Can Irrigation Be Sustainable?

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Abstract
Globally about 10 Mha of agricultural land are lost annually due to salinisation of which about 1.5 Mha is in irrigated areas. While some climate and management aspects are common to semi-arid regions the detailed mechanisms and options to secure ecological sustainability and economic viability may vary considerably from case to case. This paper applies a whole of system water balance to compare irrigation in three semi-arid regions suffering from similar sustainability issues: Rechna Doab (RD) - Pakistan, the Liuyuankou Irrigation System (LIS) – China and Murrumbidgee Irrigation Area (MIA)-Australia. Soil salinity, lack of adequate water resources and groundwater management are major issues in these areas. The MIA and LIS irrigation systems also suffer from soil salinity and low water use efficiency issues. These similarities occur in spite of very different climatic and underlying hydrogeological conditions. The key data used to compare these different regions are climate and soils, available water resources and their use, as well as components of the water balance. In addition, the history of water resource development in these areas is examined to understand how salinity problems emerge in semi- arid regions and the consequences for production. Based on the efficiency parameters and the definitions of sustainability, approaches are explored to solve common environmental problems while maintaining economic viability and environmental sustainability for irrigation systems.

Media summary
It is possible to maintain the productive function of any irrigation area by providing adequate drainage and salt export facilities that may, however require high energy and capital investments. The most cost-effective option for sustainable irrigation is to increase water use efficiency and minimize negative impacts on the environment. There is a need to radically rethink sustainability of food production, rational pricing and sharing of water and commodities to justify the investment required to maintain and enhance ecosystem function within irrigated catchments.

Introduction
Just 20 % of the world's croplands are irrigated but they produce 40 % of the global harvest which means that irrigation more than doubles land productivity (FAO, 2003). In developing countries irrigation improves economic returns and can boost production by up to 400%. On the other hand, irrigation can have unwanted environmental consequences. About one-third of the world's irrigated lands have reduced productivity as a consequence of poorly managed irrigation that has caused water logging and salinity (FAO, 1998).

Irrigation has been important for agricultural production in Mesopotamia (parts of present day Iraq and Iran) for 6000 years. The region has low rainfall and is supplied with surface water by two major rivers, the Tigris and the Euphrates. The plains of Mesopotamia have always had problems with poor drainage of soils, drought, catastrophic flooding, silting, and soil salinity. Although Mesopotamia is very flat, the bed of the Euphrates is higher than that of the Tigris; in fact, floods of the Euphrates sometimes found their way across country into the Tigris. Engineers took advantage of this gradient as soon as irrigation schemes became large enough, by using the Euphrates water as the supply and the Tigris channel as a drain.

The main engineering problems for earlier civilisations were water storage, flood control and maintenance of canals. The salinity problem was more subtle, not fully appreciated, and could not be overcome by the engineering available at the time. It was difficult to drain water from fields, and there was always a tendency for salt to accumulate in the soil.

The problems of irrigated agriculture in Mesopotamia can be summarised as:

- *Silting of canals:* silt built up quickly in the canal beds, threatening to block them
- *Soil salinity*: recorded evidence around 2000 BC, 1100 BC, and after 1200 AD
- *Water politics* arising from tension between upstream and downstream users. In Sumeria, the city of Lagash was far downstream in the Euphrates canal system. The governor of Lagash apparently decided that he would cut a canal to tap Tigris water rather than rely on water from the Euphrates, but the addition of poor-quality water from the Tigris led to rapid salinization of the soil.
- *Over exploitation of resources*: After the wave of Moslem expansion overtook Mesopotamia, the Abassid Caliphate was based in Baghdad from 762 AD until its demise in 1258. Existing irrigation schemes were renovated and greatly extended in very large projects. Abassid engineers drew water from the Euphrates at five separate points, and led it in parallel canals across the plains, watering a huge area south of Baghdad. This system provided the basis for the enormously rich culture of Baghdad, which is still remembered in legend (Scheherezade, the Caliph of Baghdad, and the Arabian Nights) as well as history. But the scheme required a high level of physical maintenance, and there was increasing salinisation in the south.
- *Institutional failure*: As the central government began to fail in the 12th century (mostly from overspending), the canals became silt-choked, the irrigation system deteriorated, and the lands became more salinised. The deathblow to the system was aided by nature: massive floods about 1200 AD shifted the courses of both the Tigris and the Euphrates, cutting off most of the water supply to the Nahrwan Canal and wrecking the whole system. The Abbasids were too weak (or bankrupt) by then to institute repairs, and the agricultural system collapsed. By the time the Mongols under Hulagu devastated Iraq and Baghdad in 1258 AD, they conquered a society that occupied wasteland. Iraq has remained a desert for more than 600 years.

