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Land and water systems: managing the hydrological risk

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Abstract

The paper suggests that the expansion of irrigated agriculture in the 20th century has de-coupled the water user from the inherent risk of exploiting both surface and groundwater resources. The apparent reliability of storage and conveyance infrastructure and the relative cheapness and flexibility of groundwater exploitation offered by mechanised drilling and pumping have sheltered the end user from natural hydrological risk. The imperative for in-field irrigation efficiency has been effectively removed since the physical and economic management of the resource is determined by command area authorities or, in the case of some groundwater pumping, by the performance of power utilities, who have no direct interest in integrated resource conservation. As a result, the resource base has been degraded, and in some cases irreparable damage has occurred. It is argued that the rigidity of the resource management in many irrigation systems is not attuned to the inherent variability of natural systems upon which they depend. Further, the paper argues that irrigation management systems can work toward sustainability by spreading risk equitably, and transparently, amongst the resource regulators, managers and users. This has to involve a much more flexible approach to natural resource management that is conditioned not only by natural parameters, but also by the socio-economic settings. A range of examples highlights the variability and scale issues involved. © 2000 United Nations. Published by Elsevier Science Ltd. All rights reserved.

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1. Introduction

The cascades of surface and groundwater have been modified across cultivated landscapes in both irrigated and rain-fed agricultural systems to minimise perceived hydrological risks. Often water is seen as a prime input to agricultural production, rather than a pervasive environmental agent that is responsible for the character of soil weathering (that occurs both in the unsaturated and saturated zones) and for the flux of soil chemicals and nutrients. Despite the water 'crisis' rhetoric that abounds these days, and the assertion that irrigated agriculture is responsible for using too large a proportion of the available water resource base, it is very hard to generalise in such categoric terms. The nature of the 'crisis' is very much conditioned by the nature of individual hydrographs, the patterns of soil distribution, aquifer responses, and local irrigation practices. Having said this, it is also possible to observe many medium and large scale irrigation schemes throughout the world that operate well below design capacities, which usually says something about the inherent variability of water resource base or competition from upstream users. Others operate at extremely low efficiencies, which is usually indicative of poor operation and maintenance. However, it is not proposed to look in detail at these apparently inefficient uses of water by irrigation schemes. This is better done by more specific regional assessments (e.g. FAO, 1999; ESCWA, 1999). Rather, the question that will be asked here is how flexible have land management and irrigation strategies been in relation to the inherent hydrological variability and environmental limitations of land and soil–water systems. In so doing, the article reviews who is exposed to risk and what risk management procedures are in place.

1.1. The nature of hydrological risk and the need for flexibility

In general terms, irrigation services attempt to deliver additional water to maintain soil moisture levels, while water and soil conservation measures in rainfed systems attempt to maximise soil moisture storage and shallow groundwater circulation. In all continents, traditional approaches have developed that have been adapted to the local realities of water availability, drainage, soil fertility and technology. It could be argued, however, that the advent of large scale surface water storage structures, mechanised

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boreholes, cheap fertilisers and pesticides in the mid-20th century may have given irrigated agriculture a false sense of security, despite being responsible for the 'Green Revolution'. Even when the technology has been available, notoriously 'conservative' farming communities have been slow to respond and apply new techniques to conserve water and the integrity of the soil systems.

With small-scale traditional systems, individual farmers and collective groups undertook management of the hydrological risk, and systems were adapted to local conditions. Without large-scale storage structures and mechanised boreholes, the buffering of drought events through over-year storage and the exploitation of shallow groundwater was generally limited. Exceptions could be found in Asia and the Middle East, where larger aquifer systems have been exploited through gravity *karez* systems. This situation changed in the 20th century as technology advanced to allow rapid construction of large dam structures and the drilling and pumping of large diameter, deep boreholes. Large irrigation command areas such as the Indus irrigation system in Pakistan were built. In Africa, the Sahelian zone dams in Senegal, Mali, and Nigeria were constructed, and downstream wetlands were subjected to artificial flow regimes. While the new infrastructure offered new opportunities and raised agricultural productivity, the nature of risk management changed. Farmers who may have relied on traditional water harvesting or recession agriculture, no longer had to manage risk themselves; this was left to the resource managers operating the new infrastructure. In this sense the creation of command areas immediately reduced the flexibility of local risk management by individual users.

At the same time, the advent of mechanised boreholes on all continents allowed individual farmers and water user associations to expand irrigation in dry zones and essentially defer the risk. As aquifers have become progressively dewatered, the evidence from well fields ranging from Senegal to Saudi Arabia to the north China Plain to the United States of America indicates the short-term luxury of apparently dependable groundwater resources. In the case of the well-documented Ogallala aquifer in the High Plains (USA), Kromm and White (1992) note that, even with remedial measures in place, the farming systems cannot be assured for more than two more generations. More interestingly, the mechanised borehole has allowed individual farmers to build back flexibility and ameliorate drainage problems in surface water schemes where canal systems have are not operated equitably and/or have induced local water-logging. The creation of informal water markets to distribute the advantage of groundwater within command areas (Shah, 1993) is further evidence of the need to build in as much flexibility as possible.

While individual farmers have benefited and domestic productivity has been enhanced, the general tendency has been to expect assured inputs of water and assured soil fertility from systems that are inherently risky, and for users to be risk averse without being directly responsible for managing the risk.

Managing hydrological risk involves not only coping with the extreme events driven by climatic variability, floods and low flows (the conventional 'stochastic hydrology' in Kottegoda, 1980); but also involves dealing with the day-to-day increments of flows, abstractions and releases, and pollution loads. Coping with flood and drought events is dependent upon the flow of good hydrometeorological information from data collection agencies, to expert agencies carrying out analysis and finally to the public institutions, authorities and communities who are responsible for implementing flood protection and drought mitigation measures. In the case of flood events, this information flow has to occur in real and near-real time. For drought events, the analysis and tracking of daily data are essential, even in humid regions. Therefore, investment in information collection, analysis and dissemination systems is as critical as establishing a strong institutional framework in which vital tasks are clearly mandated. At the limit of the resource base and in times of crisis, disputes and arguments over who is responsible for what will only result in lost livelihoods and economic opportunities. It should also be recognised that hydrological risk is manifest in financial, economic and public health/safety impacts. But while the financial risk of events presented by meteorological and hydrological time series may be managed by commercial utilities (such as power utilities buying weather derivatives), the broader economic and public health/safety risks of managing water resources do not offer the same potential for hedging risk. Equally, the rates at which hydrological processes move across and through soils and the degree to which water quality and quantity are conditioned by in situ soil properties, make any modification of natural wetting and drying cycles and soil structure (and the application of fertilisers and pesticides) an inherently risky business whose outcomes cannot always be appreciated or determined. Under these circumstances a clear understanding of the risks involved in managing land and water resources is warranted in order to make the case for the equitable and transparent spread of hydrological risk.

