Conjunctive water management: How to use the full potential

A literature research

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Irrigation and Water Engineering Group

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Noraly van den Born

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Supervisor(s):
ir Jaime Hoogesteger
Irrigation and Water Engineering Group
Centre for Water and Climate
Wageningen University
The Netherlands
www.iwe.wur.nl/uk

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Abstract

Conjunctive water management is the sustainably managed use of groundwater and canal water together. Conjunctive use is mostly done in large scale irrigation scheme whit surface water shortage that is supplemented with groundwater; this is done uncoordinated and creates problems.
The goal of this report is to get a better understanding of conjunctive water use and management (both physically and institutionally); and to explore the potential of a groundwater aquifer for temporal water storage.

An environment that enables conjunctive management has several factors. Firstly the inflow and outflow of water in an area should be in balance in long term. Secondly Groundwater quality and quantity differs per area and should be monitored. Finally management practices like irrigation efficiency and land reclamation can prevent or handle water logging.

A groundwater basin improves conjunctive water management. Drainage and the pumping up of groundwater create a buffer in the soil that can be recharged and use for storage.

Several improvements can be made to current conjunctive use and management.
It is very important to start drainage straight away. Water quality should be managed carefully.
Institutions are important to empower reallocation of surface water.

Conjunctive management theory test in testcases has the fowlowing conclusions: In San Joaquin valley textbook conjunctive management can be carried on some parts of the land after some adjustments. For other parts of the land that are to salt, alternative methods, like salt tolerant crops are needed. Because of low quality of all sources in KLBDB, the quality of all water should be monitored. Conjunctive management of water should be done across the Indus river basin, for this water policy enforceability should be improved

Chapter 1: Introduction

In many areas around the world, conjunctive use of surface and groundwater for irrigation has developed in many agricultural areas with surface irrigation systems. Conjunctive use is the use of both surface water and groundwater for irrigation (Karamouz et al. 2004). At the moment conjunctive use is the reality in many large scale irrigation schemes, where a major part of the water used is pumped up instead of supplied by the irrigation schemes (Steenbergen & Tuinhof 2009). The use of both sources gives more water security (Qureshi, Turral & Masih 2004).

Generally groundwater management has had a low priority for governments and receives little acknowledgement: National information is often only on the dominant surface irrigation source and efforts to improve groundwater management are fragmented (Jehangir et al. 2002, Foster et al. 2010). People will only work with matter they are familiar with and understand. "Given that efficient conjunctive use is information and skill- intensive, large improvements will be necessary in both the skills of irrigation managers and the quality of the management information and control systems at their disposal. Neither farmers nor bureaucrats will accept proposed solutions that are beyond their understanding and experience" (O'Mara 1988 p15). So it is of use to investigate what factors create an enabling environment for conjunctive water management and what management corresponds to this environment.

Groundwater is of great importance in conjunctive water use. The use of the groundwater aquifer as a storage basin can improve availability and efficiency of water use (Bredehoeft & Young 1983, IMWI 2010, pers.com Ritzema 2010). This BSc Thesis is based on a literature study. The main objective of this study is to summarise all physically an institutionally enabling factors of conjunctive water management. The study departs from the premise that conjunctive use requires a storage basin in the groundwater aquifer, so water is available when needed. Chapter two discusses the interaction between groundwater and irrigation this is formulated in a balance of water quantity and water quality. Chapter three discusses measures usually taken to prevent or combat waterlogging and salinity, these are the main problems in irrigation. Chapter four presents the theories on conjunctive management and groundwater storage. In chapter five two case studies where conjunctive water management is applied are presented. The two case studies are the San Joaquin Valley in Southern California and Kotri Left Bank in Pakistan. Both have large irrigation system and in both cases groundwater is used. From the successes and pitfalls of both case studies I draw conclusions and make recommendations.

Objective

The goal of this report is to get a better understanding of conjunctive water use and management (both physically and institutionally); and to explore the potential of a groundwater aquifer for temporal water storage.

Research questions

The research questions that have guided this research are presented below:

What factors create a physically and institutionally enabling environment for conjunctive water use and what management corresponds to these enabling factors?

What is the potential of the use of a groundwater basin for improving conjunctive water management?

What realisable physical, legal and institutional improvements can be advised?

Chapter 2: Irrigation-groundwater interactions

Introduction

This chapter explains the interaction between irrigation water, groundwater and drainage by introducing the water balance. A balance always consists of inflow (irrigation and rainfall or groundwater inflow); outflow (drainage and runoff); and a change in storage (water table height). How well this balance is managed influences the availability and quality of groundwater and the overall water use efficiency of both surface and groundwater in a setting of conjunctive water use. Quality is a very important factor: Water of a bad quality has a negative influence on agriculture, human health and the environment, and fresh water can easily be turned into water of low quality. Water logging and salanization are the main problems occurring with the introduction of irrigation and the source of these problems is often related to lack of drainage. Therefore they need to be properly managed.

Balance of quantity

The essence of the water balance covers what goes in and what the quality is (pers. com. Jacob Vos, Gupta 1993, Bos and Wolters 1994). The basic idea of a balance is that inflow minus outflow is the change in storage, meaning that the total volume of the balance is stable: Water does not appear or disappear. So to keep a stable groundwater level, the inflow and outflow in the area should be equal.

Irrigation with river water intercepts the natural water flow, resulting in a new water balance where the natural balance of the groundwater changes. Irrigation brings solutes and water to areas where these would not be naturally, so the natural balance of the groundwater aquifer will change significantly when irrigation is introduced. Because of this, when irrigation is started, sooner or later drainage becomes necessary (pers. com. Jacob Vos). The water balance can be changed by both entrance of surface water and how efficiently the introduced water is used, and the use of tube wells which extract water which has infiltrated or water from the aquifer (pers. com. Henk Ritzema). The basic elements of a water balance are presented, while a balance formula and detailed explanation are presented in Box A.

Inflow

Groundwater under an irrigation system is recharged by various sources: River water, canal water, water applied to the fields and groundwater flow from higher to lower elevations (Ahmad and Chaudhry 1988 in Bos and Wolters 1994). The total volume of water applied should be larger than the crop water requirement because, in addition to evapotranspiration of the crop, irrigation water will be also consumed by non-crop vegetation, evaporation, seepage, operational spills, deep percolation and tail water runoff (Bos and Wolters 1994).

The amount of seepage from the canals of the irrigation system depends on if they are lined: Lined canals have less seepage than unlined ones. But even when the system is partially or completely lined there is still some water table rise. Most of the seepage returns to the river through drains or via groundwater outflow and can be used again, although the quality is usually deteriorated (Gupta 1993, Bos and Wolters 1994).Operational spills occur when there is more water in the irrigation system than is required by the framers or when there is a reduction in demand. This water usually will return to the river within a few days and is seldom polluted (Bos and Wolters 1994).

Deep percolation, the percentage of water applied to the field that moves below the root zone, removes salt from the root zone that would otherwise accumulate there. Deep percolation adds water to the aquifer, and is therefore available for groundwater users. Excess surface water is sometimes stored in the aquifer to be recovered in dry seasons or years. Irrecoverable water is water which needs to flow out of the area to prevent salanization, or can simply not be pumped up economically (Bos and Wolters 1994).

Tail water runoff depends on field design, application, soil conditions and operational practice and happens often when irrigation is done on graded fields in order to achieve uniformity and water application efficiency. Tail water can be pumped back and re-used, reach canals as return flow, be used by non-irrigated vegetation adjacent to the crops or can be used by other users as a supplemental or primary source of water. A disadvantage is that it can destroy the end of the field. When irrigation schemes are long and water is released far before it reaches the area in need of water, random rainfall leads to excess water. Primary rainfall will result in percolation of most of the irrigation water. If the area has already been irrigated, high intensity rainfall will runoff (Bos and Wolters 1994).

Seepage losses by irrigation let the groundwater level rise. Usually there is plenty of canal irrigation water so more water enters than leaves the area. When there is only irrigation without "second thoughts", 20 years later, or sooner, the irrigation is a problem instead of a help. Irrigation interrupts a balance. A new balance will be established (pers. com. Jacob Vos).

Outflow

Irrigation has two important risks: water logging and salanization. Waterlogging is the process of the rise of the water table. When more water enters the area than the amount of water that leaves, the watertable will eventually approach the surface. Water table rise causes shortage of oxygen for plant roots. Stalinisation happens when more salts enter than leave the area. Capillary rise from the high water table facilitates accumulation of salt in the root zone (Bos and Wolters 1994, Wolters, Ittfaq and Bhutta 1994). In many areas drainage possibilities are limited because of constraints in water supply or topography (Gupta 1993).

Using the water balance of the area, the drainable surplus can be calculated, which is equivalent to the drainage requirement. Removing the drainable surplus keeps the water table deep enough to preventing water logging. Drainage also for flushing of the root zone, so that a harmful concentration of salt brought in by the irrigation cannot be reached (De Ridder and Boonstra 1994). Sometimes areas can be drained by pumps, especially in sweet groundwater areas (pers. com. Theo Boers). Keeping the water table at a proper level by preventing water logging makes an increase of storage possible and reduces peak discharges during periods of peak rainfall (Oosterbaan 1992 according to Oosterbaan 1994).

Water table balance (change in storage)

The ground water table should be managed carefully. When the water table is too high there is a drainage problem, when it is too low, the soil might not be moist enough. Soil moisture is important for processes like nitrogen fixation (pers. com. Frank van Steenbergen). Regulation of the groundwater level is possible by the regulation of irrigation. When surface water becomes less, groundwater water efficiency goes up. Canals which are not lined have seepage losses. The percolation losses under the canal make groundwater rise. This has the possible consequence of water logging in the strip of land next to the canal. These areas become evaporation pans and go out of production. As long as the water table is below 2 meter there is no problem, but when it enters the area of 2 meter below the soil surface capillary rise starts (pers. com. Jacob Vos, pers. com. Frank van Steenbergen). Site specific conditions are important in the interaction between irrigation water, groundwater and drainage. The problem is that every square meter differs from the other. For example geology is important. When an area has a difficulty the properties of the aquifer should be well known. For example if there are impermeable layers, when the type of soil does not drain easily the neighbouring land turns into an evaporation pan (pers. com Jacob Vos).

Quality

The salt balance depends on the water balance. Irrigation can cause waterlogging, and through evaporation, the water evaporates and the salt stays and becomes more concentrated, waterlogging causes salinity. In arid and semi-arid regions with high temperatures and where evapotranspiration barely exceeds rainfall, salt may become concentrated in the top of the soil, adversely affecting crop growth. Salt is left behind on the surface after evaporation because plants do not take op the salts, this leads to an accumulation of salts over the years. In areas with shallow water tables, saline water also comes to the surface by capillary rise. To prevent salanization, extra water is put on the land to flush the salts away. This is only possible when the water can leave the soil through drainage. To avoid salanization both flushing and drainage is needed (Bos and Wolters 1994, Bhutta Wolters and Siddiqui 1996, Price 1996, Oosterbaan 1994, pers. com. Theo Boers, pers. com. Frank van Steenbergen and pers. com. Jacob Vos).

Where irrigation leads to a higher water table in areas that had a low water table before the irrigation started, fossil salts that have accumulated in deep soil layers can be mobilized and transported towards the root zone. This transportation of salts gives problems for the use of tube wells (Bos and

Wolters 1994). When the groundwater is saline and there is too much water in the area, only a small amount of groundwater can be used. Close to the canal may be the only area where pockets of sweet water that can be extracted by small pumps are present. If the water table is kept low, a sweet water lens of rain water and canal water seepage can be created by infiltration (pers. com. Frank van Steenbergen). When saline water from a saline aquifer is pumped up salt water is pumped in circles. When slightly salty water is used for irrigation, evaporation seepage and pumping it up again increases the salt concentration. Eventually this will lead to salinity problems for irrigation. In these cases salty water has to be drained away (pers. com. Henk Ritzema, Kijne 2003).

Drainage water is usually saline and contains chemicals like pesticides, herbicides and fertilizer. Its reuse leads to poorer water quality downstream (Bos and Wolters 1994). Rivers in arid zones naturally contain salts from mobilisation of salts in the catchment area and saline seeps. Pumping up fossil saline water into drains that flow out into the river makes it more saline (Kijne 2003). At the end of an irrigation system water quality is low, so drainage should not be allowed to re-enter the system (pers. com. Jacob Vos).

The amount and nature of solutes determinates the quality of water. Transportation and build-up of these solutes can cause salinity and pollution of water. When drain water is reused it is necessary to estimate the quantities of salt and other solutes, this is usually estimated from the salt balance, see Box B. Salt balances can be estimated by joining movement of water with movement of salt. Salt enters the system in canal water, surface water, and groundwater inflow and through rainfall. It leaves in runoff or trough drains or groundwater outflow. In the groundwater zone salt ions follow the streamline towards drains or pumped wells. Salt and solutes from deeper parts of the aquifer can be mobilised because the streamline may reach below the drain depth (Ridder and Boonstra, 1994).