Key challenges to irrigated agriculture

About 50% of the total developed fresh water resources of Asia are devoted to growing rice (Barker et al., 2001). In Asia, current estimates show that by 2025, 17 million hectares (Mha) of the irrigated rice area may experience “physical water scarcity” and 22 Mha “economic water scarcity” (Toung and Bouman, 2002). It is projected that global rice consumption in 2020 will increase by 35% from the levels of 1995, whereas water availability for agriculture over this period is expected to fall from 72 to 62% globally and from 87 to 73% in developing countries (Rosegrant et al., 1997). Increasing water scarcity threatens the sustainability of irrigated agriculture and hence food security and the livelihoods of rice producers and consumers.

Increasing competition from domestic and industrial uses has further compounded the problem of water scarcity. The demand for freshwater for industrial and domestic urban needs is growing rapidly throughout Asia. Less water will be available for agriculture and for rice, the crop that consumes the largest amount of freshwater. In some areas, water scarcity is already a major problem and a serious limit to agricultural development. Farmers are under pressure to grow more "crop per drop". Therefore there is an urgent need to find ways to “grow more rice with less water”, to achieve this, efficient and appropriate irrigation technologies are needed.

Some of the challenges faced by present day irrigated agriculture are similar to ancient Mesopotamia and are summarised below:

- *More efficient use of inputs* (water, fertilizer, pesticides and labour) aimed at reducing negative impacts on the environment and to reduce production costs.
- *Soil salinity*: Matching landscape capability with irrigation systems, there is a need to manage salinity hazard by matching landscape capability when making decisions on new locations for irrigation development or on-farm field suitability (Khan et al, 2003).
- *Minimising environmental impacts*: Management of extraction impacts by quantifying both positive and negative externalities of different irrigation areas and sectors by evaluation, auditing and benchmarking in the irrigation industry. Management of negative environmental impacts, such as methane and nitrous oxide emission, salinity, water pollution (abuse of pesticides), algal blooms etc, especially in intensive crop production systems.
- *Balancing consumptive and environmental demands*: Balancing irrigation and environmental flow demands through real savings due to improved distribution and on-farm water use efficiency and alternative cropping options.

- *Maintaining and enhancing quality* of drainage water and minimising impacts on rivers and ecosystems.
- *Institutional robustness*: Avoid a repeat of Mesopotamia in terms of institutional and ecosystem failures through better definition of property rights.

The challenge: to improve water use efficiency in rice-based irrigation systems of Australia and Asia

Three Regional Irrigation Perspectives in Rice-Based Systems

In 2000, the world's rice production was about 600 million tones Mt), 91of which was produced in Asia. China, India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar, Philippines, Japan, and Brazil are the top 10 rice-producing countries (FAO, 2000).

Australia

In Australia, the rice crop is mainly grown on the Riverine Plain in New South Wales by utilizing surface water supply from the Murray and Murrumbidgee rivers and pumping from the Murray Aquifer System. Water is mainly supplied to the crop through a channel network serviced by irrigation companies or is pumped by the farmers directly from the rivers and creeks. According to the Australian Bureau of Statistics, gross water supplies in Australia to the rural sector (mainly used for irrigation) increased from 12.7 BCM (billion cubic metres) in 1983–84 to 15.8 BCM in 1995–96. Irrigated areas increased by 3.7% per year from 1.627 Mha in 1983–84 to 2.332 Mha in 1993–94. Water use is currently 72% of the total water used for Irrigation in Australia. Surface water diversions in the Murray Darling systems are limited to a total of 11.6 BCM out of which around 1.6 BCM are used in rice production. All operations are mechanized. From 1.2 to1.6 Mt of paddy rice are produced per year on 2300 farms. In 2001, 1.7 Mt of rice were harvested from an area of 184,000 ha (The Rice Marketing Board for the State of New South Wales 2001). The industry has a farm-gate value of approximately $350 million (AUD) and total value (export earnings, value-added) of over $800 million (Sunrice, 2002). Including flow-on effects, it is estimated that the industry generates over $4 billion annually benefiting regional communities and the Australian economy. Normally the crop is grown in ponded water from sowing or from the 3-leaf stage. Rice is often grown in rotation with leguminous pastures and dryland crops, which improve soil fertility and limit the need for pesticides. The number of farms growing rice is restricted because there is limited water available for irrigation. Due to the increasing demand and competing water uses, state and federal governments have established policies to control the allocation of water to all users and to meet necessary environmental requirements. The ability of the soil to pond water without excessive accessions to the groundwater or environmental effects to other lands are factors considered in approving areas of a farm suitable for rice production. The drainage water from paddy fields is recycled to maximize the utility of irrigation water and minimize off-farm effects of the irrigation system. Soil salinisation due to rising water tables in the rice-growing areas is a major concern for the rice based farming systems in the region. Other concerns include the volume and chemical composition of drainage waters, breeding of mosquitoes and bird control. To reduce water requirements of the rice crop, researchers are trying to shorten the growth duration and increase cold tolerance of the crop to minimize ponding duration.

