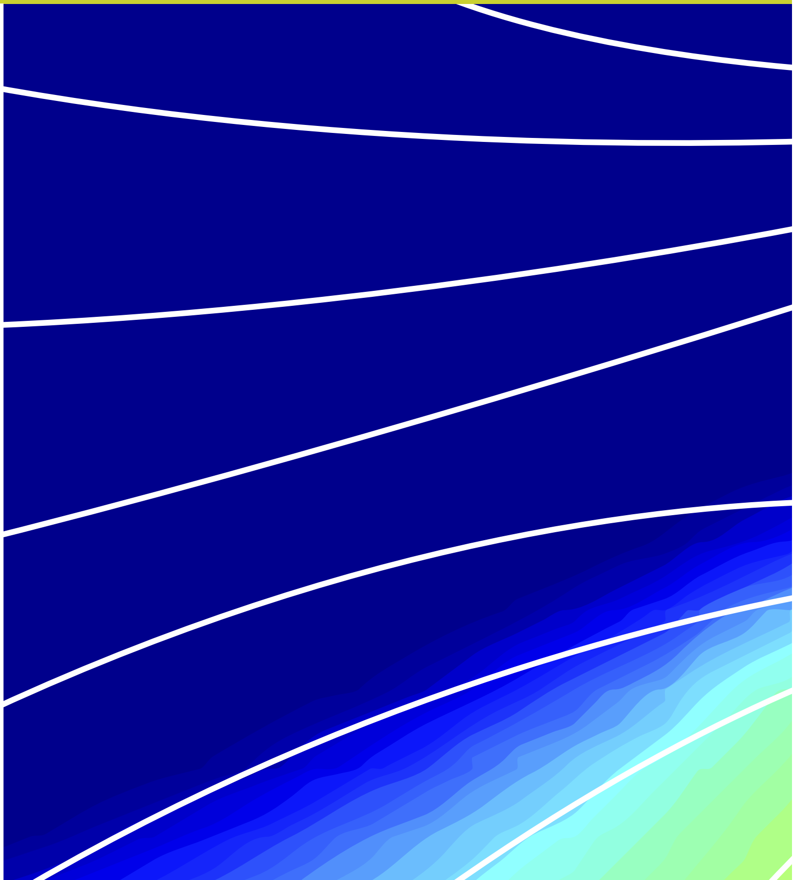
Alam, N. (2011). Time-domain electromagnetic soundings in Chaj Doab, Indus Basin, Pakistan. Technical report, Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands.

Currently millions of private wells in the Punjab are pumping groundwater as an additional source for irrigation to compensate for irregular surface water supply. Since the 1990s, most of them are skimming wells that aim to reduce the salinity of the pumped groundwater. However, salinization continues to rise over time, often above acceptable limit, which threatens food production.

This thesis aims to develop a solution to make groundwater use for additional irrigation sustainable, i.e., to limit the salinity of pumped water in the long run.

Based on a model analysis, it was shown that skimming technologies cannot prevent salinization, irrespective of parameters of subsurface, for which some unique pumping tests were analyzed and geophysical measurements were carried out in the Punjab.

Sustainability is sought in balancing both water and salt on the scale of field or farm. Both analytical and numerical models were used to show that the adopted concepts will work.



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