This paper will take two specific river basin examples in Swaziland and China to examine this tendency and assess the implications for sustainable agricultural systems from the point of view of a risky environment, and for spreading the risk through technological/operational management and institutional adaptation. Other brief cases include the impact of rural energy supplies and groundwater in India, and land and water interaction in Pakistan and eastern Australia.

2. Usutu sub-basin, Swaziland

The case of the Usutu sub-basin in Swaziland illustrates how even contemporary feasibility analysis (GFA-AGRAR, 1998) can fail to include the essential detail of hydrological

Table 1
Characteristics of Usutu sub-basins in Swaziland (*Source:* United Nations, 1999a)

Sub-basin	Total Area (km^2)	Area in Swaziland (km^2)	Altitude range (m)	Mean annual rainfall (mm)	Mean annual runoff (MCM per year)
Little Usutu River Basin	1389	1104	150–1000	900–1200	681.18
Upper Great Usutu River Basin	3377	821	400–2000	800–1000	231.24
Ngwempisi River Basin	3571	1121	400–1500	800–950	225.02
Mkondo River Basin	3894	1220	250–1500	800–950	217.02
Great Usutu River Basin	4466	4146	400–1500	650–900	280.64
Subtotal	16.697	8412			1635.1
Ngwavuma river Basin	1502	1495	250–1250	550–800	155.19
Subtotal	1502	1495			155.19
Combined total	18.199	9907	150–2000	550–1200	1790.29

risk A joint paper by the United Nations Department of Economic and Social Affairs (UN-DESA) and the Food and Agriculture Organisation of the UN (FAO) (United Nations, 1999a) concluded that the competing agricultural demands in the basin could not be reconciled without a much more pro-active approach to hydrological risk management.

2.1. The natural resource base and hydro-environmental limits

The Usutu sub-basin comprises Swaziland's portion of the Maputo basin, shared between South Africa, Swaziland and Mozambique. The characteristics of Usutu sub-basin in Swaziland are shown in Table 1 and Fig. 1, with details of gauging stations shown in Table 2 and Fig. 2. Usutu sub-basin at the Mozambique border has an area of 16,697 km^2 and an estimated mean annual runoff (naturalised) of approximately 1635 MCM per year. The Ngwavuma sub-basin has an area of 1502 km^2 and a mean annual runoff of 155 MCM per year. For both sub-basins, with mean annual rainfalls in the region of 800 mm, only 100 mm, or some 12% of annual rainfall, appears in river flow at the border

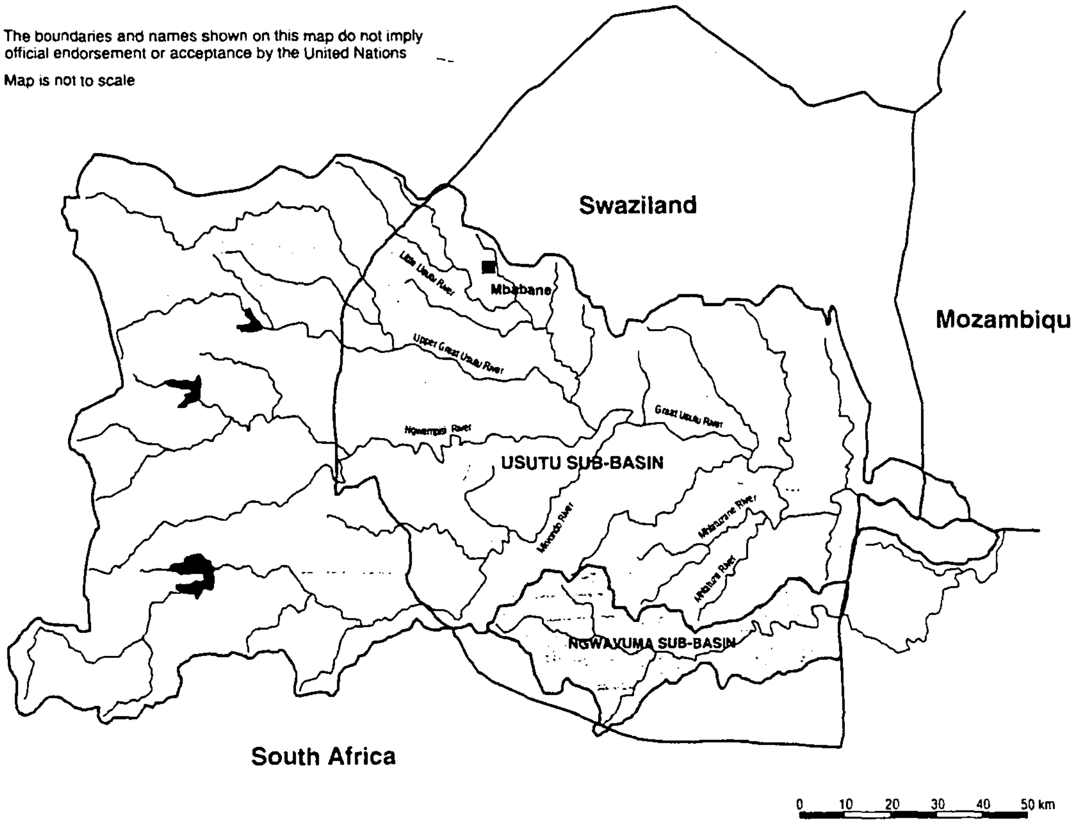
The boundaries and names shown on this map do not imply official endorsement or acceptance by the United Nations
Map is not to scale

Fig. 1. Usutu and Ngwavuma sub-basins (Maputo Basin).

with Mozambique. These mean statistics for the sub-basins as a whole, mask considerable seasonal and inter-annual variability. In addition, while there is generally good monitoring of river flows in the high and middle veld, there is no calibrated gauging section downstream of Siphofaneni (GS6). The impact and significance of water resource development in the basin will be most critical in the reach between Siphofaneni and Great Bend, where most abstractions currently take place and where the offtake (the proposed Bulungapoort weir) for a proposed smallholder irrigation project will be located. The regional and national significance of the Usutu and Ngwavuma needs to be appreciated when considering the resource availability within the Swaziland borders. These two hydrological entities make up 50% of Swaziland's territory, account for more than 50% of the overall national resource and provide water and soil resources for about 60% of the national population. For the purposes of this analysis, the Usutu sub-basin and Ngwavuma sub-basin in Swaziland will simply be referred to as the Usutu sub-basin.