Pakistan

The cultivated area in Pakistan is about 20 Mha of which more than 16 Mha are irrigated. About 11 Mha of the irrigated area (i.e. 73 % of the total) is situated in Punjab Province which is in the rice-wheat agro-ecological zone of Pakistan.

The Indus Basin Irrigation System in Pakistan is the largest integrated irrigation system in the world. This irrigation system diverts approximately 123 BCM of annual river flow and spreads it over 13.5 Mha of cultivable land, of which nearly 9 Mha can be irrigated throughout the year. This controlled distribution is accomplished by means of 17 barrages and canal diversion works, 42 major canals, 6,000 km of minor canals, 600 km of link canals, and 78,000 watercourses. The total capacity is nearly 7,000 m^3/sec. This flow is supplemented with over 150,000 tube wells, which pump 24.5 BCM/year from groundwater. Rice cultivation in Pakistan is concentrated in the central Punjab and north-western districts of Sindh, where both surface and groundwater irrigation systems are well developed. Basmati rice is the principal cash crop in the Kharif (summer) season and wheat in the Rabi (winter) season. Rice occupies about 25 % of the cultivated area in the summer monsoon season and 10 % of the total cropped area. Wheat, being the staple food, occupies 75 % of the cultivated areas in the winter season and about 38% of the total cropped area. Pakistan is among the four major rice-exporting countries, but produces only 5 million tons compared to Bangladesh (34); Myanmar (21); India (132); Japan (11); Philippines (13); Thailand (26); Vietnam (32); China (182) and the world (581 Mt). In Pakistan, rice transplanting coincides with the onset of monsoon rains, which meet the major portion of the rice water requirement. Pakistan has a huge potential to increase rice growing on a large scale due to its relatively level terrain, heavy soils with good water holding capacity, sunny days, appropriate climatic conditions and abundant supply of farm labour. Unfortunately, inadequate supply of irrigation water at critical times of growth, lack of drainage, saline and sodic soils, low quality seeds, antiquated farm implements, imbalances in farm inputs, unsatisfactory agriculture and irrigation practices are major constraints limiting rice area growth and generally crop production in Pakistan. Since the introduction of canal irrigation, waterlogging and soil salinity have become the major problems impeding agricultural growth and development.

China

Asia produces 90 % of the world's rice in a climatic zone which can have an annual precipitation of more than 1,500 mm. China is the major rice producing country having about 30 Mha under rice paddy cultivation with a total rice yield of 190 Mt, which is 32% of world rice production. China has a long history of irrigation. Two thousand years ago, the world-famous Dujiangyan irrigation district in Sichuan Province was built and remains in use after many periods of rehabilitation and modification. With a current irrigated area of 670,000 ha it is a highly developed economic centre of great importance to China's food production. In 1949, the irrigated area of the whole country was 16 Mha accounting for only 16% of the country's farmland, and the per-capita food consumption was 209 kg. Development in the last half century has resulted in the irrigated area growing to 53 Mha, accounting for 40% of the farmland, and the per-capita food consumption was 400 kg by the end of 1998. The total water use for irrigation gradually increased from approximately 100 BCM in 1949 to 358 BCM in 1980, after which it stabilised. Irrigation water use has been stable since 1980. Industrial and municipal water use has increased rapidly and reduced the proportion used in irrigation to 92, 80, and 65% in 1949, 1980 and 1997, respectively. The efficiency of irrigation water use and the production efficiency have progressively risen over the past several decades, especially since 1980. The average water use for irrigated agricultural was 875 mm in 1980 decreasing to 780 mm in 1997. The average specific food yield during the same period increased from 0.6 kg/m^3 to 1 kg/m^3.