Besides the use of surface irrigation water and drainage water, reuse of industrial and municipal wastewater as an extra source of irrigation water is wide spread. Much of the reused waste water is not treated, causing environmental hazards. In developing countries many treatment plants operate below design capacity and in this way contribute to discharge of untreated water into irrigation and drainage canals. Concentrations of salts and solubles in samples often exceed the levels allowed by drinking water quality guidelines. Water can also be unfit for reuse because of the pollutant load instead of salanization (Wolff, 2001, according to Kijne 2003).

Management

"Good management has proved difficult" (Kijne 2003 p43) both in surface water and in groundwater management. Overall, groundwater is individually managed, while surface water is usually managed by a government agency of by water use collectives organized in water user organizations (pers. com. Frank van Steenbergen). It is important that surface water is better managed and tubewells are used more efficiently. When multiple users make use of the same source, such as an aquifer, there should be cooperation (pers. com. Henk Ritzema).

In surface water the main problem is water logging. Only 22 percentage of land in the world that is irrigated has a drainage system. Most of the time poor farmers loose land to water logging and salinity (Kijne 2003). When an irrigation project is carried out, often there is no drainage laid out. Drainage is a costly component of canal irrigation and is usually excluded from the project design to keep the investment low (Gupta 1993). "But high groundwater levels and salinity could generate costs in the form of lower yield and income"(Scheuman 1997, p76). At the planning stage of the project, groundwater levels are usually low enough for farming. When the irrigation starts, the water table rises due to seepage, and after ten years drainage has to be installed. This is more expensive than when it is installed as part of the irrigation system right from the start.

High water tables due to seepage losses give secondary salanization (pers. com. Theo Boers). Secondary salanization (irrigation-induced salanization) of land exists in irrigated areas due to excessive and inefficient water use, where water losses raise the level of the groundwater table and cause waterlogging and land salanization (Kitamura et al. 2006).

There are two points of view regarding the timing of drainage implementation. Some hold that drainage can be postponed if it will take several years for problems to surface, allowing for a prosperous economy to be established first. The opposing point of view holds that irrigation and drainage should be implemented simultaneously because when drainage is installed later some land will have severe damage already. Additionally the total costs are higher when damage has already been done. This position therefore concludes that management that influences the performance of the irrigation system should be carried out all in one time (Gupta 1993).At the head of large irrigation schemes there is usually a lot of excess inflow and if the farmers do not need water, it is diverted away from their fields, causing operational spills which are collect in depressions for times of low water supply. The lack of a well-defined surface drainage system and the stagnation of water behind infrastructure make using the lower-lying lands impossible (Bos and Wolters 1994).

In management of groundwater the quality of the water is the main issue. Lack of data on water- and salt balance and of knowledge on water quantity and quality for downstream users, frustrates the improvement water productivity due to the difficulty of allocating water more equitably to users. Groundwater development is primarily an individual initiative, there is no large implementation department but the government often facilitates the process by subsidies and rural electrification. Frequent direct contact with groundwater users is rare and groundwater extraction is not allocated, monitored or managed by established institutions (Kijne 2003). The problem arising when farmers pump up water is: That they have no knowledge on water quality and will pump up salt water even when an advisor says not to do this, assuming that salt water is better than no water, but this salinizes the topsoil. When an area has too much salt in the topsoil percolation stops. The solution to this is flushing, but there is not always enough water present to do this (pers. com Theo Boers).

Operation and maintenance is a problem for surface water as well as groundwater. Also, the cost effectiveness of the irrigation system is a problem. Framers can hardly pay the costs of the system (pers. com. Henk Ritzema). Water from irrigation adds more to the groundwater than the amount which leaves through natural drainage. This excess water will percolate and flush down salts so the salt level at the rootzone is accepted by the crop. When a farmer applies more water, because he thinks flushing down of slats, also known as leeching, is needed, this will make the water table rise and cause water logging and salinity more severe than the problem for which he began to leach (Bos and Wolters 1994).

Conclusion

Inflow and outflow of water in an area should be in balance, when there is too much difference between inflow and outflow water shortage or quality problems will occur. Salinity stems from the fact that plants don't take up salts, so the small amounts of salts present in rain and river water accumulate in soil. To get rid of this salt it is very important to flush the soil and use drainage, however drainage and flushing will not have the effect intended when not done together.

In areas of saline groundwater, tubewell should be managed very carefully, because of the risk of pumping up salty water. A sweet water lens can be created be keeping the water table low, and this water can be pumped up, but when too much is pumped up salt water will enter the wells. Reuse of drainage water or wastewater should be banned or done with great precaution because the quality of this water can be extremely low.

Although drainage is necessary it is almost never laid out at the same time as the irrigation canal because it is costly. But even when the water table is at a good level before irrigation starts it will rise because of the irrigation and drainage is still needed. Spills collected in depressions and lack of drainage makes using the lower lying lands impossible.

Farmers should be made aware of quantity and quality of groundwater, for example when there is more water irrigated than drained. If the framers think the ground needs leaching and add too much extra water, water logging and salinity occur. Groundwater is mainly used individually and should be overseen by an institution, because individual users have no insight into the available quality and quantity. When a farmer runs out of fresh water and hits saline water, he will continue to pump because he assumes salt water is better than no water, but this accelerates the salanization of his soil. Because regulation has failed in many countries and waterlogging and salinity have already occurred, the next step is adding measures to the regulation making these problems stop and reverse the effects.

Box A: The water balance

To calculate the water balance, the soil profile is split into two zones:

1. "The unsaturated zone, which extends from the land surface to the water table, is the zone where favourable conditions for crop growth must be created in. The unsaturated zone consists of pores that are filled partially with water and partially with air"(De Ridder and Boonstra, 1994 P604).

"The water balance of the unsaturated zone reads:

$$I - E + G - R = \frac{\Delta Wu}{\Delta t} \quad (16.3)$$

where
I= the rate of infiltration into the unsaturated zone (mm/d)
E= the rate of evapotranspiration from the unsaturated zone (mm/d)
G= the rate of capillary rise from the saturated zone (mm/d)
R= the rate of percolation to the saturated zone (mm/d)
ΔWu = the change in soil water storage in the unsaturated zone during the computation interval of an equivalent layer of water (mm)
Δt= the computation interval of time (d)" (De Ridder and Boonstra, 1994 p 606)

"Infiltration in the unsaturated zone can be expressed by the following Equation:

$$I = \mathbf{P\text{-}E,} + 1000\,\frac{\mathbf{Qsi} - Qso}{\mathbf{A}} - \frac{\mathbf{\Delta Ws}}{\Delta t} \quad (16.4)$$

Where
P= precipitation for the time interval Δt (mm)
Eo = evaporation from the land surface (mm/d)
Qsi= lateral inflow of surface water into the water balance area **(A).** (m3/d)
Qso = lateral outflow of surface water from the water balance area **(A).** (m3/d)
A= the water balance area (m2)
ΔWs = the change in surface water storage (mm)" (De Ridder and Boonstra, 1994 P 607)

2. "the saturated zone, also called the groundwater balance .The water balance can generally be expressed as follows:

$$R - G + 1000\,\frac{Qgi - Q\,go}{\mathbf{A}} - P = \mu\,\frac{\Delta h}{\Delta t} \quad (1\,\mathit{6.5})$$

Where
G= the rate of capillary rise from the saturated zone (mm/d)
R= the rate of percolation to the saturated zone (mm/d)
Qgi = **Qgih** + **Qgiv** = the total rate of groundwater inflow into the shallow unconfined aquifer (m3/d)
Qgo = Qgoh+ **Qgov** = the total rate of groundwater outflow from the shallow unconfined aquifer (m3/d)
Qgih = the rate of horizontal groundwater inflow into the shallow unconfined aquifer (m3/d)
Qgoh = the rate of horizontal groundwater outflow from the shallow unconfined aquifer (m3/d)
Qgiv = the rate of vertical groundwater inflow from the deep confined aquifer into the shallow unconfined aquifer (m3/d)
Qgov = the rate of vertical groundwater outflow from the shallow unconfined aquifer into the deep confined aquifer (m3/d)
µ = the specific yield or effective porosity, as a fraction of the volume of soil (-)
Δh = the rise or fall of the water table during the computation interval (mm)" (De Ridder and Boonstra, 1994 p 609)

"All three balances integrated the overall water balance reads

$$P - Eo - E + 1000\,\frac{Qsi - Qso}{A} + 1000\,\frac{Qsi - Qso}{A} = \frac{\Delta Wu}{\Delta t} + \frac{\Delta Ws}{\Delta t} + \mu\,\frac{\Delta h}{\Delta t} \quad (16.8)$$

Equation 16.8 shows that the vertical flows I, R, and G (all important linking factors between the partial water balances)disappear in the overall water balance. Nevertheless, these linking factors determine to a great extent whether there are drainage problems or not" (De Ridder and Boonstra, 1994 p 611)

Box B: Salt water balance

The balance of soluble salts at the land surface is:

Ssi - **Sso** + **Sp** + **Sc** - **Si** = ∆**Ss**(1 6.9)

Where

Ssi = the quantity of salt brought in by surface water and canal inflow (tons/ ha)

Sso = the quantity of salt removed by surface drainage (tons/ha)

Sp = the quantity of salt brought in by precipitation (tons/ha)

Sc = the quantity of surface salt brought in by capillary rise (tons/ha)

Si = the quantity of salt removed by infiltrating surface water (tons/ha)

∆Ss = the change in the quantity of salt stored at the land surface for the given time interval At (tons/ha). (Ridder and Boonstra., 1994 p 617)

The salt balance of the unsaturated zone, excluding the capillary fringe is:

Si - Sc + Sg- **Sr** = ∆Su (16 .10)

where

Sg = the quantity of salt brought into the unsaturated zone by upward flow from the groundwater zone (ton/ha)

Sr = the quantity of salt removed by downward flow to the groundwater zone (ton/ha)

∆Su = the change in the quantity of salt stored in the unsaturated zone for the given time interval At and for the other symbols as defined for Equation 16.9 (tons/ha). (Ridder and Boonstra., 1994 p 618)

The salt balance of the groundwater zone, including the capillary fringe, is:

Sr - **Sg** + **Sgi** - **Sgo** - **Sq** = ∆Sg(16.11)

Where

Sgi = the quantity of salt brought in by the inflow of groundwater (tons/ha)

Sgo = the quantity of salt removed by the outflow of groundwater (ton/ha)

Sq = the quantity of salt removed by subsurface drainage flow, either by tubewells or subsurface drains (tons/ha)

∆**Sg** = the change in the quantity of salts stored in the groundwater zone for the given time interval At and for the other symbols as defined for Equation 16.10 (tons/ha)

Integrating the three salt balances, neglecting **S,** (because the quantity of salt introduced with precipitation is usually small compared with the other components), the total salt balance is:

Ssi – Sso + Sgi – Sgo – Sq = ∆Ss+ ∆Su + ∆Sg (1 6.1 2)

In all these balances, the change in salt storage refers to salt in solution and salt solids. Storage of highly soluble salts in the surface water and groundwater zone is assumed to be constant (de Ridder and Boonstra, 1994 16 p 619)

Chapter 3: Measures

Introduction

As stated in the previous chapter the biggest problems in case of irrigation and groundwater are water logging and salinity. When these problems have occurred drainage is the primary measure commonly taken. But good water management can also save a lot of trouble. This can be done by preventive measures, conjunctive use and irrigation efficiency.

Drainage

“The percentage of abandoned land has been decreased due to drainage” (Bhutta Wolters and Siddiqui 1996 p1). Drainage gives drier soil and less waterlogging, indirectly drier soil removes salts and other harmful substance. This increases aeration and stabilizes the soil, which increases infiltration and drain discharge and decreases runoff. This results in soil that is better workable an gives a higher and more diverse crop production and the drained water is available for other purposes. Drainage can: reclaim land, increase yield, make cultivation of more valuable crops possible, and makes it possible to cultivate more than one crop per year (Oosterbaan 1994).

A surface drainage system prevents water logging unnecessary standing water and flooding. In semi-arid zones rainwater inundation and flooding is common. This ads a large amount of water to the groundwater. Borrow pits for example, store water and let a lot of infiltration unmonitored. This can be prevented by canalizing the borrow pits to the nearby surface drain (Gupta 1993).

Subsurface drainage can be a series of well systems. Both surface and subsurface systems consist of a field system that takes the water from the field and a main drainage system that takes the water to the outlet (Oosterbaan 1994). Evaluating the number of tube wells needed to keep the water table below 2 meters is very important in vertical drainage (Gupta 1993). Surface drainage systems are usually applied when frequent waterlogging occurs on the soil surface, due to low infiltration or high rainfall. When the main problem is high water tables subsurface drainage should be used. When the land suffers from waterlogging on the surface as well as underground, also both systems should be used. Irrigation efficiency and leaching requirement are the basis for the design discharge of subsurface drainage systems. This is when the efficiency is low and the leaching is abundant due to percolation losses (Oosterbaan 1994).