The limiting factors for the development of any surface water resources in the Usutu and Ngwavuma sub-basin are the generally 'flashy' hydrological character of runoff events and the length of the dry season recession flows which can reach less than 25 m^3/s. Even near the bottom of the basin (at gauging station GS6), the short duration of peak flows during periods of summer rains, limits the reliability of abstractions. This hydrological risk is of particular significance for a proposed EU-funded smallholder irrigation scheme that aims to expand the smallholder cultivation of sugarcane and citrus. The feasibility study for the scheme based its positive findings on an analysis of monthly flows in the basin (GFA-AGRAR, 1998). Given the known flashy response of the Usutu basin and the knowledge of intense and persistent droughts in the region, the actual hydrological risk will have been severely under-estimated. Fig. 3 illustrates the nature of the flashy hydrology and the inter-annual variation in the Little Usutu River.

2.2. Water demand and socio-economic trends

Current (1993) and projected (2010) water demand in the Usutu sub-basin is dominated by irrigation (400/500 MCM) and commercial forestry[1] (120/130 MCM). The bulk of the demand is generated by irrigated agriculture. Part of this demand can be negotiated through improved irrigation efficiency and management. On the other hand, potable supplies and instream environmental requirements are non-negotiable at present levels of development. The present official figures on irrigation allocations by issued permits are 1200 MCM, far greater than the amount utilised. However, this has to be set against the mean annual runoff for the Usutu and Ngwavuma sub-basins (1635 and 155 MCM, respectively). While the service coverage for domestic water supplies is low, this can be expected to rise with increased demand for raw water. More significantly, national level demand for water in the basin is likely to rise by 180 MCM per year if the 11.500 ha scheme, proposed in the Feasibility Study for the Development of Smallholder Irrigation in the Lower Usuthu River (GFA-Agrar, 1998) is developed.

Rapid expansion of the national population (currently estimated at 950,000) and slower growth of jobs, is resulting in increased unemployment and social tension. While water management can address *some* basic social issues, this presumes an equitable allocation of the basin's resources and the means to regulate and conserve the already limited water resource base. Population in the Usutu sub-basins is expected to increase from about 500,000 currently to 2.2 million in 2050, indicating the scale of the issue.

2.3. Shared international waters

The surface water resources in Swaziland are located within and form part of the system of rivers that flow eastward from South Africa, where they originate, some through Swaziland to the Indian Ocean at Maputo Bay in Mozambique. The two main drainage systems are Inkomati Basin, with the Sabie, the Crocodile and Komati Rivers and the Maputo Basin with the Usutu and the Phongola rivers. The approaches taken toward negotiation of transboundary resources of any one basin need not prejudice the others. However, there are economies of transaction and scale that can be achieved by adopting common approaches at national level.

What is clear is that interbasin water transfers in South Africa affecting the Usutu sub-basin in Swaziland are significant and represent approximately 14% of the Usutu basin's yield (see Table 3). The extent to which the dams modify annual hydrographs and minimise (smooth out peaks) or maximise (reduce baseflows) hydrological risk downstream in Swaziland and Mozambique is not clear, but the abstractions do not reduce overall hydrological risk to irrigation downstream. The development is also indicative of the disparities in the opportunity cost of water across international borders. The degree to which these opportunity costs will change over time represents a level of economic risk in the basin.

The three riparian countries, South Africa, Swaziland and Mozambique, are all seeking to satisfy national water demands from the Maputo basin. There are no binding tripartite agreements on water sharing for the Maputo basin. In particular, the obligations in regard to the Maputo system, stemming from the South African Development Community (SADC) Shared Waters Protocol, will need further refinement at both the bilateral and trilateral level. This has to be done with a view to pinning down the prerequisites and requirements for harmonised action in

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[1] The 'demand' of commercial forestry is a debated subject since afforestation also has beneficial impact on the runoff distribution and enhancement of river low flows.

Table 2
Selected gauging stations and water years. *Source:* United Nations, 1999a

Gauge Name	Gauge No.	Sub-basin	Physiographic region	Area (km^2)	
Usushwana	GS2	Little Usutu	Highveld	1207	
Mankayan	GS5	Ngwempisi	Highveld	3189	
Siphofaneni	GS6	Usutu	Highveld/ Middleveld/ Lowveld	12.559	
Mkvondo	GS7	Mhkvondo	Highveld/ Middleveld	3608	
Lubili	GS8	Ngwavuma	Middleveld/ Lowveld	1305	
Bhunya	GS9	Great Usutu	Highveld	2681	
Sithubela	GS12	Mhlatuzane	Middleveld	366	
Siphocosini	GS15	Mhlatuze	Middleveld	585	
Madlenya	GS19	Mhlatuzane	Middleveld/ Lowveld	668	
Representative rainfall station	**Wet year Rainfall (mm)**	**Mean year Rainfall (mm)**	**Dry year Rainfall (mm)**	**Baseflow (m^3/s)**	**Baseflow (mm)**
482357	1971/1972 (1240)	1972/1973 (810)	1981/1982 (774)	3–7	78–183
482357	1971/1972 (1240)	1972/1973 (810)	1981/1982 (774)	6.5–14.5	64–143
482357	1971/1972 (1240)	1972/1973 (810)	1981/1982 (774)	50–100	126–251
482357	1971/1972 (1240)	1972/1973 (810)	1981/1982 (774)	11–31	96–271
409460	1971/1972 (846)	1972/1973 (729)	1981/1982 (500)	0.2–1	5–24
482357	1971/1972 (1240)	1972/1973 (810)	1981/1982 (774)	0.8–3	9–35
445863	1971/1972 (994)	1972/1973 (742)	1981/1982 (453)	0.2–0.8	17–69
482357	1971/1972 (1240)	1972/1973 (810)	1981/1982 (774)	1–2	54–108
445863	1971/1972 (994)	1972/1973 (742)	1981/1982 (453)	0.3–0.9	14–42