Rice contributes over 39% of the total food grain production in China from 31 Mha (28% of 113 Mha which is the total agriculture area). In 1999, the total rice yield reached 200 Mt, which accounts for 39% of the total national grain production of the country (Editorial Committee of the Year Book of Chinese Agriculture, 2001). Before the 1970s, the traditional irrigation regime for rice was "continuous deep flooding irrigation". Under this regime, a low yield of rice was obtained with a large amount of water. As the industrial, urban and rural domestic water consumptions have increased continuously, there are less water resources available for irrigation year by year. These pressures on the water supply are similar to those experienced around the world and have raised the importance of water worldwide. Recognising the need to improve both water and land productivity China has introduced a Water Efficient Regimes programme (WEI) for their rice industry. Since the introduction of the programme in the 1980s many regions have adapted one of the three WEIs:

- S.W.D. Combining shallow water depth with wetting and drying
- A.W.D. Alternate wetting and drying
- S.D.C. Semi dry cultivation

By 1997, 5.7 Mha had been converted to one or other of these systems (Mao 1997; Peng et al. 1997; Mao and Xu 1998; Li 1999). A reduced environmental impact has been claimed for each method.

Climatic, water balance and hydrological comparison of three subsystems

The key water balance components are compared for three irrigation areas, viz., Murrumbidgee Irrigation Area (MIA), Rechna Doab (RD) and the Liuyuankou Irrigation System (LIS). The MIA has an arid climate with low rainfall whereas Rechna Doab and LIS both receive considerable rainfall. In all cases rainfall is clearly below potential evapotranspiration. Rainfall and Penman-ET for the three areas are presented in Figure 1.

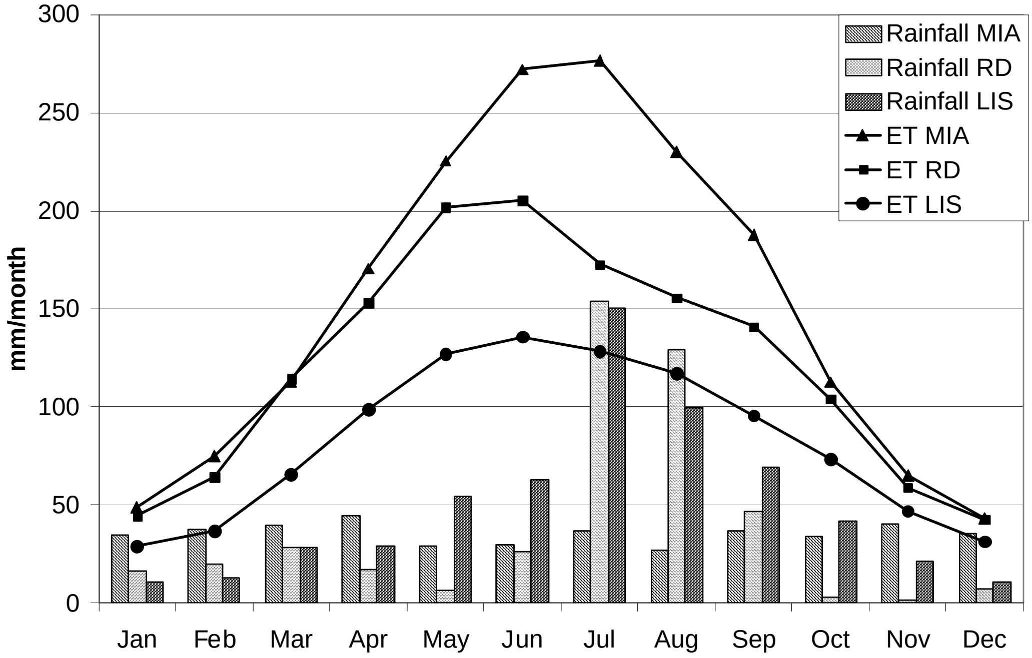

Figure 1: Rainfall and potential ET (calculated according to the Penman Equation)
For ease of comparison, the MIA's July-December and January-June Rainfall and Penman-ET have been transformed as January-June and July-December respectively.

Australia – the Murrumbidgee Irrigation Area

The Murrumbidgee Irrigation Area (MIA) is situated in the central New South Wales region of south-east Australia. Irrigation suitability studies were undertaken along the Murrumbidgee River in the 1890s, with development taking place between 1906 and 1913. By 1914, there were 677 farms in the MIA. Water was supplied by the first major reservoir built for irrigation – Burrinjuck Dam, which was completed in 1924. Rice growing started in the MIA in 1924, although rapid development of rice areas occurred in the 1970s and 1980s. The total area for the MIA is 156,605 ha and the main agricultural products are rice, grapes and citrus. Rice is the most dominant water user with more than 32,000 ha (14 % of the total landscape) in 2000. Irrigation demand for crop production is mainly met by water drawn from the channels and less so by groundwater pumping. A simplified average annual water balance of the MIA is presented in Figure 2.