When the volume of groundwater increases, capillary rise gives water and salts an upward flux. Salinity can be controlled by draining percolation water and by keeping the water table at minimum depth, which depends on soil type (Bos and Wolters 1994). To control salinity in dry soils the required water depth is related to the upward capillary flow from the aquifer. When land is irrigated and drained the saline water flows down away from the crop. When there is saline groundwater present it is better to use shallow pipes closely spaced than deep pipes widely spaced (Oosterbaan1994).

For salinity control drainage can be transported in the wet season, when the river has a high discharge. In the dry season with less drainage flow evacuation of salt drainage water contaminates the river to much. The drainage water can better be reused for irrigation after it is mixed with fresh water to an acceptable quality level (Oosterbaan 1994). “For surface irrigation and sprinkling, and for a large range of soils provided with sufficient drainage, we can estimate the long-term minimum percolation losses to be around one quarter of the diverted irrigation water. The required design drain discharge for salinity control will be in the range of 1 - 2 mm/d” (Bos and Wolters 1994 p 520).

It is not recommendable to drain unsupervised, because this can result in a level of groundwater that is to low. To control the level of salt in the soil enough water is needed. It is necessary to apply more water than needed by the plants one or two times a year (pers. com. Theo Boers). Saline water should only be pumped by public tube wells or, if it is difficult to treat or dispose, be drained by tile drainage because this gives less effluent. When fresh water aquifers link to the water table, tube wells can provide additional irrigation resources (Gupta 1993).

Water management

To support drainage there are several preventive measures against water logging: Reduce seepage by lining of water distribution systems. Another is to plant plants where waterlogging is likely to build up amongst others along the banks of the canals, distributaries and watercourses and along a seepage line from where inflow enters to the area. Next to that selection of crops with low water requirements helps. When there is less water needed there will be less percolation losses (Gupta 1993). Also good irrigation management through the efficient use of the irrigation water once it reaches the field is an example of preventive measures that can be used in any irrigation project. Efficient land levelling and shaping, efficient design and layout of the irrigation methods works are examples. Finally scientific scheduling of irrigation under both adequate and deficit water supply and crop planning for optimum yield per unit of water applied with minimum loss of soil and plant nutrients gives efficient water use (Gupta 1993).

When land is already flooded it can be reclaimed with the right management. For land reclamation projects both flood protection and drainage systems are used. When an area easily inundates only drainage is a waste of money because only flooded protection can stop the water logging (Oosterbaan 1994). Drainage only stabilizes the soil to cultivate reclaimed saline soil measures should be executed (Gupta 1993). “Rao et al. (1990) have shown that the time-averaged depth of the water table during the critical drainage season (i.e. the monsoon season) need not be much more than 0.8 m below the soil surface to allow the adequate reclamation of saline soils” (Oosterbaan 1994p 653). Reclamation can only be done by extensive drainage and the availability of fresh water for flushing. Flushing without drainage and flushing with poor quality water will cause the land to go out of production even faster. An other option for these lands is the growing of salt tolerant crops like eucalyptus or phreophytes (pers. com Theo Boers). Reclaimed soils can increase agricultural production but the land should be carefully managed: Leaching of salts, levelling and bunding and a good crop rotation that doesn’t leave the soil bare long to prevent salt build up by high evaporation especially in summer months (Gupta 1993).

The quality of the pumped water should be monitored. In wet periods shallow groundwater can be pumped up, but when the sweet water is finished salt water will come up. How to pump up water sustainably is a management problem. The pumping up of water used to be about quantity, but a more recent issue is water quality. (pers. Com. Theo Boers). The management of the salt and the water balance of irrigated land include minimizing the amount of water required to remove salt from the root zone and minimizing the land required to store the salt temporarily (Kijne 2003). “To prevent salinization and stabilise water table in 5 to 6 meters depth below ground level, an understanding of the behaviour of groundwater region is essential” (Sehgal and Vyas 1994 p130). In saline groundwater areas investment in drainage and control of private tube wells is required (O’Mara & Duloy 1988). Additional to salts there is a lot of effluent discharge, for example hue of tanneries in Lahore Pakistan. The water turned red and eventually it showed up in the drinking water of Lahore. There is no good management system to monitor the laws of water quality (pers. com. Theo Boers). “In several cities in India Pakistan and Mexico peri urban farmers have developed practices to use urban wastewater and groundwater conjunctively for irrigation” (Buechler and Devi 2003 according to World Bank 2005 p 157).

Both water taken from the river and water taken from the ground in a catchment causes water reduction in the catchment. Groundwater used for industries or public supply gives little reduction in stream flow, because it is not consumed and can be returned to the catchment it came from. However to prevent a reduction in quality it is vital that the water is treated. Problems arise when non consumed water is returned to another catchment further downstream, or when groundwater is used for irrigation most of it is lost by evapotranspiration. Because of this there should be a limit to the water taken from the aquifer of a specific area. Also, many countries already have systems to control abstraction (Price 1996).

Irrigation efficiency

“Increasing demand and decreasing water quality has put enormous pressure on the agriculture sector to use its available water resources more efficiently. These pressures are a result of the increasing demand for food and inter-sectoral competition for water, particularly from the municipal and industrial sector. Therefore, in future, irrigation’s contribution to food security will largely depend on the use of low-quality water in agriculture in addition to renewing efforts to achieve water conservation” (Qureshi et al. 2004 p 1).

Many irrigation systems increase the efficiency of water used, as a consequence a larger area can be irrigated with the same amount of water and the water can also be kept in storage. Furthermore there will be less flooding and there will be less need for controlling waterlogging and salinity. Supplying smaller amounts of water more uniformly over the flied increases application efficiency. But Irrigation efficiency can counteract harmful toxic elements in drainage water by means of less water outflow, for example in the San Joaquin valley (Bos and Wolters 1994). “Another expectedly-beneficial effect of increasing irrigation efficiency is the availability of more water. But, if the ‘extra’ water were then to be used to expand the cultivated land in an area like the San Joaquin Valley, the effect might even be counter-productive, because sources of toxic solubles that are at present immobile might be mobilized and enter the environment” (Bos and Wolters 1994 p 528).

Improving irrigation efficiency is important with saline groundwater. When more water than the crop requirement is applied to the field it will reduce land salanization but the seeping of water into saline aquifers is a waste. Matching the given water to requirements and losses will improve productivity and sustainability (IMWI 2005). On the other hand when groundwater levels fall, aquifers recharge will be less and soil salinity can increase without leaching. When the salt balance is in equilibrium less water leads to salinization and leaching is in contradiction with less water supply (Bos and Wolters 1994).

It can be stated that conjunctive use is a positive thing but if there is no water it cannot be used. When an area has only a small amount of water but a high population density there is shortness of water. Water cannot be made, people need water to drink and for industry. The solution is to produce crops with less water, this can be done for example, by growing crops in closed greenhouses and recycle the evapotranspiration (pers. com. Wouter Wolters). An example of 'agro-forestry' was presented by Ochs et al. (1995) in this example drainage water is re-used for increasingly salt-resistant crops and trees, the drainage water becomes more concentrated in the process. Ultimately that water is disposed of into a solar evaporator, where the salt is converted into a crystalline form (Bhutta and Wolters 1997).

In a lot of Arab countries there is a shortage of water, for example in Saudi-Arabia famers pump up groundwater from the desert so this retreats deeper in the soil. A Dutch company Dacom introduced soil irrigation sensors in dozens of countries. The soil meter sends the data to a databank, software translates the date to concrete advises. Before Dacom there was no sensor that gave advice, with only data farmers do not know how to treat their fields. For example in Tunis farmers irrigated there grapes every day, with the sensor they know this is not necessary and water use decreased with 50 per cent. When it is easy to irrigate more water is used, roots gets spoiled and stay short. In this scenario a short period of water shortage has a positive effect: the roots go deeper in the soil and are more resilient (Hulshof 2011).

Groundwater VS Surface water

To farmers groundwater is an addition to surface water and they will maintain their surface irrigation rights. They hold on to surface water because of the higher quality. People, who provide their land for the digging of a tube well, try to build political strength with it (Gautam 2006). Because groundwater is pumped up close to the irrigation site and has almost no losses during transport, groundwater irrigation is more productive than canal irrigation. When groundwater is used framers can control the amount and the moment of irrigation. Yields per cubic meter groundwater in India for example is around 2 times higher than irrigation with surface water (Kijne 2003). Groundwater can be used for both drainage and irrigation so that it is an addition to surface water supplies and prevents water logging. Marginal water can be used by the crops non usable water can be pump by tube wells to keep the water table low (Gupta 1993).

At the tail end of a system a lot of water from tube wells is used for irrigation because there is little surface water. Operation of tube wells fluctuates because of the cost of the source of power which is directly linked with the cost of the tube wells. It explains most of the differences in groundwater use, canal supply and groundwater quality are of little influence (Malik and Strosser 1993). Pumping stations and boreholes cost less than a river intake or a reservoir with the same input (Price 1996). “Farmers with private shallow tube wells refuse to pay for the water from collective deep tube wells”

(Gautam 2006 p127). “Huge investment on pipe drainage projects could only benefit if proper operation and maintenance is done” (Bhutta, Wolters and Siddiqui 1995 p8).

“Transport of water from one basin to another increases the input which must be taken care of by natural or artificial drainage for not letting the water table rise. Therefore, any approach to irrigation development should have an integrated use of the surface and groundwater” (Gupta 1993 p 132).

Conclusion

Surface drainage prevents flooding and inundation. Subsurface drainage can be done by tube wells. Fresh water can be reused, salt water should be evacuated. Salt water should only be evacuated through the river when there is enough water in the river to keep the quality. Amongst others drainage can: increase crop yield and make the production of higher value crops and more than one crop per year possible. It is not recommended to drain unsupervised because the groundwater can become to low.

To prevent waterlogging some plants can be planted along the cannel lines where water builds up so it can be evaporated and if a crop is chosen that does not need a lot of water little water will be spilled.

When the land is already flooded and reclamation is needed it is recommended to use both flood protection drainage and saline soil measures. After reclamation the land should be managed extra careful to prevent salinization.

Also the water quality should be managed carefully. Groundwater should be monitored to prevent use of saline water that is pumped up. Also a lot of farmers use drainage effluent of cities with toxins. This should be managed careful. A new way of monitoring is introduced by completing data with advice.

When land is saline framers can divert to alternative measure like salt resistant crops, green houses that recycle evaporation.

Irrigation efficiency creates a lot of benefits: when less water is needed more land can be irrigated, flooding will be less and when the soil holds toxics less of them occur in the drainage effluent. The only disadvantage is salanization, because less groundwater can make the soil more saline and when the soil is already saline irrigation and leaching cross out each other.

Chapter 4: Conjunctive management

Introduction

The use of groundwater and canal water in conjunction is widely used. In many countries pumps are introduced to promote that farmers supplement surface water with groundwater in times of shortage. When there is groundwater in abundance this should disappear, and why not by pumping it up and using it, considering the quality of the water of course. Because of reluctance to drain and increasing demand of water for better quality crops, in many irrigation systems one or both of the above mentioned shortages and abundance is present. This chapter is about the origin and obstacles of conjunctive use, the improvement by conjunctive management and the possibilities of a groundwater basin.

Conjunctive use

"In many surface irrigation systems a system of conjunctive use has evolved. Supplementary irrigation using groundwater resources has become common practice" (Chevalking et al. 2008 p98). When irrigation with only canal water is insufficient to meet requirement the farmers' only choice is to supplement irrigation with groundwater (Malik and Strosser 1993). An irrigation system can be insufficiently maintained and is not able to sustain the design flow in all parts of the canal. The system can be overstretched, to much land for the water source, so there is not enough water in the dry season. Or it is unable to respond to crop needs in the water delivery schedule and allows illegal oversized off takes due to lack of administration. In the problems motioned above the irrigation system does not suffice and conjunctive use of groundwater and surface water usually appears (Foster et al. 2010).

"Management of surface irrigation impacts on groundwater quality and availability. The two resources are inextricably linked and cannot be sustainably managed separately" (IMWI 2005 p 2). Often water resources are double counted due to the assumption of independent surface water and groundwater. For example when dams where build to store water from a river with the result that aquifer below the dam was rapidly depleted because it was no longer recharged. An other example is when canals are lined to save water, elsewhere there is water shortage (FAO 2010). To have the most benefit of conjunctive use the development should be properly managed. This consist of taking into account the balance of groundwater and the recharge and also prevent impact of pumping and surface water off take in periods of low river flow. It is very important to keep in mind the hydraulic connection of alluvial aquifers and overlying surface water (Foster et al. 2010).