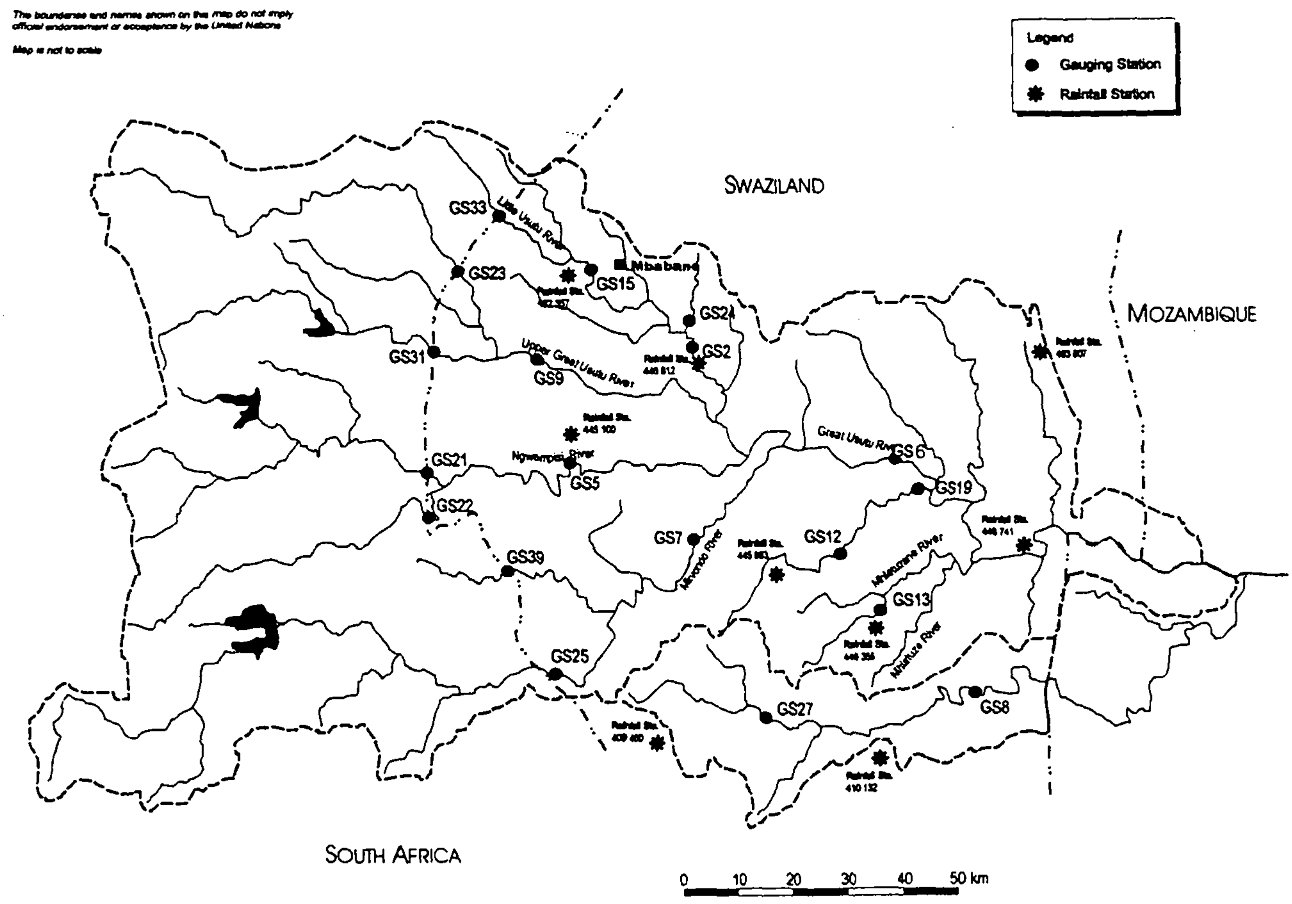

Fig. 2. Rainfall stations and stream flow gauging stations.

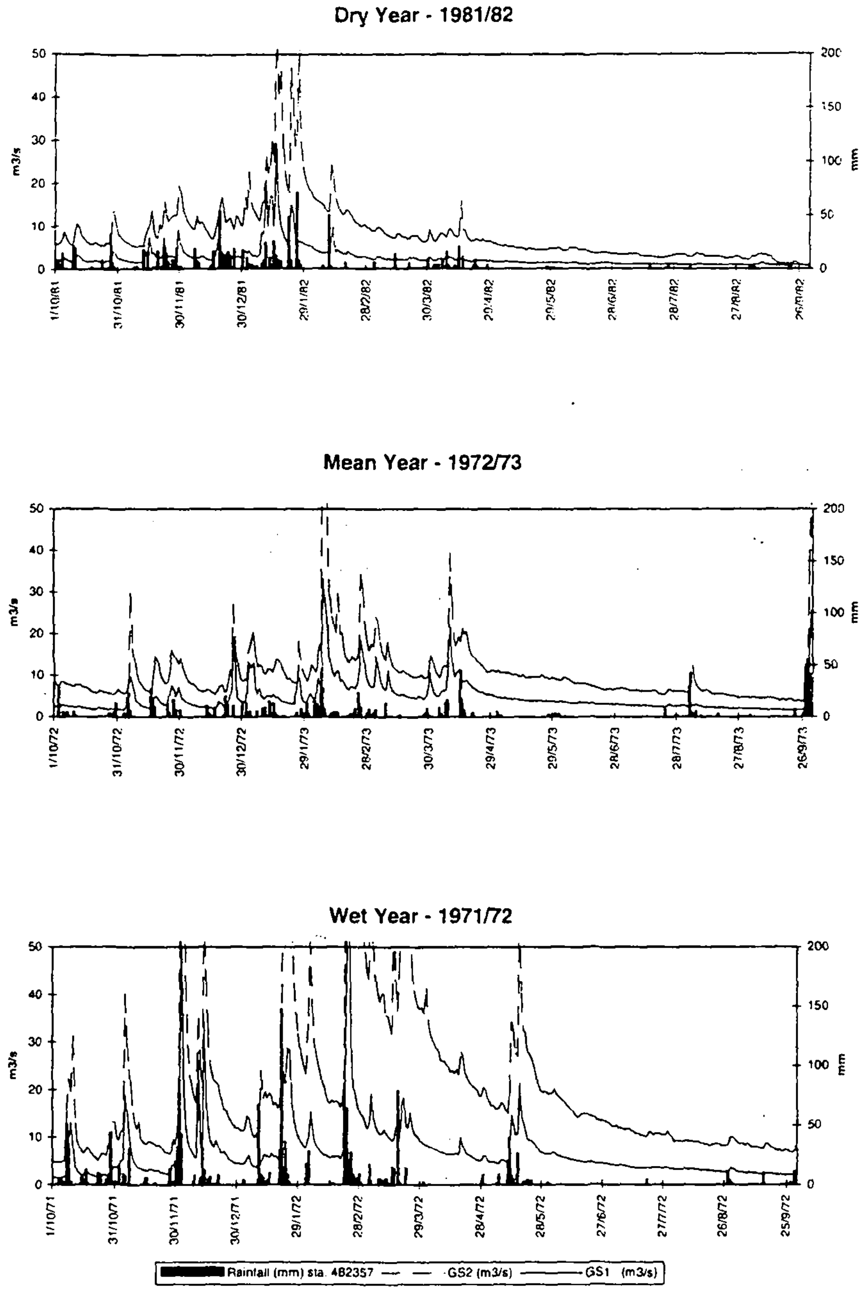

Fig. 3. Representative annual hydrographs: gauging stations GS15 and GS2.