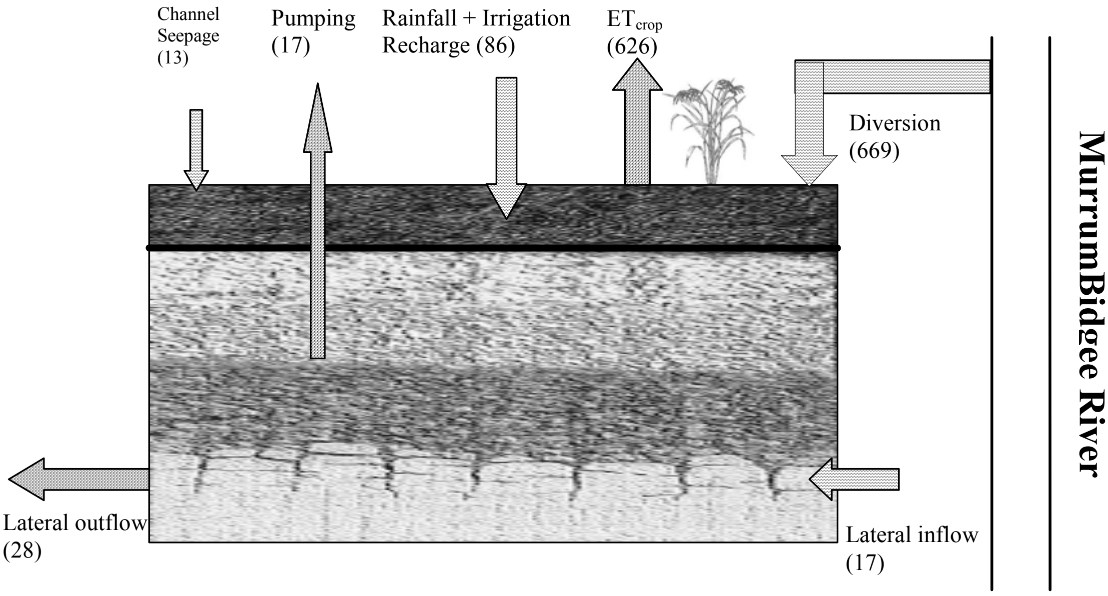

Figure 2: Lumped water balance of MIA [MCM] (period 1995-2000)

These inputs and outputs have been aggregated from a spatial model (750m grid) of the MIA to provide a lumped water balance for discussion in this paper. From the point of view of overall sustainability, it is

necessary to consider total flow to and from the aquifer system in relation to total lateral outflow potential of the system. If there is continuous accumulation of flows and salts then the area will eventually become waterlogged and salinised. This has already happened in many of the horticultural areas, which have been under an intensive irrigation regime for 60 years and therefore needed artificial drainage.
The total (lateral+ pumping) outflow of the aquifer, within the considered spatial boundaries of the system, is less than the total (vertical recharge and lateral) inflow to the aquifer. If these trends continue the groundwater pressure will rise and overall rate of soil salinisation will increase. This will result in substantial yield decline over time, environmental degradation within and outside the area, depreciation of natural capital and therefore a corresponding reduction in water use benefits from the system. For long term sustainability of this system there is a need to export salts from the area by establishing surface and subsurface drainage.

China – the Liuyuankou Irrigation System
The Liuyuankou Irrigation System (LIS) is located in Kaifeng County in the Chinese province of Henan and has been operational since 1967. The major crops are maize, rice and cotton. Eight branch channels were constructed between 1984 and 1988. Irrigation for crop production is met by water drawn from the channels as well as by groundwater pumping. During recent years irrigation conditions have become more efficient due to the improvement and maintenance of the hydraulic structures. In spite of this improved efficiency and the presence of a drainage system, the groundwater table has risen alarmingly. In the northern part of the LIS the groundwater tables are very shallow, within 1 m of the land surface. The lateral outflow of the aquifer is very small compared to the total inflow of water (within the considered spatial boundaries of the system), a significant amount of the irrigation water leaves LIS through fallow evaporation and crop transpiration. An overview of the average annual water balance for the shallow aquifer is given in Figure 3.