The pumping of groundwater in conjunctive water use can prevent salinization, when drainage is not enough to keep the water table at critical depth, and can reduce water logging, when recharge by infiltration of excess rainwater increases (Lingen 1988). Conjunctive use uses the aquifers large natural groundwater storage to be a buffer for flow variability and drought risk of al lot of surface water courses, and deals with problems like water logging on alluvial plains and groundwater salinization. Effective conjunctive use of groundwater and surface water has the positive outcomes of: More water supply and yield, better timing of water delivery, it increases water security and precision of water delivery so cropped area can be expanded and higher value crops that need precision irrigation can be grown. It also reduces waterlogging and salinization and increases a buffer in the subsoil that enables: Less salinity problems in shallow aquifers, less malaria and water related diseases and a better capacity to reduce flood run-off by buffering rainfall (Foster et al. 2010).The pumping up of water percolated from the surface irrigation by shallow pumps is in fact recycling and can be the sustainable answer to water shortage. Forcing farmers to fluctuate between periods of using surface water from canal and periods of pumping up the percolated water by shallow pumping can be a way to make conjunctive water use more sustainable (pers. com. Frank van Steenbergen). Prolonged drought often results in a rise (rather than a decline) in agricultural productivity since the deterioration of surface-water delivery in canal commands triggers more groundwater development and conjunctive use (Foster et al. 2010).

When conjunctive use is not monitored or regulated appropriately this result in a number of problems amongst others: over use of groundwater and the use of bad quality groundwater or saline water (pers. com. Frank van Steenbergen). The fact that farmers operate the tube wells themselves is both an advantage and a disadvantage. Users depend on each other for an equal share. It isn't cost effective to invest in both wells and an irrigation system. If you invest in both, the costs double. As long as the government pays for the irrigation system, farmers are prepared to pay for the pumps. It may be an idea to make the surface water system smaller, transport water through the year and store excess water (pers. com. Henk Ritzema).

Conjunctive management

"Conjunctive water use refers to simultaneous use of surface water and groundwater to meet crop demand individually and uncontrolled. Conjunctive management refers to efforts planned to optimize productivity equity and environmental sustainability by simultaneously managing surface and groundwater resources" (World Bank, 2005, p 156). When the groundwater and the surface water is simultaneously controlled by system administrators, this is conjunctive management. Improved main system management by conjunctive management is important, because surface irrigation influence groundwater. Introducing planned conjunctive management through coordinated strategies at various political levels gives a great opportunity to enhance gains (World Bank 2005).

Institutions are important; when the amount of water applied needs to be changed everyone will protest. Water rights are politics; people will not admit they get too much water, even though too much water has negative effects. This is both because lack of knowledge and feelings of power. In the lower parts of Pakistan there is too much water but it isn't there at the right time. When people in an area have stated over a long period that there is a shortness of water, they can't suddenly take this back (pers. com. Frank van Steenbergen). "By considering groundwater availability and quality when allocating surface water, water managers could improve the situation of millions of poor farmers with inadequate access to both surface water and groundwater and overall productivity in irrigated systems" (IWMI 2005 p1). "For many systems, allocating more canal water to areas with saline groundwater may be a big part of the answer to improving average yields and overall productivity. Improving equity within schemes will require enforceable water rights and strong political commitment—particularly in this situation where canal water is being taken away from an advantaged group and reallocated to the disadvantaged" (IMWI 2005 p5). Irrigation production will improve when good quality canal water is allocated more equally, with a preference to areas with saline groundwater. Domestic supply and health will also improve (IMWI 2005).

"In irrigated areas, there is an intimate connection between groundwater and surface water, yet these resources are often managed completely separately" (IMWI 2005 p2).The fragmentation of the governmental institutions that manage water is a major obstacle to conjunctive management. Salinity control and land reclamation can be done perfectly by tubewells. The only problem is lack of coordination. Spatially coordination of groundwater and surface water use is critical in a saline environment but in most development countries poor monitoring infrastructures preclude this. Gains can be enhanced by conjunctive management on basin level (World Bank 2005). Separate surface and groundwater management has contributed to salinization of poor groundwater quality areas and made farmers at tail end suffer from low productivity (IWMI 2005).

"There are now many calls to move from conjunctive use to conjunctive management so as to maximise water productivity" (Chevalking et al. 2008 p98). "Secondary salinization could be avoided but only with appropriate conjunctive management of the different sources of irrigation water" (Malik and Strosser 1993 p 28). Tube well irrigation raises the productivity, extends the area that can be served and reduces yield loss due to unreliable water delivery. Tube well irrigation provides vertical drainage reduce waterlogging and investment in drainage. It is costly but it offers control (World Bank 2005). In regions with primary salinity, such as the Indus basin in Pakistan and India the objective of conjunctive management is to maintain both water and salt balance. It is a risky business and requires a sound conceptual model of the fate of the salt mobilized; if it is not done it can cause more problems than it solves (World Bank 2005)

Quality

Groundwater salinity has many different origins. It can appear because excessive canal seepage or groundwater application starts waterlogging and with that salinity. It can occur when irrigated saline soil leach salts or by intrusion of saline water from the sea or saline basin because of excessive abstraction of fresh groundwater. Finally there are areas where all groundwater is saline except where canal leaching forms a fresh water lens; this requires careful management to avoid saline up coning or excessive infiltration and water table rise feeding salanization (Foster et al.2010). "Often decennia are needed before a column of brackish or salt groundwater has disappeared because the groundwater table has to be rebuilt by percolation losses” (pers. com. Jacob Vos).

Groundwater salinity is related to recharge amount, recharge water type (ground- surface- or precipitation- water), lateral groundwater flow and mobilised salts from the unsaturated zone. When irrigation starts, salt from the unsaturated zone move down into the groundwater. To get rid of not useful saline groundwater it can be stored and deposited in the river during high tide so it is mixed enough for downstream users and will arrive harmlessly at the sea. The concentration of salts accelerates in the near surface zone when poor quality groundwater is used for irrigation (Phetheram et al. 2008). Canals should be lined in humid areas where the groundwater is fresh but shallow here seepage can contribute to water logging and secondary salanization. In arid areas where the groundwater is saline and deeper lying water is fresh, lining of canals is a priority to prevent water loss, water logging, and salanization (Foster et al.2010). In areas which are no longer receiving as much irrigation water, monitoring groundwater is important. Irrigation supply and domestic wells are affected by the impact that decreased irrigation supplies have on the availability and quality of groundwater in these areas. In arid and semi-arid areas poor people of rural communities use irrigation water for domestic, industrial and fishing purposes. When this is not taken into account the water quality deteriorates. Irrigation water quality standards should consider health of domestic users as well as crops (IMWI 2005).

“In marginal groundwater areas, a slight decrease in irrigation amounts can have serious consequences on the root zone salinity and ultimately on the crop yields. Considering these fragile equilibriums between leaching, root water uptake and groundwater interactions in semi-arid climates and saline soils, the farmers of marginal groundwater areas need to precisely know irrigation and leaching requirements in order to halt environmental degradation and foster crop production” (Qureshi et al. 2004 p17).

Within an area quantity and quality of groundwater varies, so the quantity, depth and quality should be monitored and taken into account in irrigation water allocation. When groundwater is fresh, sustainable pumping should be promoted. When it is saline irrigation efficiency should prevent further salinization (IMWI 2005). On-demand fresh groundwater can make water availability and yield more predictable and secure, poor quality groundwater ads salt and makes salinity worse. Around the world and especially in arid environments, a large part of irrigation land is salinized because of poor quality groundwater and a lot is under threat, only because framers do not have the knowledge how to handle different qualities of groundwater for irrigation (Qureshi et al. 2004). Increasing groundwater salinity that is not noticed and controlled will make agricultural productivity decrease and be a threat to drinkwater security. To reverse the trend of groundwater salinity total abstraction should be controlled so natural discharge can occur. Furthermore irrigated agriculture on saline desert land should be prevented (Foster et al. 2010).

Private tube wells are in a situation of good canal water supply used to stabilize fluctuations. When canal water is available, the quality of the total water can be kept in an acceptable range by mixing both sources. This is especially important when groundwater is marginal so soil salinization can be prevented (Malik and Strosser 1993). At the present level of groundwater salinity in for example India and Pakistan, use of only groundwater would reduce yields, to improve the productivity conjunctive use of groundwater and irrigation water should be promoted (IMWI 2005). Conjunctive use is more common than groundwater use because of the improvement of groundwater quality through dilution, but farmers are not fully aware of the mixing ratios. Their strategies are unsuitable and increase secondary salinization. They do not have the sufficient knowledge of fitting use of different qualities and do not use their land and resource optimally (Qureshi et al. 2004). When farmers are allowed to pump unlimited water quantities in response to a rising water table, many will still be limited because they already use the optimum groundwater- surface water mix possible with the quality of the groundwater (Phetheram et al. 2008).

Poor quality groundwater is usually applied in conjunction with canal water. an mixing example in Punjab Pakistan gives the following results: 1:1 mixing, the total amount of water applied is half groundwater and half canal water, with fresh groundwater leaches the salt to below 1.0m, reducing upward movement of salts during dry and hot years. 1:1 mixing with marginal groundwater only pushes the salt to 90 cm below the soil surface, occasional leaching is necessary. When the additional leaching with saline water, especially with shallow groundwater, it should be done carefully

(Qureshi et.al. 2004). "Irrigations with saline groundwater directly or in conjunction with the canal water by any ratio will be a complete disaster. The root zone salinity will start shooting up; the whole soil profile will be highly salinized making any crop production almost impossible" (Qureshi et al. 2004 p18). When fresh groundwater is used alone, salanization will immediately enhance in years with below average precipitation (Qureshi et.al. 2004).

Groundwater storage

Already in 1986 it was stated that "optimal water resource policy should include the use of groundwater storage" (Correa 1986 p 483). To overcome the mismatch in time and space between water demand and availability, optimal allocation of available water supply is needed. In this light it is important to optimise conjunctive management because both ground and surface water are possible supply sources. For long term management of groundwater storage it is essential to know the sequence of dry and wet periods for some time to balance groundwater withdrawal in dry periods can increase recharge in wet periods (Correa 1986). In India the monsoon recharge local aquifers. This water is used for a second crop during the dry season. The drawdown of the aquifer maximizes the potential of water storage in subsequent monsoon period (Chevalking et al. 2008).

Reducing waterlogging by drainage creates a buffer capacity and a possibility of water storage during peak recharge so discharge is steadier and smaller than the recharge. Tube wells drain 5 to 10 m deep and create a large buffer capacity. The buffer capacity of drainage pipes and ditches is medium (Oosterbaan 1994). In dry weather conjunctive use schemes use stored groundwater to augment the water supplies. Groundwater that is used for irrigation comes from excess irrigation and canal seepage. This is reused by pumping up the shallow aquifer below (Chevalking et al. 2008). Peak runoff usually occurs in the season of the smallest water demand (FAO 2010). " Introduction of surface irrigation will definitely lead to rise in water table varying from 80% in the case of only surface irrigation to almost nil in the case of a conjunctive use scenario, assuming high irrigation efficiency. To control the rise of water table, utilisation of accumulated groundwater storage should be planned to meet the water shortage during the lean period drought" (Sehgal and Vyas 1994 p 142).

Supply reliability can be improved by efficient operation policies that take advantage of the differences between subsurface and surface storage. When subsurface storage is seen as a backup storage to surface storage, the different capabilities of both are not recognised. Most large water supply systems depend on surface supply and don't develop the potential to use the subsurface for storage; groundwater is only used for backup during shortages. Both types of water reservoirs differ in storage capacity, recharge and depletion rates, and operating costs. Surface storage meets the short term demand of next season or year and is effective whit rapid fluctuations in level, and subsurface storage meets long term demands for drought of several years and is effective where fluctuations in level are more gradual. They also both have drawbacks; in a surface reservoir water can be lost by spills, subsurface storage can be limited and partly inaccessible. Especially when a system fully uses all water resources pumping and recharge should be actively use by control policies to allocate the stored water and meet the demands (Philbrick and Kitanidis 1998).

Surface reservoirs have the drawbacks of evaporation, los of storage capacity by sedimentation, human health hazard, flooding of good land and high costs. In semi-arid areas there are less vegetation cover and higher erosion hazards (FAO 2010). Natural aquifers should be used as reservoirs because surface reservoirs occupy too much land and have negative effects on the environment (Chatdarong 2001). Farmers are not willing to irrigate at night and night storage is expensive. Season storage is also expensive; a reservoir behind a dam suffers from a lot of evaporation (pers. com. Henk Ritzema). Storage for large water demand as big irrigation schemes is usually done by surface storage. Aquifers are not big enough, don't absorb quick enough, and have a discharge that is too small. Surface storage gives political influence because of the high investments involved (FAO 2010).