response to the shared water resources management issues—notably, data collection and exchange, equitable apportionment of regulated and unregulated flows, investment development planning and control of pollution.

2.4. Implications for institutional development

The institutional implications of the present legislative and planning proposals in Swaziland are profound. With no water resource policy or planning guidelines in place, water resource management has had a low profile in the basin. Day-to-day water resource management is effectively determined by the principal users of the basins' water resources, not by an independent basin resource manager. This situation is tenable only if the users behave responsibly, through self-audit and regulation, and there is no competition for water. This is not the case in Usutu and Ngwuvuma sub-basins, where the allocation decisions have also to be determined by an economically strong upstream user, and the environmental and resource requirements of Mozambique still need to be agreed upon. The potential for licensed abstractions to exceed the available resource base is serious and can be expected to have significant social and economic impacts. The need to optimise

Table 3
South African interbasin water transfers. *Source:* United Nations, 1999a

Sub-basin	RSA DAM	Date commissioned	Volume Transferred (MCMper year)	Receiving Basin
Usutu	Westhoe	1980	40	Olifants
Usutu	Morgenstond	1980	20	Olifants
Usutu	Jericho	1983	70	Olifants
Assegaai/Usutu	Heyshope	1986	100	Vaal
Total			230	

the system in terms of quantity, particularly, is a pressing concern. but cannot be done without a capable and 'smart' basin agency to develop, agree and implement allocation rules and criteria on a day-to-day basis. In this regard, the basin agency will need to act as a manger of risk more than a passive regulator of water use licences. More importantly, the levels of hydrological risk need to be understood and accepted by the sectoral interests seeking to develop the resource base.

2.5. Implications for sustainable economic development

The economic productivity associated with the water resources of the Usutu and Ngwavuma basins is high, particularly given the present value of irrigated agriculture to GDP. If this stream of economic benefits and employment opportunities is to continue to be realised and the Swazi Nation Lands area under irrigation expanded, attention has to be paid to the economic optimisation of water allocation throughout the water year. This would point to the need for near real-time hydrometric monitoring and the constant supervision of abstraction/release rules.

One key issue is how to resolve the macro and micro-economic pressures that are building up in the basin. On one hand, there remains little economic incentive within Swaziland to optimise the use of water, either through comprehensive demand management, pricing policies or the use of tradable user permits. On the other hand, at the international level, the water resources in the basin as a whole are subject to highly variable economic values. The difference between the value of a unit volume of water in South Africa, where industrial and potable use priorities prevail, and a unit volume in Swaziland and Mozambique, where agriculture use prevails, is startling. Estimates for the opportunity cost of raw water in South Africa for the adjacent Incomati basin have been made as high as one Rand per cubic metre (approximately US$ 0.20/m^3). While each country would, in accordance with generally accepted principles, ultimately decide on the utilisation of its allocated share, any further development of the Usutu basin water, in particular, needs to be assessed against these competing demands and associated values.

The cross-border stream of economic and environmental benefits is equally significant, particularly for Mozambique. In the interests of regional co-operation, trade and joint economic development, there are clear economic and political incentives for engaging in transboundary negotiation with a view to optimised and harmonised allocation of the basins' resources. However, given the disparity in economic development among the three countries, the economic value and the derived opportunity costs for water along the course of the Maputo basin are highly variable. The value of a cubic metre of Maputo Basin water in South Africa, where it can be used to add value in power generation, industrial and potable supplies, is clearly going to be much higher than its value to produce economic output in Swaziland or Mozambique through irrigated agriculture.

3. Huaihe basin, China

The Huaihe basin in south-eastern China illustrates how the lack of clarity of mandates, roles and responsibilities amongst national and provincial agencies can block or thwart the implementation of a most elaborate set of policies and regulations. One of the conclusions of a recent study carried out by a United Nations group of experts (United Nations, 1999b) was that the physical and financial risk resulting from floods, droughts and pollution was neither perceived nor apportioned in a transparent manner.

3.1. Challenges facing the Huaihe river basin

3.1.1. The water resource base

The Huaihe river basin covers 270,000 km^2 (2.8% of China's land area) and contains an estimated population of 156 million. This makes the basin area one of the most densely populated in China. The basin straddles four provinces, Henan, Anhui, Jiangsu, and Shangdong, with 36 cities and 189 counties (Fig. 4). The mean annual water resource availability (surface water and recoverable groundwater) within the basin is estimated at 96 Bm^3 of which 74 Bm^3 (77%) is derived from surface water (Table 4). The remainder is derived from exploitable groundwater resources.

The average annual precipitation and mean annual runoff show wide variation along the basin, with the bulk of the rainfall and runoff concentrated in three months from June to September. The available records show a high dispersion of the annual water availability. The rainfall in a wet year is 30% higher than in a normal year and 210% higher than