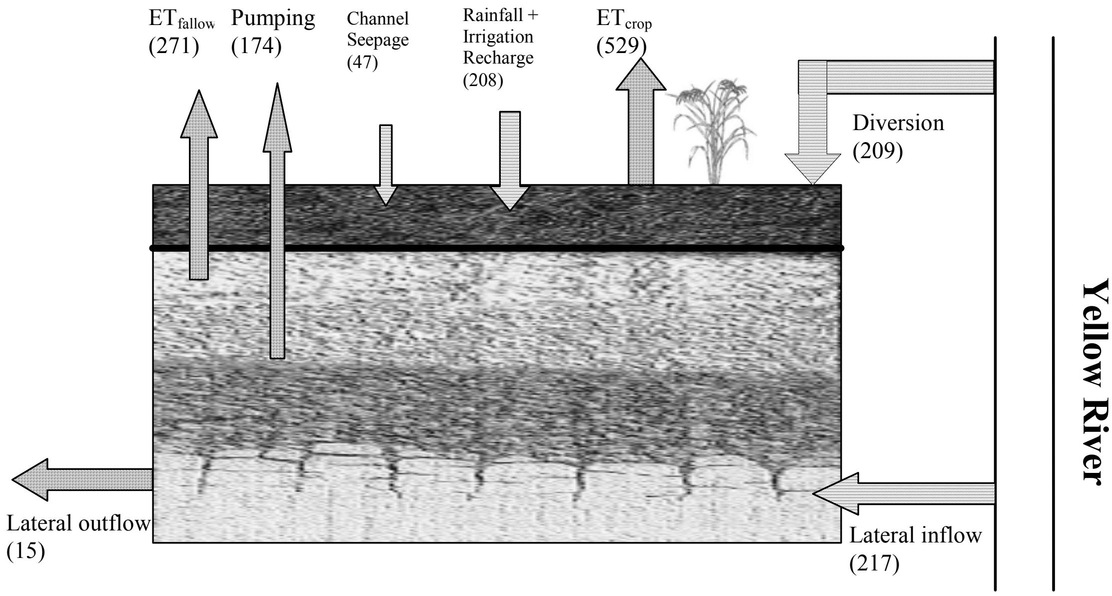

Figure 3: Average water balance of LIS [mm] (period 1981-2001)

A significant component of the overall water balance is the large lateral seepage from the Yellow River, which equates to an overall water supply of a similar order to the surface diversion. This is attributed to greater hydraulic conductivity of the aquifers and the height of the Yellow River above the surrounding plains. The lateral outflow from the aquifer, within the considered spatial boundaries of the system, is very small compared with the total vertical recharge and lateral inflow to the aquifer. The groundwater aquifer is already full and there is risk of soil salinisation if hydraulic loading due to rice is reduced as it is mainly responsible for pushing salts down through the aquifer system. Since the overall outflow is very small this area is a net salt sink and is recycling these salts through the system by groundwater pumping. This feature of the system could cause substantial yield decline in the future. There is need to change groundwater pumping to shallow watertable areas and introduce more surface water supplies in the present groundwater-dependent areas.

Pakistan – the Rechna Doab

The Rechna Doab ("land between two rivers") is the interfluvial sedimentary basin of the Chenab and Ravi rivers in Pakistan. It is one of the oldest, agriculturally-richest and most intensively-populated irrigated areas of Punjab Province. Irrigation water is pumped from the aquifer and drawn from the rivers. The gross area of Rechna Doab is 2.97 Mha, with a longitudinal extent of 403 km and a maximum width of 113 km. The area falls in the rice-wheat and sugarcane-wheat agro-climatic zones of the Province, with rice, cotton and forage crops dominating in summer, wheat and forage in winter. In some parts, sugar cane is also cultivated as an annual crop.

The water balance of the upper and lower zones of Rechna Doab indicates a reduction in groundwater storage in the upper and the lower zones (Figure 4).