For groundwater storage the following key components should be carefully studied: Underground storage capability, potential discharge and natural, induced natural and potential artificial recharge of the aquifers. Recharge suitability is estimated by high permeability of the surface material and unsaturated zone, also by percolation, the absence of less impermeable clay layers and a high transmissifity in the aquifer but not so high that the water can't be recover. Also the water level must be lower than 5 or 10 m and the soil should have adequate transmissivity for recharge and return. Storage capacity, recharge suitability and the easiness of returning the water when it is needed are important to determine for a underground reservoir that will store water for later use. Between the reservoir and the groundwater table there should be some distance so the water can't vanish (FAO 2010).

Before the first irrigation of the season is initiated the unsaturated zone should have a large water deficit. It can for example be done by increasing groundwater extraction, improving irrigation efficiency due to reducing furrow length and improve irrigation scheduling to meet the crop demands. This buffer against large recharge events serves to minimise diffuse deep drainage and groundwater growth. The key factor of groundwater growth next to diffuse drainage is canal leakage. On the other hand water table rise is inevitable because leaching is necessary to prevent salt accumulation in the root zone and the water table should be drained to 2m or below (Phetheram et al 2008). Because of the pumping it will take longer for streams to flow again because it takes longer to come to the water table maximum. This way surplus water in the winter will not be wasted and will no longer be the source of trouble (Price 1996).

An important component in the groundwater recharge of unconfined water layers is irrigation returns: both seepage and excess application to the field. Attempts to improve irrigation distribution and application efficiency will have impact on groundwater resources (Foster et al 2010).
When intensive use results in local depression of the groundwater level close to a river and water flows in from the river this is induced natural recharge. In semi-arid areas when depression of an aquifer is close to a temporary river this can be filled during floods (FAO 2010).There are upper limits to aquifer use, in relation to how much water can be recharge (Foster et al 2010). The storage capacity can be of further use by artificial recharge: During Surplus River flow suitable water can be pumped in the aquifer and pumped out when water is scares (Price 1996). Artificial recharge can be done by surface spreading, increasing the surface by releasing water from the source to a basin pond or canal. This is effective but only suitable for unconfined aquifers. Another possibility when the aquifer is confined is recharge wells, then the water is injected to the aquifer by a conduit access like a well or shaft. A drawback of well recharge is clogging due to suspended and organic matter gas or air bubbles chemical precipitates or clay swelling. Using well for both injection and pumping is the most economical way (FAO 2010).

Conclusion

In many irrigation systems farmers turn to groundwater irrigation when surface water irrigation does not suffice. Groundwater and surface water irrigation are connected and to manage water, both should be taken into account. Conjunctive use can lead to better security and timing of water more supply and yield and reduction in water logging and salinity. To experience the full benefit conjunctive use should be properly managed.

Conjunctive management refers to efforts planned to optimize productivity equity and environmental sustainability. Institutions are important to for reallocation of water. The fact that surface water and groundwater is managed separately gives problems, this should by spatially coordinated. There is motivation to change toward conjunctive management.

Groundwater salinization has different origins. Irrigation moves salts from the unsaturated soil into the groundwater. Saline groundwater can be stored or drained into the river when there is enough water in the river to dilute the drainage effluent. Groundwater quality and quantity differs per area and should be monitored and irrigation should be allocated accordingly so farmers are encouraged to pump up freshwater and practice irrigation efficiency when saline groundwater is present. A lot of land is out of order because farmers don't know how to manage different groundwater qualities. To reverse the trend of groundwater salinity, total abstraction should be controlled, so natural discharge can occur. To use lower groundwater qualities safely, groundwater can be mixed with canal water.

It is important to know the sequence of wet and dry spells to balance replenishment and withdrawal.
Drainage and the pumping up of groundwater create a buffer in the soil that can be recharged and use for storage. Surface and subsurface storage can be used. Both have different advantages and disadvantages. Surface storage can be used the following season and is efficient with fluctuating demands. But water can be lost by spills or evaporation and the structure occupies a lot of land.
Groundwater storage can be kept for several dry years but the discharge can be too small and the capacity can be limited, the aquifer can be to small or the absorption to slow. For groundwater storage

the storage capability and recharge capability should be known. High Permeability and transmissivety and percolation makes soil suitable for recharge and the water level should be lower then 5 m. Before irrigation there should be a large water deficit in the soil so there is a buffer for much recharge to minimise defuse deep drainage and groundwater growth. Recharge can be done induced natural, when a river recharges a groundwater depression made by intensive use or artificial when water is let in to a pond to increase the percolation surface or by simply pumping it in the aquifer.

Chapter 5: Two case studies of conjunctive water use and management

In the last chapter, both the theory behind conjunctive management and possibilities to improve existing approaches are brought up. To check if the proposed improvements are viable, two locations where water is used conjunctively for decades are described, to see if the improvements are implementable. The first area is the San Joaquin Valley in the United States of America, this area is relatively wealthy, has access to technology and government institutions are relatively well organised. The second area is the Korti Left Bank in Pakistan, this area is less wealthy, has less technological knowledge and possibilities and is less governmentally organised. Both areas have semi-arid climates and are adjacent to the sea.

San Joaquin valley, California

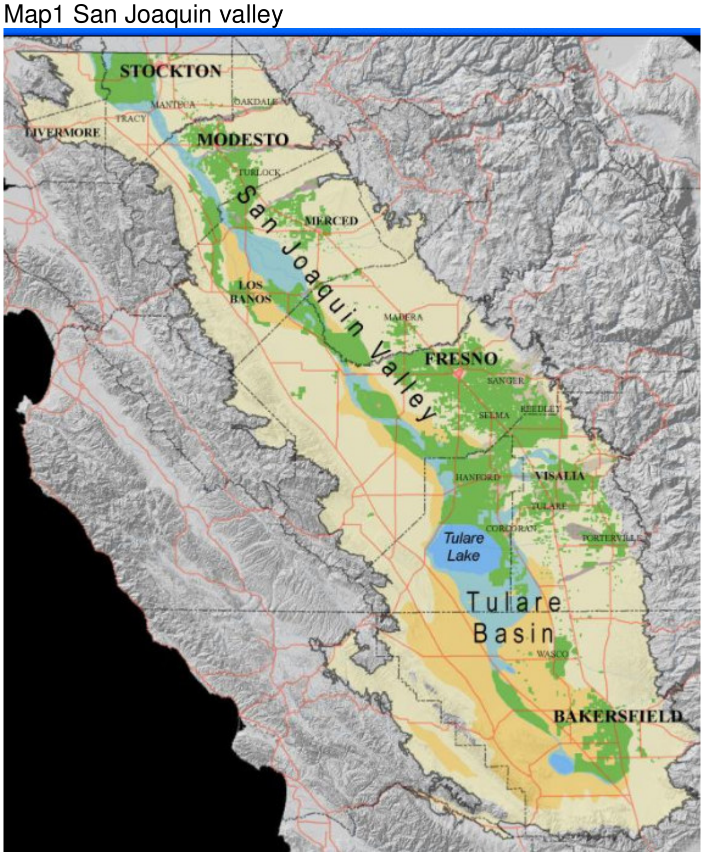
Characteristics

The San Joaquin valley is the largest and most productive agricultural area in California; it depends highly on surface water irrigation for a year round growing season in a semi-arid climate. However the salt build-up in the soils and groundwater is threatening its productivity and sustainability (Domagalski et al. 2009, Chatarong 2001, Schoups et al. 2005, Ruud 2004). The San Joaquin Valley (SJV) occupies the south of Central Valley (Schoups et al. 2005, Chatarong 2001). From the Tehachapi mountains in the south to the san Joaquin- Sacramento river delta in the north it covers 402 km and from the Sierra Nevada mountains in the east to the coast in the west 128.7 km. The valley floor gradually slopes to the northwest. “At about mid-point there is a low broad and indistinctive divide that separated the valley into two hydraulic basins, in the north the San Joaquin basin that drains to the ocean via the San Joaquin River and the San Francisco bay, in the south the Tulare basin with no output to the ocean” (Letey et al. 2002p225). See map 1.

The SJV has a semi-arid Mediterranean type climate of dry hot summers and foggy rainy winters (Schoups et al 2005). The majority of rainfall occurs during November through March and ranges from 100 mm in the southern end to about 450mm in the north (Domagalski et al. 2009 Chatarong 2001). Agriculture in the SJV depends on irrigation because there is no rainfall in the growing season from March to October, the main source is surface water from the Sacramento River, and in dry years groundwater is used as a supplement (Schoups et al. 2005, Domagalski et al. 2009). Groundwater represents a long term storage reservoir with inputs and outputs. In a normal year, the aquifers are recharged with excess irrigation deliveries and rainwater these exceeds groundwater withdrawals. In wet years groundwater pumping accounted for only 30%-35% of the total applied water, in critically dry years 80%. Severe droughts lasting several years can cause groundwater basins in the SJV to become severely over drafted in a matter of a few years (Ruud et al. 2004, Miller et al. 2009).

The soil in the east of the valley comes from granitic rock and is coarse and sandy. In the west the soil originates from the coast and has a finer texture and higher clay content. This soil also has a higher level of salt and trace elements as selenium, chromium, arsenic, boron, lead, mercury, cadmium, copper, and zinc (Domagalsky et al 2010, Letey et al. 2002, Price 1996, Purkey et al 2004). Lithification of some of early marine deposits under the overburden of fluvial deposits produced the low permeability Corcoran Clay lying between 60 and 150m below the present valley floor (Purkey et al. 2004). The Corcoran clay layer divides the groundwater in a primary semi-confined aquifer to less than 2m below ground surface. Below the Corcoran Clay layer lays a confined aquifer contained in older sediments. Irrigation water is primarily pumped from the confined aquifer (Schoups et al. 2005, Purkey et al. 2004).

Map1 San Joaquin valley



Source: http://esrp.csustan.edu/gis/historical

History

Initially, from the 1920s on, irrigation water was pumped up from the aquifer without any thought of the consequence. It was tough to be inexhaustible but this water only slowly recharged and the groundwater level severely declined. This brought up environmental issues amongst others land decrease and salt water intrusion from the sea. In response to this problem later massive surface irrigation projects where introduced, that caused the water table to rise toward the soil surface. Less irrigation water was applied to prevent water logging. This in turn reduced salt leaching and increased soil salinity. Droughts in 1977 and 1991-1992 increased soil salinity because more saline groundwater substituted surface water (Chatarong 2001, Schoups et al. 2005, Purkey et al. 2004, Price 1996).

The initial irrigation project did not include drainage, agricultural and wetlands where historically drained by the San Joaquin river (Chatarong 2001, Schoups et al. 2005, Purkey et al. 2004, Price 1996). Eventually a sub-surface drainage system was installed. During the 1970s and the 1980s, drainage water was used to replenish wetlands and other wildlife habitats. In the mid-70s drainage construction was interrupted when it was discovered that toxic levels of selenium and other trace elements moved up the food chain and caused deformities and deaths among aquatic birds. These potentially toxic particles come from salts that occur naturally in the regions' soils which were derived from marine sediments. There is no treatment to remove this contaminants from drain water (Wallender et al. 2002, Letey et al. 2002, Purkey et al. 2004, Shouse et.al. 2006).

Problem statement

The sustainability of irrigated agriculture is at risk in the SJV. This is caused by a shortness of drainage and fresh water supply combined with high water tables and salinization of soil and groundwater, which is al related to each other (Schoups et al. 2005). Next to importation of salt, irrigation also dissolves native salts. Restricting drainage salinizes the soil profile and increases root zone concentrations of phytotoxic trace elements such as Boron (B). Accumulation of b can be more limiting to crop growth than salt concentrations. High salt concentrations and high B concentration are highly correlated in arid and semi-arid areas. B is a micronutrient that pants need but in high concentrations it is toxic. The tolerances vary within species and among different breeding types, but the optimum range is very narrow. In irrigated semi arid regions, excess B often occurs in association with moderate to high levels of soil salinity. The effect of B can be mistaken for salt accumulation associated problems (Shouse et al. 2006).

The deeper aquifer below the Corcoran clay accumulates salts, making deeper groundwater of a lower quality (Schoups et al. 2005). “The salinity problem on the west side of the San Joaquin Valley is partly attributed to the continuous presence of a low permeability Corcoran clay ranging in depth from 30m near the San Joaquin River in the east to en depth of 250 m in the west” (Schoups et al 2005 p 15352). In the west the shallow water tables above the Corcoran clay layer. “To prevent the water table from rising to the crop root zone and decreasing agricultural productivity, many fields have had tile-drains installed to collect the water once it has passed through the root zone” (Ohlendorf et al. 1986; Ohlendorf 1989; Skorupa 1998 according Wallender et al. 2002 p312). Upward flows of saline groundwater in areas with drainage problems make the root zone saline. In areas with shallow saline groundwater the water table is generally less than 1.5 to 3(Hanson& Ayars 2002).

Lack of acceptable drainage water disposal methods makes traditional subsurface drainage methods impossible on the west side of the valley. Most of the valley has no drainage disposal and presently no acceptable drainage water disposal method exists for most of the San Joaquin Valley. Only the northern water districts with existing outlets are allowed disposal into the San Joaquin River (Hanson and Ayars 2002). “Monthly and annual selenium loads discharged into the drains limit the total discharge. Many in-valley disposal options (evaporation ponds, deep well injection, desalinisation, drain water reuse, water treatment to remove selenium) are either technically environmentally and/or economically unsatisfactory” (Hanson and Ayars 2002 p 261).