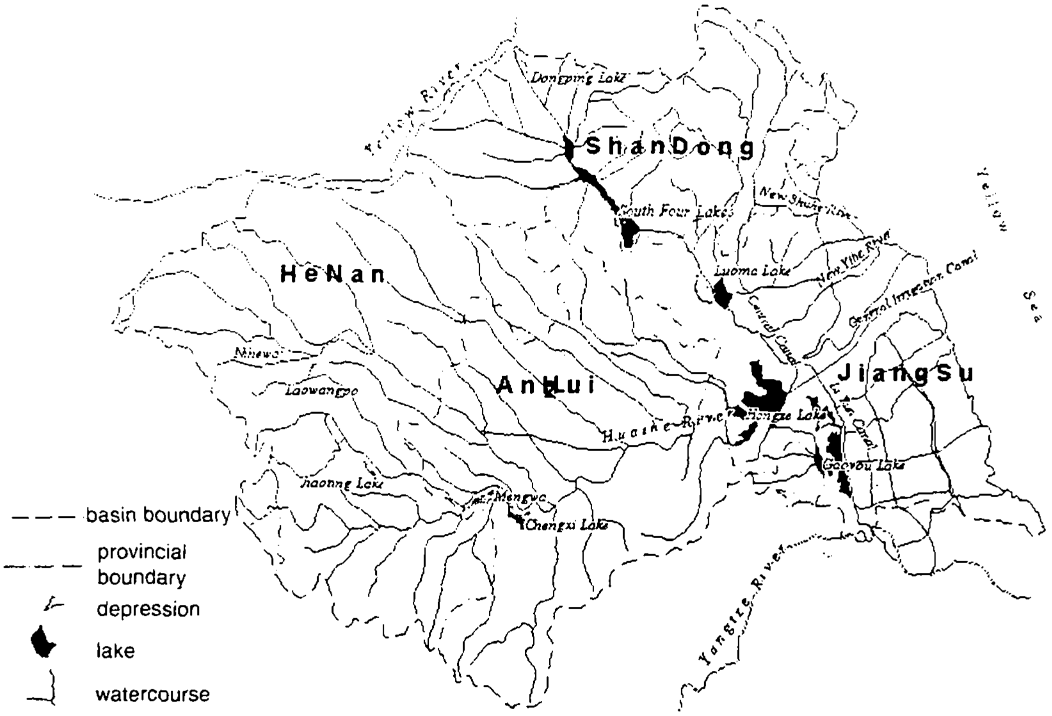

Fig. 4. Huaihe river basin.

that of a dry year. Droughts occur with a return period of four years and large floods caused by frontal storms and typhoons occur with return period of approximately 15 years. The hydrology of the basin is characterised by a marked attenuation and diffusion of sub-basin hydrographs, as flows progress across the basin through control structures and sluices. The volume of in-stream storage behind sluices and in dyked lakes is particularly significant. The hydrological water balance is heavily conditioned by the managed conveyance of water across the basin. The hydrogeology of the basin is characterised by a phreatic aquifer in the central portion of the basin with indirect recharge from watercourses and lakes and direct recharge from the percolation of rainfall. This drives a very shallow groundwater circulation system that is vulnerable to pollution.

3.2. Water utilisation: socio-economic driving forces

The Huaihe river basin accommodates 12% of the total population of China and generates over 8% of national GDP with less than 4% of the nation's land and water resources. Economic development is not spread evenly over the basin; the eastern portion of the basin is much more developed, with a much higher proportion of urban areas. Approximately 17% of the basin's population are estimated to live in urban areas, and this proportion is expected to increase significantly. This intensifying spatial disparity poses an allocation dilemma across the basin. With opportunity costs for water increasing downstream (to the east of the basin), there is little upstream incentive to use water efficiently unless water user rights can be transferred or traded downstream. Equally, downstream users cannot send a signal reflecting the higher opportunity cost upstream. This disparity is partially offset by the ability of downstream provinces, notably Anhui, to import raw water from the Yangtse. However, the externality produced by water quality deterioration that inevitably occurs downstream still has to be absorbed by the downstream provinces. This reduces productivity progressively across the basin from west to east.

Actual raw water use in the basin is estimated to have risen between 1980 and 1993 by approximately 10%, with over 70% of abstracted and diverted water accounted for by irrigation. The most recent estimate of actual and projected water use in the basin has been compiled by IWHR (1998). The figures for the Huaihe basin are presented in Tables 4 and 5, together with the MWR (1998) estimate of water use for 1997. It should be remembered that this type of aggregate management balance and projection is predicated on mean flow and recharge statistics. The use of water in the basin has been dominated by irrigated agriculture. The cultivated land area in the basin is currently estimated at 12.2 Mha. This area furnishes approximately 15% of the national grain output. However, it is important to note that with the same irrigated area and water consumption, the grain output almost doubled from 1980 to 1993, increasing from 40.4 to 73.6 million tons. This may point to a significant improvement in agricultural and irritation practices over a short space of time, but is probably due to the largely uncontrolled expansion of groundwater irrigation to supplement existing surface schemes. The industrial sector in the basin has been growing rapidly, increasing its output by a factor of six between 1980 and 1993, particularly in coal, electric power, textiles, machinery, chemical pulp and paper, tannery and building materials (Table 6).

The 1997 estimate indicates that approximately 50% of the available surface water resources of the basin are abstracted across the basin. The volumes of degraded water returned to watercourses and aquifers for downstream or down-gradient use are significant in terms of the overall hydrological balance. This rate of abstraction is typical of many industrialised basins. What is significant in the case of the Huaihe is the projected rate of conversion from agricultural use to urban and industrial use. The capital investment required for wholesale treatment of return flows is simply not available, so that integrated approaches to water quality management through progressive environmental and economic regulation become the only alternative. Equally it is probable that enhanced investment in operation and maintenance of existing infrastructure will do more to improve productivity and prevent environmental degradation than wholesale rehabilitation or new construction.

3.3. Water management in practice: evidence from the field

3.3.1. The pattern of abstractions

The abstractions are changing across the basin and intensifying as economic development prompts increasing levels of demand for water-related services. The spatial distribution of water abstraction and use (consumption and disposal) in the basin is changing and intensifying. This pattern remains partially understood, and its impact upon the resource base, and on the associated economic activity, is inadequately researched given the instrumental value of water in the basin. The economic trade-offs also become apparent when the relative position of each of the provinces is considered. The upstream provinces may be required to release useable water downstream, but if lower Anhui is able to import unconstrained amounts of water from the Yangtse, the incentive to maintain quality and quantity across the basin is weakened.

3.3.2. The role of storage

There are 5723 reservoir structures in the basin, with a combined storage capacity of 26.8 Bm^3. This represents approximately one third of the mean annual runoff generated in the basin. Meanwhile, the shallow and deep aquifers in the basin represent an important resource and storage potential, although understanding of groundwater systems as a whole is poor in relation to surface water systems. Water table depths are less than 6 m in 90% of the plain area, but concentrated abstraction, particularly in the vicinity of major cities, is inducing significant cones of depression, well interference and breakdown of leakage processes and aquifer configuration. Subsidence in urban areas is one symptom of this, but there are larger implications in the loss of water resource supply and management opportunities, particularly for conjunctive use with surface water. The regulation of groundwater development is therefore an immediate priority for the basin as a whole.