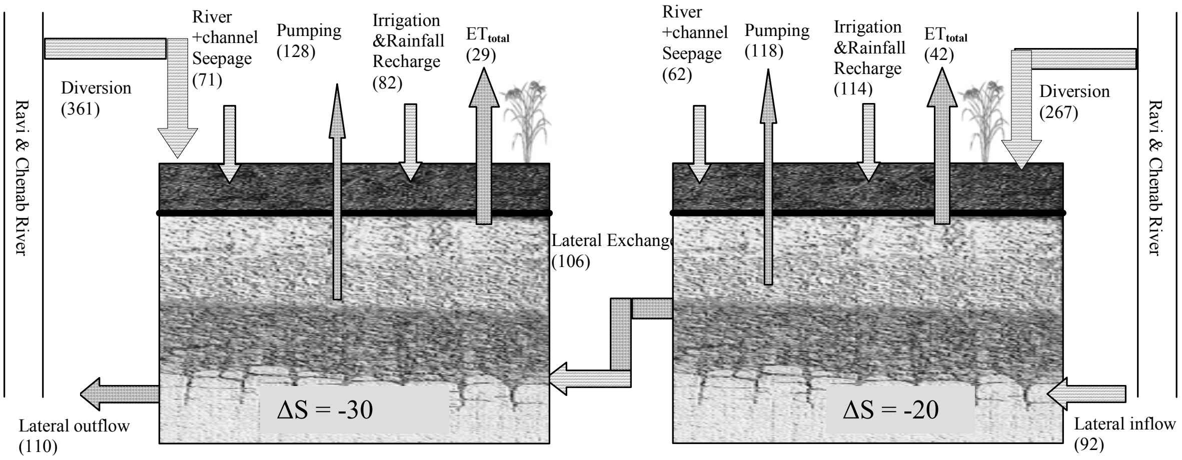

Figure 4: Lumped water balance (1993-2000) of the upper (right) and lower (left) zones of Rechna Doab [MCM]. ΔS is the change in groundwater storage.

In the upper part of Rechna Doab a significant amount of surface water is used for irrigation. Relatively low volumes of surface water are available in the lower part of Rechna Doab, therefore crop demand is met to a larger extent by groundwater pumping. The declining groundwater levels in the lower part of Doab are reducing profitability as costs for pumping groundwater increase (Figure 5). In contrast to the upper Rechna Doab, there is no evaporation from fallowed soil in the lower Doab. However, salinity is a bigger problem there because the groundwater used for irrigation contains increasing concentration of salt in water leached water below the root zone of crops. Larger scale drawdown of the watertable in the lower part of Doab is also promoting lateral flow of saline groundwater from its central part.

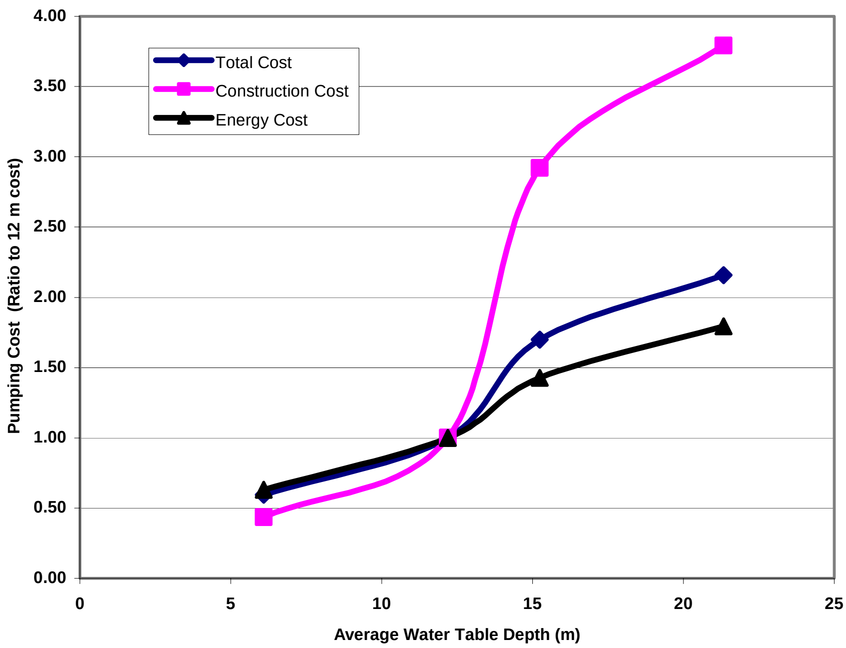

Figure 5: Increase in the cost of GW pumping with decline in watertable

Comparison of Water Use Efficiency of the three Systems

Table 1 provides a comparison of the surface water efficiency of the three irrigation systems. It reveals that the surface water efficiency is lowest for the Rechna Doab and LIS irrigation systems where only 32 to 47 % of the total surface water are made available to crops. In the MIA the efficiency is over 77 %. This difference can be explained by relatively heavy soils and disconnected aquifer systems underlying the MIA where hydraulic conductivity of the shallow soil horizons can be less than 0.01 m/day and the depth averaged shallow aquifer conductivity (top 30 m) is less than 1 m/day. In the Rechna Doab and LIS areas the soil hydraulic conductivities are higher (more than 0.1 m/day) and aquifer systems are continuous with shallow aquifers (top 30 m) with hydraulic conductivity of 10-100 m/day. The higher hydraulic conductivities combined with lower groundwater salinities (less 1000 µS/cm) enables reuse of "losses" from LIS and Rechna Doab systems through groundwater pumping. Lower hydraulic conductivities and higher groundwater salinity (2,000 to 20,000 µS/cm) means reuse of losses from MIA is not viable or sustainable in most locations.