Management

To deal with the drainage issue, In 1990 state and federal agencies combined published a management plan for irrigated agriculture, the San Joaquin Drainage Valley Program (SJVDP), with possible steps: 1) Source control through better irrigation efficiency; 2) Drainage reuse on salt tolerant plants and trees; 3) Evaporation systems; 4) Land retirement ; 5) Groundwater management, coordinated pumping of private irrigation wells and 6) Discharge to the San Joaquin River (Letey et al. 2002, Purkey et al.2004, Schoups et al. 2005). The San Joaquin Valley drainage implementation program management group oversees progress in resolving the salinity drainage problems in the western San Joaquin Valley. Four federal and four state agencies “signed a memorandum of understanding whereby they agreed to use the SJVDP 1990 plans as a guide to correct the valleys subsurface drainage problem” (Letey et al. 2002 p 256).

“One strategy for source control is to restrict outflow in field drains such that the height of the water table is maintained at a shallow depth that allows certain crops to utilize groundwater to satisfy a portion of their water requirements. The timing and amounts of surface water impact the extent to which crops will utilize shallow groundwater “(Shouse et al. 2006 p337).

Subsurface drainage water source reduction in shallow, saline groundwater areas can according to the San Joaquin Valley Drainage Program (1990) be done by: At first improved water management, improvement of irrigation scheduling and practices and/or adoption of new irrigation methods. Also water management can be improved by improvement of management of irrigation systems and through management of the water table to increase its contribution to crop evaporation. Secondly drainage water can be reduced by ceasing irrigation of lands that have high salinity and selenium concentrations, shallow groundwater and that are difficult to drain. A fee on drainage discharges is a policy incentive to encourage source reduction and make it possible that economic benefits exceed cost of improvement (Hanson and Ayars 2002). Engineered subsurface drainage prevents waterlogging in leaching. To reduce the build-up of soluble salts and leach the salts out of the root zone pre plant irrigation is necessary. Together with winter rainfall it leaches salt from the top 1 m of the field (Shouse et.al. 2006).

In land retirement irrigation is stopped on lands with shallow groundwater that is contaminated with selenium and other substance and has poor drainage. When irrigation is stopped, the water table should drop and can become a sink by receiving contaminated water from adjacent lands. The goal is to reduce the load of dissolve constituents in subsurface drainage in particular trace elements. The down side of this is possible loss of agricultural productivity and loss of income in the surrounding communities. Benefits are the money from the sale of land and water supply and reduced drainage cost (Wallender et al. 2002).” The recommended management approach to retired land is: Measure biologic hydrologic soils and economic consequences in the short term and the long term and manage and monitor retired lands based on dynamic biologic, hydrologic and soil conditions” (Wallender et al. 2002p 325).

Managed groundwater pumping reduces drainage and prevents waterlogging. Because the quality of the semi confined aquifer is poor, it is not usable. Pumping up water below the Corcoran clay layer relieves the head on the subsurface tile drainage system and positively influences drainage decrease, the water is of better quality and sometimes can be used for irrigation (Purkey et al.2004). Famers in the Central Valley have historically increased groundwater pumping during drought periods; the water pumping is greater than the reduction in surface water to compensate for the reduced precipitation experienced during drought years (Miller 2009). Famers are organised into larger water districts to manage irrigation, water distribution and drainage (Schoups et al. 2005).

When discharge could be timed to match the assimilative capacity of the river it is called real time management. Real time management controls the amount of drainage water released over time so more salt and selenium can be discharged without violating water quality objectives. This requires storage which might be accommodated within the soil profile but the water table cannot be maintained too high in the root zone. When storage of drainage water is done in holding ponds wildlife using the ponds and being exposed to the selenium toxicity of the drainage effluent. For sustainable water quality protection biological and chemical impact should be included in research (Letey et al. 2002). “The California Department of water resources (CDWR) see potential for surface and subsurface storage to limit the adverse impact of drought and snowpack reduction on water supply “(Miller et al. 2009 p858).

Conjunctive reality and possibilities

In San Joaquin valley textbook conjunctive management can be carried on some parts of the land after some adjustments. For other parts of the land that are to salt alternative methods are needed. In SJV there is a high groundwater table and the groundwater is of low quality. In theory the solution is to drain the low quality groundwater and let better quality canal water infiltrate in the soil to make fresh water lenses that can be reused. In reality the groundwater pumped up is not allowed to drain away and there is no canal water that can infiltrate because the crop production is year round. So other types of management should be carried out. A possible solution is the reallocation of land use and management. Retirement of low quality land, so water can efficiently be used on workable land, and management of effluent in the drainage so more groundwater can be evacuated to the San Joaquin river and the sea support a long term planning of making water lenses on lands of decent quality. On the low quality land drainage water can be reused for salt tolerant crops. In san Joaquin valley textbook conjunctive management can be carried on some parts of the land after some adjustments for some parts of the land that are to salt alternative methods are needed.

Conclusion

The San Joaquin Valley has high agriculture production, irrigation makes it year round and rain falls from November to March. The main water source is surface water only 30 % is groundwater. In dry years this number rises to 80% and when the drought continues the aquifer can be dried out. The soil in the east is sandy but in the west it has a higher clay content of clay and also of trace elements. In the soil is a low permeable layer of clay that divides the soil in a confined- and a unconfined aquifer, irrigation water is mainly from the unconfined aquifer.

Because of exhaustive groundwater use in the past see water intruded into the soil. Then because of shortage irrigation was introduced, initially without drainage, and water logging occurred. Eventually a drainage system was installed but this water cannot be reused because of the toxic trace elements.

Restrictions on drainage increased salinization and let trace elements concentrate to toxic levels. The Corcoran clay layer has makes the groundwater shallow in the east and makes the deeper aquifer accumulate salt. Only the north district with existing outlets are allowed to dispose drainage in the San Joaquin River, for the rest of the valley subsurface drainage is not possible without disposal possibilities. Selenium loads limit the total disposal.

In 1990 federal and state agencies published a plan for irrigated agriculture and signed a memorandum that they would use it as a guide. Source reduction is done trough improvement of water management or stop irrigation on land of low quality. Water pumping is efficient to reduce drainage volume; water below the clay layer is of better quality and can be used. Storage can be used to manage the drainage so more water can be drained within the boundaries of quality objectives. Also storage can be used to tackle potential future increase of water shortness.

In San Joaquin valley textbook conjunctive management can be carried on some parts of the land after some adjustments. For other parts of the land that are to salt alternative methods, like salt tolerant crops are needed.

Kotri Left Bank Basin, Pakistan

Characteristics

Sindh is the southernmost Province in Pakistan, located at the tail of the Indus system. There are six drainage basins – Ghudu Left Bank; Ghudu Right Bank; Sukkur Left Bank; Sukkur Right Bank; Kotri Left Bank; Kotri Right Bank. The Kotri Left Bank Drainage Basin (KLBDB) consists of the irrigation schemes on the left bank of the Indus River, under the command of Kotri Barrage in the administrative districts Hyderabad, Mirpur Khas and Badin. This basin is bounded by the Thar Desert on the eastern side, Indus River on the western side, Kotri Barrage on the northern side, Rann of Kutch and coastal area on the southern side (Woldbank 2004). At the seaside, the area is separated from the deep sea by an extensive strip of muddy coastal forelands (pers. com. Frank van Steenbergen). See map 2.

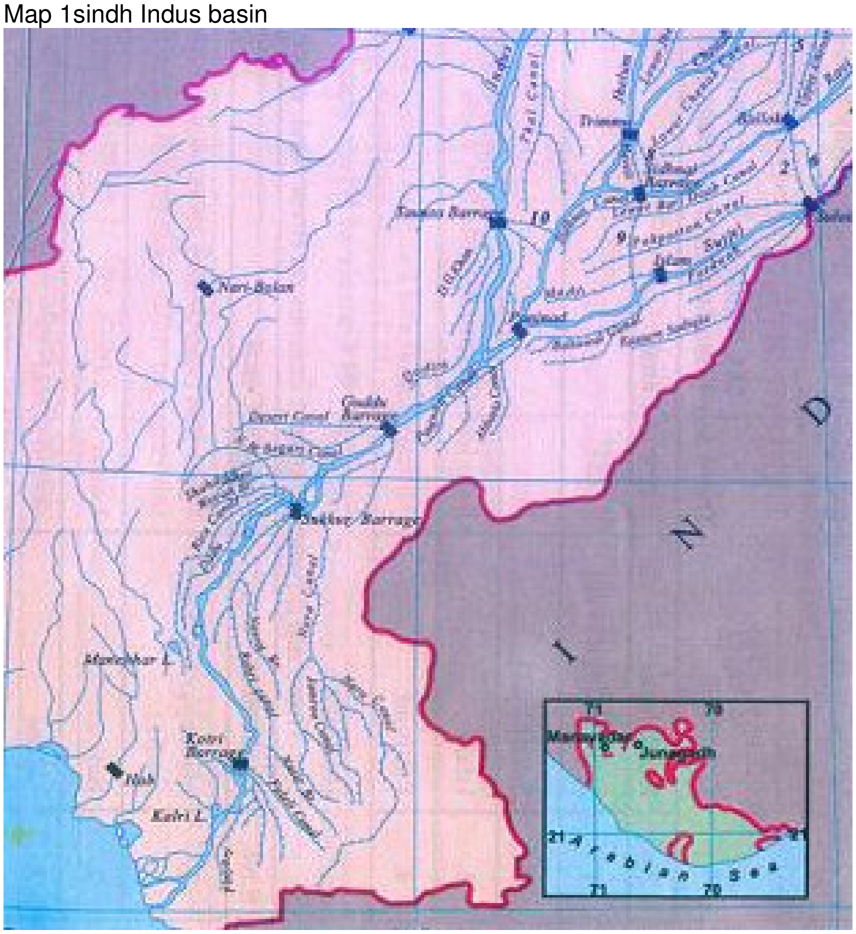
Climate in KLBDB is semi-arid with a mean annual rainfall in the basin of about 250 mm/yr. Concentrated in the monsoon from July to September. Pakistan water supply originates mainly in swift flowing glacial melt from the Himalayas in late spring and monsoonal activity between June and October. To take advantage of this tremendous resource, the country has been highly engineered in hydrological terms with irrigated areas representing 82% of all the farm land (Mustafa and Wrathall 2011 p76).Pakistan has the largest contiguous irrigation system in the world of 16 million ha. The irrigation system is simply a continuous flow until the tertiary unit off take. The irrigation system is so large that it takes 20 days for the water to travel from the main reservoirs in the north to Sindh (Wolters and Bhutta 1997, Malik and Strosser 1993). The canals serve as the main source of drinking water in the area. Small groundwater pockets are used as a source of drinking water during the closure of the canals (pers. com. Frank van Steenbergen). People need to pay for drinking water but not for irrigation water (pers. com. Wouter Wolters).

The Indus River downstream of Kotri Barrage has practically zero discharge. The freshwater reached the deltaic area infrequently during the summer (July-September). The intake of irrigation water at the barrage is virtually the only hydrological link between the KLBDB and the Indus River. This intake is fully controllable. However, the response time between changing the intake and a noticeable effect at the downstream end of the irrigation systems is fairly long. This may pose serious water management problems (pers. com. Frank van Steenbergen).

The KLBDB has clay soil, flat but slightly sloping to the sea with low elevation above Mean Sea Level (MSL). The groundwater is shallow and marine saline, About 49% of area is suffering seriously from waterlogging and salinity. Drainage outfall to the sea is constrained by the tidal regimes. In Pakistan deep groundwater always has been saline, because the area used to be in the sea area (pers. com. Theo Boers). The saline groundwater is overlain with a freshwater layer of varying depth. The groundwater table also varies with time (climatic cycles over years) between near surface to depths of over 10 metres (pers. com. Frank van Steenbergen). The water table is lowest in June before the monsoon starts (Khan et al. 1997). Survey round 1998 indicated that in Sind 15 to 23 percent of gross area has a water table less than 1.5m (Bhutta , Wolters and Siddiqui 1995).

The left bank outfall drain is a winding drain that begins at Ghotki at the top of Sindh has many different names passing to many district on his way to sea at Badin. The final stretch that drains into the sea known as the tidal link was widened and deepened because of a design fault that let seawater backwash into the drain (Ali 2011). The drains are used intensely to convey excess irrigation supplies, storm water and municipal and industrial effluent and reused for irrigation, animal drinking and, in some tail-end areas, even for human consumption (Worldbank 2004).