3.3.3. Reliance upon structural solutions

While the predominant approach has been supply oriented, demand management has made its mark. In irrigation, efficient water use is an important programme that is reported to have had significant impact during the last 15 years. However, the scope for demand management throughout all sectors has not been explored. It is probable that a more aggressive demand management programme would yield results if adequately financed. Of more significance is the maintenance of existing supply infrastructure. It is apparent that dam and embankment safety will need to be addressed and financed as a matter of priority.

3.3.4. Groundwater as a buffer

Groundwater has been the ultimate victim of development in the Huaihe basin. Groundwater abstractions (there are an estimated 781,000 drilled wells in the basin) appear to proceed and expand with no overall attempt to limit to known recharge rates, resulting in local subsidence and increased pumping costs. Pollution of aquifers from point and non-point sources and from transmission losses along watercourses is not checked or regulated in any systematic fashion. The legacy of rapid development, particularly in

Table 4
The water resource base in Huaihe river basin. 1956–1979 series. *Source:* MWR (1992)

Basin Area	270,000 km^2
Mean Annual Precipitation	800 mm
Mean Annual Runoff (MAR)	74 Bm^3
Net Groundwater recharge	39 Bm^3
Groundwater Component of MAR	17 Bm^3
Estimated Net Resource Availability	96 Bm^3

Table 5
Huaihe basin: water management balance. *Source:* For 1993 and 2050: IWHR, 1998; for 1997, MWR, 1998; for 1956–1979 mean, MWR, 1992

	Resource utilisation (total abstractions of raw water across the basin, in Bm^3)		
	1993 base year	1997 estimate	2050 projection
Surface sources	44	47.9	45
Groundwater	20	18.5	22
Total	64	65.7	67
Net water resource 1956–1979 mean	96		

Table 6
Projections for raw water abstraction. *Source:* IWHR. 1998

Year	Use (Bm^3)					
	Urban	Rural	Industrial	Irrigation	Forestry	Total
1993	1.7	4.0	7.2	53.0	3.2	69.1
2020	8.5	5.3	19.5	48.0	3.7	85.0
2050	12.0	4.5	23.5	47.0	4.0	91.0

the low gradient groundwater flow systems in the eastern part of the catchment area. are a set of shallow aquifers that are irretrievably lost. The utilisation of the basin's deeper groundwater resources is even more ad hoc. Well fields are developed to service urban areas, but without any borehole catchment protection, and aquifers are pumped to exhaustion. Individual boreholes in rural areas are similarly unprotected, but are pumped at lower abstraction rates. There is an indication that for mitigation of the effects of drought it is necessary to rehabilitate and protect strategic boreholes and wells. Indeed, during drought events, a systematic 'race to the pump-house' can be observed. Most of the wells are reported to be out-of-date and in need of rehabilitation. In future, the conjunctive use of surface water and groundwater will be essential to mitigate the effects of dry years. It is probable that, in additional to direct recharge from rainfall, there is significant indirect recharge to the shallow aquifer from irrigation canals and infiltration in the irrigated areas.

3.3.5. Poor optimisation of resource use

It is evident that water is intensively managed within the basin and the landscapes of the basin are indeed determined by irrigated agriculture. In general, the Huaihe basin gives the impression of an ordered control of water across the landscape. But behind such apparent order, there is in fact a haphazard and often conflicting set of water operations. This is particularly the case during low flows where the operation of water diversions and storage structures is whimsical, at best, with no co-ordinated operational plan at basin scale. Counties and municipalities vie with one another for access to stored water, sometimes in accordance with their established water user rights but more often on the basis of prior appropriation or political leverage, particularly if upstream users or municipalities are involved. It is clear that operational plans and release rules on the basis of a basin-wide optimisation for a range of surface flows and groundwater abstraction have not been developed. Those rules that do exist are not necessarily followed even in times of flood. The need is therefore for comprehensive basin orchestration just to maintain economic benefits and environmental integrity, let alone improve them. This points to the need for overall basin co-ordination through a strong institution to ensure that clear hydraulic and economic criteria can be applied.

3.4. Reaching hydrological limits: physical and economic impacts

3.4.1. Impact of flooding

A principal feature of the hydrology of south-eastern China is the high and devastating incidence of extreme events: floods and droughts have such disastrous consequences that they have historically been a main consideration behind Chinese water policies and institutional arrangements. Additionally, floods and droughts exacerbate existing, and already serious, pollution problems. Floods disseminate pollution, and droughts reduce dilution capacity. These extreme events set limits for the management of the physical resource. Within those limits a degree of risk has to be managed to ensure continuous operations and investment planning. Precisely who takes the varying levels of risk is less of a concern in China than it might be in more mixed economies. However, with the growth in the private sector, this issue cannot be ignored, particularly if commercialised bulk water utilities are to be created in the future.

In the 20th century there have been two extraordinary floods in the Huaihe basin, in 1931 and 1954. These impacted the whole basin. The maximum 30-day flood volumes above the Hongze Lake were both greater than 50 billion m^3. In 1954, the maximum peak flow at Zhengyangguan was 12,700 m^3/s and the peak flow entering the Hongze Lake reached 15,800 m^3/s. Before 1949, there was neither control at the outlet of the Hongze Lake nor enough channel capacity for discharging the flood to the Yangtze River. The flood protection levees along the Liyun Canal were often breached or the protective dam had to be opened for the flood water to flow directly overland to the sea.

The 1931 flood inundated 5.13 million ha of land and left 75,000 dead. The protective levee of the main stream and the tributaries had many breaches, and the east levee along the Liyun Canal was breached at several locations. The protective dam, opened to allow the flood water to flow to the sea over the land, caused the whole plain area to the north of the Huaihe River and the Lixiahe area to be flooded. During the 1954 flood, the completed flood control projects in the Huaihe River had played an important role, since the Sanhe sluice controlled the Hongze Lake and the east levee along the Liyun Canal protected the Lixiahe area from flood. However, the flood damages were very serious in the upper and middle reaches. Overall 4.27 million ha of farmland and over 20 million people were affected.

The response to these floods has been major capital investment and management response for structural flood control at the state and local levels, but without a commensurate response in basin co-ordination during times of drought and during pollution events. The economic impact of drought has not evoked the same level of response and has only been recognised as a limit on development in the past few decades. While there is reliance on groundwater in times of drought, there is no co-ordinated attempt to look at conjunctive use as a way to smooth out peak demands and shortfalls. The resulting impact on grain production is significant, but difficult to capture, since the effects are felt both in space and time across the basin The average drought affected area in Huaihe River Basin was 2.5 million ha from 1949 to 1990, with the area of severe or 'disaster' drought affected area amounting to 1.3 million ha, or 20.1% and 10.6%, respectively, of cultivated area (12.4 million ha).