Table 1: Surface Water Irrigation Efficiency

Key Indicators	LIS	Rechna Doab	MIA
Area (ha)	40,724	2,970,000	156,605
Losses from Supply System %	35	41	12
Field Losses %	18	15	11
Net Surface Water available to crop %	46	32	77

Table 2 presents a comparison of water loss components in the three systems. The greatest losses from irrigation channels and fields occur in the Rechna Doab (248 mm, 98 mm) respectively. In case of the LIS surface irrigation is only supplementary, with 98 mm required to meet crop water requirement of over 530 mm. The relative surface water efficiencies of three systems are summarised as the ratio of net crop water requirements (ETC_{net}) and net surface water availability (net SW Ratio). The MIA has the lowest ETC_{net}/SW ratio indicating net crop water requirement is mainly met by the surface water supplies. Whereas LIS has the highest ETCnet/SW ratio of over 5 indicating that it is strongly dependent on groundwater seepage from the Yellow River and shallow groundwater pumping and root water uptake.

Table 2: Water Balance (MCM)

Flow Term	**LIS (Area 40,724 ha)**		**RD (Area 2,970,000 ha)**		**MIA (Area 156,605 ha)**	
	(MCM)	(mm)	(MCM)	(mm)	(MCM)	(mm)
Canal Water Diverted	85	209	18639	628	1048	669
Main Canal Losses	30	74	7380	248	125	80
Net Distributed	40	98	8981	302	923	589
Conveyance and Field Losses	16	39	2903	98	115	73
Net Surface Water Available to Crops	40	98	6078	205	808	516
Net Crop Water Requirement ETC_{net}	216	530	13577	457	981	626
Groundwater Requirement	176	432	7626	257	173	110
Net Pumping	71	174	7304	246	26	17
ETC_{net} /Net SW Ratio	**5.4**		**2.2**		**1.2**	

Table-3 summarises the components of net crop water requirement supplied by surface water, groundwater pumping and direct root water uptake. The dependence on groundwater pumping and direct root water uptake is highest in the LIS. In the case of Rechna Doab the groundwater pumping supplies over 50% of the total crop water requirements. The shallow groundwater uptake by crops is only 11 mm/yr which indicates the groundwater is relatively deep due to excessive groundwater pumping. Higher groundwater use combined with lower leaching fractions may cause soil salinisation in the Rechna Doab. In the case of MIA around 15 % of the crop water requirements are met by direct root water uptake from the shallow watertables. This situation is not sustainable in the long run due to the risk of salinisation of soils from higher groundwater salinity (2,000 to 20,000 µS/cm).

Table 3: Water Components for Crop Production

Water Component	LIS (mm/yr)	*Percentage*	Rechna Doab (mm/yr)	*Percentage*	MIA (mm/yr)	*Percentage*
Net Crop Water Requirement	529	*100*	457	*100*	626	100
Net Surface Water Availability	98	*18*	205	*45*	516	*82*
Ground Water Pumping	174	*34*	246	*53*	17	*3*
Spatial Average of Shallow Water Uptake	258	*48*	11	*2*	93	*15*

Conclusions

The challenges faced by present day irrigated agriculture are not much different to those faced by ancient agricultural systems such as those of Mesopotamia. A close examination of the water balance components of three irrigation systems in Australia, China and Pakistan show that surface water efficiency is highest for the Murrumbidgee Irrigation Area (over 77 %) whereas surface water efficiency of Rechna Doab in Pakistan and LIS in China are less than 50 %. All these systems are dependent on direct or indirect use of groundwater. The direct shallow groundwater uptake by crops is very high in the LIS and MIA. If the direct groundwater use by crops continues in both the MIA and LIS, it will accelerate the rate of salinisation of soils. In the case of Rechna Doab more than 50% of crop water requirements are met from groundwater pumping which may result in salinity and sodicity unless adequate leaching of the root zone is not maintained. A key question for systems such as Rechna Doab and LIS is whether it is more cost effective to reduce seepage from channels or to pump groundwater.

There is a need to quantify regional water quality trends, downstream environmental impacts and the trade-off between yield reduction and direct regional groundwater use by crops in these systems. We can maintain the productive function of any of these areas by providing adequate drainage and salt export facilities, which have high energy and capital requirements. The most cost-effective option may be to increase water use efficiency and reduce negative impacts on the environment thereby reducing the associated costs of maintaining our natural capital. There is a need to radically rethink sustainability of food production, rational pricing and sharing of water and commodities to justify investment that will maintain and enhance ecosystem function within irrigated catchments. Under present operational conditions none of the three systems discussed in this paper is sustainable.

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