Map 1sindh Indus basin



Source:http://pakistan360degrees.contentcreatorz.com/canal-system-of-pakistan/

History

Already in 1333 the river was altered making it wider and increasing discharge deposition and sediment load, embankments build up raising the rivers above the floodplains. Irrigation canals reduced peak discharges and trapped sediment to prevent flooding (Da Silva and Koma 2011). In 1859 British colonials began to build canal networks; the current system is still based on it. Colonial flood management was based on the strategically breaching of bunds by the army. 1960 mega dams where placed and withdrawal from the systems increased (Mustafa and Wrathall 2011). From 1982 to 1999 extra water was available because of the construction of the Mangla and Tarbela dam and rapid tube well growth. But sedimentation reduces the storage capacity of the Mangla dam by 20 % from 1967 to 2000 and the Tarbela 40 % from 1975 to 2000 (Khan et al 2008).

Already in the 1950s in the south of Pakistan deep seawater was pumped. Salts problem started in Pakistan in the early seventies. When America introduced deep tube wells that pumped deep groundwater (pers. com. Theo Boers). In 1960 and 1970 the salinity and reclamation project (scrap) constructed more than 20.000 public wells producing 80 liters per second to combat waterlogging; water with a reasonable quality was used for irrigation. Power subside and diesel engines, made in the country, led to growth of private tube wells with 18l/s capacity in the 1970 an 1980s (Bhutta and Wolters 1997,Quersi et al 2004). Population growth makes water demand escalate and much of the crop water requirements are met by pumping making the water quality decline and soil salinity and sodicity increase. The massive fresh water withdrawal caused saline water intrusion (Khan et al. 2008).

A cyclone 1998 destroyed a weir on the Northern bank of the Tidal Link. The Dandhs became permanently linked to the Tidal Link and changed from fresh/brackish conditions into saline. Another cyclone in 1999 worsened the situation as incoming high tides caused serious degradation of the tidal link. The development of an extensive network of surface drains in central Sindh lowered the high water tables. However, during the exceptional high rainfall event the surface drains transported the storm water to the lower basin causing downstream flooding. The design capacity served to transport the saline effluent and to cope with modest rainfall events. This capacity was inadequate to remove all the storm water in the exceptional (once/10 years) heavy rainfall in this area. As a result there was substantial flooding in the lower section during the unusual rainfall events in 2003. This was made worse by 'cuts' into the open drains by upstream farmers in order to quickly remove the excess water on their land – creating even larger flood peaks. The flooding in the downstream area was further aggravated because the local drains in that particular area did not work due to high tide and also because irrigation canal supplies to the area were 'shut off' too late. The situation was further aggravated because the outfall drain scoured out and cyclonic winds pushed seawater into the tidal link thus entirely blocking the drainage of storm water from the Kotri left bank area. Badin area was seriously flooded reportedly causing the loss of over 100 lives. Damages to Tidal Link are considered beyond repair (Worldbank 2004).

August 2010 Pakistan experienced the worst flood in over 80 years, 2000 civilians were killed, one eight of the population. Villages and cities next to the river where destroyed (Da Silva and Koma 2011). Also 2010 was the hottest year on record in Pakistan and glacier runoff had filled the river to its capacity before the monsoon began in July. The flooding overwhelmed water management capacity and inundated large swaths of farm land. Although the rainfall had already almost stopped begin September, contaminated flood waters continued to rise. Whilst some of the flooding was caused by overwhelm levees and flood barriers, considerable amount of inundation was the result of deliberate breaching of the embankments by irrigation authorities to prevent damage on infrastructure. 3.6 million Ha agricultural land is ruined and planting for next season is in jeopardy. December 2010, 4 months after the river flood subsided 42100 ha of southern Sindh was still inundated (Mustafa and Wrathall 2011). The government and institutions involved did not react when already on the 20th of July meteorologists predicted that rainfall in the monsoon would be 40 present higher than average. When the water came drainage canals where not maintained in Punjab and Sindh millions of people settle in dry river beds, the government didn't present an alternative to these poor people (Brummelman 2010).

Problem Statement

The water shortage of protective irrigation is high, the design capacity in Pakistan is 2mm/d while the in May to June the crops need 15 mm/d(Bhutta and Wolters 1997). The irrigation system in Pakistan was designed to spread the available water thin over an large area to prevent crop failure, in times of shortage the water is rotated between secondary canals. This forces farmers to use only part of their land(Wolters and Bhutta 1997). The continuous irrigation system was design to irrigate 75 %of the area, many canals don't convey their design capacity any more do to siltation (Quersi et al 2004). Sediment load let the canals run at less than 70-75 percent of their design capacity (Wolters, Habib and Bhutta 1997).

Seepage in Sindh is high because almost all canals are built in earth. Maintenance of in particular the smaller branches and tail ends of the canal system is lacking. Major issues are the direct outlets on the main canals – both sanctioned and illegal. These direct off-takes are usually not fitted with gates and take water whatever the level in the canal and whether it is their turn or not. They cause create fluctuations in water availability for downstream users (Worldbank 2004). Continuous drought in the Indus Basin has decreased the freshwater flow downstream of Kotri Barrage (pers. com. Frank van Steenbergen). In rural areas with saline or absent groundwater reservoirs people take water directly from canals. At the tail end where canals run dry frequently water is taken from the drains. On many occasions it was observed that farmers have constructed small weirs in the drains in order to lift drainage water to irrigate their fields (Worldbank 2004). The main source of drinking water (65%) for villages as well as urban water supply schemes is canals and watercourses and open wells and ponds. Due to shortage of freshwater downstream of Kotri Barrage severe shortage of drinking water is faced by tail-enders and coastal communities. Because there is no organized public tanker program, most purchase water cans at heavy prices. The water so purchased is not quality controlled and results in the outbreak of many waterborne diseases (pers. com. Frank van Steenbergen).

In the Kotri Left Bank Basin municipalities, starting with Hyderabad city, discharge untreated waste water into the canals – causing serious health hazards, particularly as the water from the canals is the main source of drinking water in the Kotri Basin. The six sugar mills of the basin dispose processing water into as many main or branch drains. About 45 towns spread-out over the basin, have sewage flows into the drainage systems which surpass the natural purification capacity of these waters. Hazardous persistent chemical residues remain undetected (Worldbank 2004). Drainage water can contain not only salts and trace elements but also domestic sewage, industrial effluent and fertilisers and pesticides. Some farmers use untreated effluent, this damages the crops and can be a danger to public health (Wolters and Bhutta 1997). Canal water in Sind is drainage water of higher areas that re-enters the river. From upstream to downstream of the river the water quality declines. The outfall drains should be lengthened to avoid the water quality in the river to decline (pers.com. Jacob Vos).

In the Indus basin is a drainage problem. There is little natural drainage, discharge by gravity is impossible with a slope of 0.20m per km. The constructed drainage system is inadequate and poorly maintained. Both tube well and pipe drainage effluent cannot be reused where pumped (Khan et al. 1997). In Sind province there a lot of tube wells are out of order due to poor management (pers.com. Jacob Vos). “The entire middle and lower Indus valley of Pakistan the extension and thickness of freshwater lenses decrease downstream to a minimum in parts of the Sindh province” (Foster et al. 2010 p 14). Cattle and buffaloes cause damage to embankments when they make use of drains for drenching (Worldbank 2004).

On most of the surface drains in Kotri there are no control structures – though farmers have made in some places their own seawater barriers. The absence of gates in the surface drains let high tide seawater flows in. Because of the increased tidal effect after the scouring of the Tidal Link and the generally flat gradient sea water intrusion extends much far inland. At high tide seawater intrudes at the open tail ends of the drains; the water may move up the drain some 10 km (Worldbank 2004). The growth of the tidal link also in width leads to salinity in the groundwater and loss of grazing land (Ali 2011). Surface runoff during high intensity rainfall storms is ends up in the downstream part of the Basin, causing extensive flooding from time to time. Combined spring tides, and cyclone events may cause flooding by seawater of the lower part of the KLBDB. The frequency in the lowest parts is in the order of once per three years. High tides at sea create drainage obstruction and inward intrusion of seawater, especially during monsoon when south eastern winds push the Arabian Sea into the coastal creeks (Pers com Frank van Steenbergen). The twin menace of almost total absence of fresh water in the river downstream of Kotri and heavy sea water intrusion from the delta has destroyed large areas of prime agricultural land (Worldbank 2004).

Due to rapid population growth groundwater use has increased what made groundwater decline and deteriorate the quality (Khan et al 2008). To much private tube well pumping will deplete the fresh groundwater which is replaced by saline groundwater. Increased irrigation efficiency increases soil salinity because of reduced leaching (Bhutta and Wolters 1997). The salt balance of Pakistan shows that twice the amount of salt is entering the country than leaving (Wolters, Ittfaq and Bhutta 1996). People buy more expensive pumps and can pump deeper. Deeper pumps are very likely to pump up salt water. Shallow pumps pump up fresh water provided it is complemented. When the fresh water is finished, up-coning of saline groundwater occurs, so that more salty water will be pumped (pers. com. Wouter Wolters). Vertical drainage in Pakistan is extremely dangerous, because it mobilises the salt the pumping up of fossil brackish water. A decade is past before a column of brackish or salt groundwater has disappeared. The groundwater table has to be rebuild by percolation losses (pers.com. Jacob Vos).

Silt decreases the capacity of retaining the flood flow by leaving less room for the water of monsoon and snowmelt. Wetlands used to take up the flood but erosion reduced floodplains, now little floodplain are unable to retain water resulting in flooding. This flooding events can be stopped by restoring the wetlands and maintain levees with planting threes (Da Silva and Koma 2011). Design assumptions of the infrastructure and the carrying capacity of the canals in reality are mismatched because the system is not adapted to natural processes like erosion. The large use of irrigation water leaves to little water in the system to flush the canals. Constructions of embankments along the river for flood protection protects for short and medium term but sediment deposition makes peak floods worse, and flood damage is worse in regions that supposed to be protected by embankments. In Pakistan aggradations is a dominant process caused by both excessive water withdrawals and levee construction. Flooding in Pakistan stems from breaching embankment to let the water flow back to the river. Water in de inundation zone with a drainage path blocked by levees and roads will not drain and become as cesspool of diseases (Mustafa and Wrathall 2011).

Management

The strategy to improve water in Pakistan includes water conservation for a better irrigation efficiency, improvement of surface drainage systems, implementation of subsurface drainage systems where it is urgently needed (due to high cost). There is a wish to improve management like provincial water authorities and area water boards. For salanization is the goal to initiate studies on salt monitoring effluent disposal and groundwater mining. Seepage mitigatory measures like lining and interceptor drains are adopted to reduce the groundwater recharge but this is not a complete solution. If al losses are preventing the water table slowly gets lower whit less speed than is rose before because there is still irrigation. For responsible reuse of drainage water data is needed on the quantity and quality (Bhutta and Wolters 1997).

The possibility of surface drains as a solution to water logging and salinity is neglected. Engineers in Pakistan see the function of surface drainage to be disposal of rainfall runoff and pumped up drainage. The groundwater table drops after improvement of surface drainage (Khan et al 1997). One possible cause of water logging is the law that nor the irrigation department nor the farmer is allowed to close the tertiary canal if they don't need water, without drainage this water stagnates in low lying areas making them unusable (Wolters and Bhutta 1997). The provided drainage consists of a low-density surface drainage system only. It intermingles with the irrigation canal system (pers. com. Frank van Steenbergen). Pipe drainage projects are performing well in Pakistan. Due to flat topography the drain pipe water is collected in a sump from where it is pumped to surface drain. But even just after the construction operation of all the pumps was not possible (Bhutta , Wolters and Siddiqui 1995). "Pipe drainage projects control the water table at 1.0 10 1.5 meters below the surface, reduce salinity and the percentage of land abandoned in Pakistan" (Bhutta , Wolters and Siddiqui 1996 p1).

The installation of drainage system, sections where simply added without integrating, leading to diffused responsibilities. When the canals where finish the provincial irrigation departments did not receive addition funding for operation and management so this cannot be done properly (Wolters and Bhutta 1997). "The national drainage program proposes to directly involve framers in the planning, design, construction, Operation and maintenance of on farm drainage systems" (Wolters and Bhutta 1997 p10). But" there still is, at decision taking level, a serious lack of understanding of what it takes to involve farmers, especially in the planning implementation and ultimately transfers for O&M of drainage systems (Wolters and Bhutta 1997p 11).

Subsurface drainage can be done by a pipe system or a tube well. In Pakistan tube well drainage is common, it cheap en effectively lowers water tables but also mobilises salt from the deep aquifer. Shallow groundwater drained with pipes shows improvement of quality. With tube well drainage quality is constant or declines (Wolters Ittfaq and Bhutta 1996). Famers are prepared to pump for irrigation but not for drainage, sincere involvement of farmers takes time, at decision taking level there is a lack of understanding what it takes to involve farmers especially for planning implementation and organisation and management of drainage systems (Bhutta and Wolters 1997). A rotation was introduced whereby the area was provided with irrigation for two weeks out of three. This caused a sharp increase in private shallow tube well development, waterlogging disappeared from the area. The prolonged drought of 2000–02 in India and Pakistan brought main system water management back to attention. Agricultural production increased slightly, because there was less waterlogging in previously oversupplied command areas. In Sindh Province for instance water logging reduced from 35% to less than 10% of the command area after 2 years of low canal supplies (Worldbank 2004).

Hyderabad is planning a significant investment in three sewage treatment facilities. Formal legislation and norms for waste water of industries exists in Pakistan but are only halfheartedly implemented. However, the Sindh Environmental Protection Agency has recently started activities aimed at controlling the most severe polluters. EPA is planning to install 7 laboratories next year aimed at improving the monitoring and law enforcement capacity in the province. Problems also occur with the capacity of EPA to prepare cases for court; so far a legal cell is lacking within EPA (Worldbank 2004).

"The national water policy document exists as a draft since three years, because the main stakeholders (provinces) could not agree on the institutional aspects. Water sector organisations function at a national central level. Many organisations carry out similar type of projects and research without much collaboration. For example 13 organisations are involved in climate related studies without a comprehensive agenda. The water sector is also not able to resolve regional disagreement on actual water available in the system, surface water storage and regulation to share the shortage"(Habib 2008 p11).

Water management in Kotri Basin is nonexistent in some fields and areas and in other fields dispersed over several organizations. There is no coordination mechanism or effective lead agency in water management. In fields such as: main system irrigation efficiency, storm water removal, drainage reuse there is no management. There is also no water quality management and no interest in the situation of drinking water. Reforms in irrigation and drainage are incomplete. New organizations are under reform and not effectively operationalize. Emphasis is on water distribution and limited on maintenance, there is no flood management plan (Worldbank 2004). Flood policy is not an important subject for Pakistani water managers the priority for dam and barrage management has always been irrigation and power generation. The national disaster management authority (NDMA) has little budget and dubious authority in normal times (Mustafa and Wrathall 2011).

The present government in Pakistan has taken away an essential part of local level representative government. Local level institutions are better suitable for responding to environmental disasters than the national government. People in charge of disaster management are frequently transfers and don't have local knowledge or public accountability. Reservoir operators are not empowered to make split second decisions about flow adjustments and reservoir managers release water that turns in to deadly downstream flows because the system was not coordinated. Water managers should be trained for multi criteria management of the system, with long term flood management as a priority and work with the rhythm of the rivers instead of controlling rivers. After training manger should be given the authority to operate infrastructure and flush canals, inundation zones and restore of wetlands will moderate flood peaks. Now anomalous meteorological events become frequent past experience of main conditions will not hold, water managers should be more attentive to the future by reworking their operating procedures and focus on vulnerability reduction (Mustafa and Wrathall 2011). Policies of integrated planning and management need harmonious directions on basin level and specific local actions based on past experiences and potential. Possibilities to improve are allocation and accounting of water, addressing supply demand gap and increasing agricultural productivity through different crops. Pollution control at the source and waste management measures need stakeholder involvement (Habib 2008).

Conjunctive reality and possibilities

The fluctuation of resource availability is high in the KLBDB. River water reaches only the Kotri barrage during monsoon and is short of water the rest of the time makes the use of groundwater as substitute necessary. People use water from canals, drainage canals and groundwater without consideration of the quality. The groundwater is saline and the quality from both the groundwater and the river water is low because of effluent in the river, both should always be monitored. There are projects planed to treat the sewage and control polluters but this is not yet fully implemented.

When the water arrives it is often too much and causes trouble. The cause to this flooding is the old and poorly designed canal system. To make the water flow more balanced a better water management in Pakistan as a whole is necessary. When water is stored during the monsoon across the total Indus River there will be less flooding in peak periods and if framers at the top of the Indus River use the stored river water in dry periods there will be more water left in the river for the Kotri basin. For this it is necessary to improve the government. National water policy that carries out conjunctive water management should be made official fully implemententent and enforced.

Better water management will make the water flow trough the canals more balanced. But does not take away the fact the canals are 150 years old, build for protective irrigation, not lined, without gates, suffer from a load of siltation, are eroded so seawater can com in and have breaching of embankments as flood management. The full potential of conjunctive management will be reached when the canals are updated.

Conclusion

Rainfall in KLBDB is 250mm a year concentrated during the monsoon from July to September; this together with glacial melt from the Himalayas is the water resource. Only from during monsoon Freshwater reaches the delta, the rest of the time the river has zero discharge downstream Kotri barrage. The clay soil has shallow saline groundwater overlain with a fresh water layer. The left bank outfall drain reaches from top of Sind till the sea. The final meters, tidal link, is widened and deepened and lets seawater in.

The large network of canals was constructed in 1950. In 1960 and 1970 tube wells where introduced and subsidized to combat water logging. Then the salt problem started because American pumps reached to deep and pump up saline sea water. From the 1970 dam construction made extra water available but this stopped already in 2000 because of siltation. Cyclones and rainstorms destroy the drainage system and seawater comes far inland. Also the drainage canals is not design to high rainstorm whit a probability of one in 10 years and causes flooding in south Sindh. Storm water and seawater intrusion clash and cause congestion. In 2010 a major flood destroyed cities and lives, 4 months after the flood parts of southern Sindh where still inundated. The government didn't react on predicted higher rainfall during monsoon. Flooding was caused by breaching of embankments to protect infrastructure.

Protective irrigation and siltation in the system causes a shortage of surface water, farmers can only use parts of their land. There is no maintenance and no management. People who do not get enough surface water take water from the drains. Cities towns and sugar mills dump untreated sewage flows in the canal making the water a quality hazard. Drainage systems are badly maintained and broken. Sea water can come far inland. Groundwater is made even more saline by pumping up deeper more saline water and the low quality of the water applied to the soil. Siltation by lack of flushing makes the capacity of the canals decrease further and this increases the impact of flooding.

Pakistan has the intention to improve the drainage system, irrigation efficiency and water management. Drainage in Pakistan is done by both surface drainage and tube wells, surface drainage can also make the groundwater drop. The management of drainage needs improvement. Tube well drainage is common. When there is a drought people are forced to pump and there is less waterlogging, but the quality of the groundwater can decline. Environmental protection agency started activities to control pollution. There is no national water policy water management is absent or institutions are not cooperating. There is no local representation of the government although management on the local level is more suitable to respond to disasters. Local water managers have no authority this should change and they should be trained to work with the rhythm of the river.

Because of low quality of al sources, the quality of all water should be monitored. Conjunctive management of water should be done across the Indus river basin, for this water policy enforceability should be improved. To reach the full potential of conjunctive water management the canal system should be updated.

Chapter 6 findings

An environment that enables conjunctive management has several factors. Firstly the inflow and outflow of water in an area should be in balance in long term, to get fresh water storage in saline groundwater the groundwater level should be low for a short time, but when there is too much difference between inflow and outflow for a longer time severe water logging or shortage will occur. Water management should be based on the balance, when irrigation is creates water inflow drainage possibilities should be made available for outflow otherwise water will rise to high and land goes out of order. Surface drainage prevents flooding and inundation. Subsurface drainage can be done by tube wells. Fresh water can be reused but salt water should be evacuated. Salt water should only be evacuated through the river when there is enough water in the river to keep the quality. Amongst others drainage can: increase crop yield and make the production of higher value crops and more than one crop per year possible. It is not recommended to drain unsupervised because the groundwater can become to low.

Secondly Groundwater quality and quantity differs per area and should be monitored.
Groundwater salanization has different origins. Irrigation moves salts from the unsaturated soil into the groundwater. Or salinity stems from the fact that plants do not take up salts, so the small amounts of salts present in rain and river water accumulate in soil. To get rid of this salt it is very important to flush the soil and use drainage, however drainage and flushing will not have the effect intended when not done together. Reuse of drainage water or wastewater should be banned or done with great precaution because the quality of this water can be extremely low. Saline groundwater can be stored or drained into the river when there is enough water in the river to dilute the drainage effluent. A lot of land is out of order because farmers don't know how to manage different groundwater qualities. To use lower groundwater qualities safely, groundwater can be mixed with canal water. irrigation should be allocated accordingly so farmers are encouraged to pump up freshwater and practice irrigation efficiency when saline groundwater is present.

Finally management practices can prevent or handle water logging. Irrigation efficiency creates a lot of benefits: when less water is needed more land can be irrigated, flooding will be less and when the soil holds toxics less of them occur in the drainage effluent. The only disadvantage is salanization, because less groundwater can make the soil more saline and when the soil is already saline irrigation and leaching cross out each other. In an alternative way to prevent waterlogging some plants can be planted along the cannel lines where water builds up so it can be evaporated and if a crop is chosen that does not need a lot of water little water will be spilled. When the land is already flooded and reclamation is needed it is recommended to use both flood protection drainage and saline soil measures. After reclamation the land should be managed extra careful to prevent salanization.

A groundwater basin improves conjunctive water management. Drainage and the pumping up of groundwater create a buffer in the soil that can be recharged and use for storage. Surface storage is efficient with fluctuating demands, but water can be lost by spills or evaporation and the structure occupies a lot of land. Groundwater storage can be kept for several dry years, but the discharge can be too small and the capacity can be limited, the aquifer can be to small or the absorption to slow. For groundwater storage the storage capability and recharge capability should be known. High permeability and transmissivety and percolation makes soil suitable for recharge and the water level should be lower then 5 m. before irrigation there should be a large water deficit in the soil so there is a buffer for much recharge to minimise defuse deep drainage and groundwater growth. Recharge can be done induced natural, when a river recharges a groundwater depression made by intensive use or artificial when water is let in to a pond to increase the percolation surface or by simply pumping it in the aquifer. It is important to know the sequence of wet and dry spells to balance replenishment and withdrawal. In areas of saline groundwater a sweet water lens can be created be keeping the water table low, and this water can be pumped up, but when too much is pumped up salt water will enter the wells.

Several improvements can be made to current conjunctive use and management.
It is very important to start drainage straight away. Although drainage is necessary it is almost never laid out at the same time as the irrigation canal because it is costly. But even when the water table is at a good level before irrigation starts, it will rise because of the irrigation, and drainage is still needed.

Water quality should be managed carefully. Groundwater should be monitored to prevent use of saline water that is pumped up. Groundwater is mainly used individually and should be overseen by an institution, because individual users have no insight into the available quality and quantity. Farmers should be made aware of quantity and quality of groundwater. If the framers think the ground needs leaching and add too much extra water, water logging and salinity occur. When a farmer runs out of fresh water and hits saline water, he will continue to pump because he assumes salt water is better than no water, but this accelerates the salanization of his soil. A lot of farmers use drainage effluent of cities with toxins.

To experience the full benefit conjunctive use should be properly managed. The fact that surface water and groundwater is managed separately gives problems, this should by spatially coordinated. Institutions are important to empower reallocation of surface water.

In San Joaquin valley textbook conjunctive management can be carried on some parts of the land after some adjustments. For other parts of the land that are to salt, alternative methods, like salt tolerant crops are needed. In the SJV the main water source is surface water only 30 % is groundwater. In dry years this number rises to 80% and when the drought continues the aquifer can be dried out. The low permeable Corcoran clay layer has makes the groundwater shallow in the east and makes the deeper aquifer accumulate salt. Only the north district with existing outlets are allowed to dispose drainage in the San Joaquin River, for the rest of the valley subsurface drainage is not possible without disposal possibilities. Restrictions on drainage increased salinization and let trace elements concentrate to toxic levels. In 1990 federal and state agencies published a plan for irrigated agriculture and signed a memorandum that they would use it as a guide. Source reduction is done trough improvement of water management or stop irrigation on land of low quality. Water pumping is efficient to reduce drainage volume; water below the clay layer is of better quality and can be used. Storage can be used to manage the drainage so more water can be drained within the boundaries of quality objectives. Also storage can be used to tackle potential future increase of water shortness.

Because of low quality of all sources in KLBDB, the quality of all water should be monitored. Conjunctive management of water should be done across the Indus river basin, for this water policy enforceability should be improved. To reach the full potential of conjunctive water management the canal system should be updated. Drainage systems are badly maintained and broken. There is no national water policy water management is absent or institutions are not cooperating. There is no local representation of the government although management on the local level is more suitable to respond to disasters. Local water managers have no authority this should change and they should be trained to work with the rhythm of the river. Before the flood of 2010 the government didn't react on predicted higher rainfall during monsoon. Flooding was caused by breaching of embankments to protect infrastructure. Only during monsoon Freshwater reaches the delta, the rest of the time the river has zero discharge downstream Kotri barrage. In 1960 and 1970 salt problem started because American pumps reached to deep and pump up saline sea water. Cyclones and rainstorms destroy the drainage system and seawater comes far inland. Protective irrigation and siltation in the system causes a shortage of surface water. People who do not get enough surface water take water from the drains. Cities towns and sugar mills dump untreated sewage flows in the canal making the water a quality hazard.

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