3.4.2. The impact of pollution on public health

According to the data derived from 283 monitoring stations and 14 hydrometric centres in the basin, the water under well-regulated and protected conditions would meet national standards for drinking water supply, fisheries and recreation. However, under the present circumstances, surface water is severely polluted by organic mater, including nitrates and heavy metals such as As and Hg. Pollution is severe in dry and wet seasons with particularly high concentrations at the beginning of the flood season in June. This is due to the mobilisation of impounded waste-water concentrates and sludges that have accumulated in reservoirs and locks during the dry season. Surface water quality is expected to continue to deteriorate unless action is taken to control pollution from cities and towns, industry and non-point sources related to agriculture and waste disposal from villages. Water quality monitoring in 1994 indicated that pollution caused extensive damage to fisheries, municipal water supply, public health, and other economic activities in the basin. It is evident that the current regulations to control water pollution are not being implemented and that waste-water discharge fees are not being collected. The only indication of a strategy is factory closure—a power vested with provincial government. While the overall level of pollution in the basin has been highlighted and action taken, this has concentrated on surface water in the basin. As the cost of groundwater clean-up across the basin will be prohibitive, the only realistic solutions lie with progressive regulation to protect existing productive aquifers and to reduce pumping in over-abstracted aquifers.

3.4.3. Risk management

The recommendations of a UNDP funded study carried out by the UN Department of Economic and Social Affairs in 1998 conclude that the overall system of basin governance needs to be unblocked (United Nations, 1999) and that risk management needs to be made operational in a much more comprehensive fashion. Provincial governments, municipalities and water user groups need to be aware of the benefits of spreading and co-ordinating the environmental risk across the basin. While the Huaihe River Basin Commission (HRBC) has been very active in implementing and executing flood control, managing the pollution risk has proved much more problematic. This is not surprising since it presents a much more challenging task. It relies on a system of management that not only responds to day-to-day changes in water quality, but is also capable of feeding relevant information to the environmental agencies and local authorities responsible for regulating effluent outflows. Here the recommendations of the study were to enhance risk management through a two-level approach. First is to promote the concept of risk management through public awareness and promote land and water conservation programmes to reduce the overall level of risk in the basin. These are long-term measures with variable impacts. Second is to make risk management across the basin operational through the use of water resource management models that combine quantity and quality in near real-time. Here the HRBC will need to be active in assessing the level of the exposure to hydrological risk at key points in the basin. This needs periodic updating throughout the water year and has to be particularly intensive during flood seasons. More importantly such risk analysis should be instrumental in updating operating rules and procedures across the basin at key sluices, flood gates and control points.

4. Groundwater and energy utilities in India

Groundwater pumping dominates rural energy demand in India and creates tremendous pressure for increases in electricity generation from coal, nuclear, and Himalayan hydropower sources. Increases in generation from all of these sources entail major negative environmental externalities. At the same time, current energy pricing policies encourage rapid expansion of groundwater extraction for irrigation. In some areas this has led to major overdraft problems which threaten the sustainability of agriculture and other activities requiring reliable access to exploitable groundwater.

At present, electricity for pumping groundwater in India is supplied free of charge or on the basis of flat annual connection fees. This encourages widespread waste of both water and electricity and eliminates incentives for demand side management. As a result of power pricing policies, India's base load electricity deficit now runs at 19% and peak load at over 30%. In most states, agricultural demand, which consists almost exclusively of pumping, now exceeds 40% of consumption and in some states, such as Haryana and Rajasthan, it exceeds 50%. Pump efficiencies are low and tariffs for irrigation provide no incentive to improve either them or efficient water use (World Bank, 1998).

There are, however, strong institutional incentives against tariff reform within the State Electricity Boards (SEBs). Unmetered power permits high 'non-technical' losses and encourages rent seeking behaviour. Furthermore, farmers are unwilling to permit metering or tariff increases when service quality is poor and groundwater levels are dropping. A vicious cycle results. Users demand more power. The government and private sector respond by trying to increase generation through damming Himalayan rivers, or by building new nuclear facilities and new coal fired plants. Little attention is paid to the 'sticky' issues of end-use or distribution efficiency. As a result, actual energy services at the end-use point decline, groundwater overdraft concerns expand and the cycle begins again. To this extent, India's energy demands, and the environmental impacts associated with them, are expected to escalate rapidly (ISET, 1999).

A second important dimension of the groundwater-electrical power equation in India has been the emergence of local water and (to a lesser extent) power markets. Flat rate tariffs for electricity have encouraged farmers to sell groundwater to other farmers. This has had major positive equity impacts by enabling resource poor farmers and other water users to obtain access to water without the need for capital to install their own wells. At the same time, the ability to sell water has encouraged groundwater extraction and exacerbated overdraft concerns. As pumping and water markets have expanded, the reliability of electricity supplies has declined. In many areas this has led farmers to adopt diesel pumps and, in a few instances, small local energy markets have emerged. Recently, in some states such as Uttar Pradesh and Andhra Pradesh, the government has initiated major power sector reforms. These reforms are likely to have a large impact on existing water and power use patterns. The nature of these impacts has, however, never been analysed. In addition, the reform process may present opportunities for change that could enable energy prices and the development of local energy supply systems to be used as major tools for groundwater management.

As the World Bank report (1998) notes, the era of groundwater development in India has passed, and the imperative is for a workable system of groundwater management. Given the state of dependence upon groundwater and the state of many of India's aquifers, the complex of issues surrounding rural power supply for groundwater pumping will need resolution. It is evident that the risk management undertaken by individual farmers will need to fit into a broader hydro-environmental and socio-economic frame in which the management of the risk is effectively institutionalised and shared among all those agencies involved in groundwater resource management—including the electricity utilities.

5. Damaged land and water systems: who takes on the risk?

The following two examples illustrate the rate and scale at which pre-existing natural equilibria in land and water systems can be upset by both engineered application of irrigation water (the Indus basin, Pakistan) and by land clearance (the dryland salinity of southern Australia). Efforts to reclaim salinised soils are occurring in both cases, but against widely contrasting socio-economic conditions.

5.1. Indus basin, Pakistan

Recent estimates are that irrigated land furnishes 90% (by value) of Pakistan's agricultural production, accounting for 26% of GDP and employing 54% of the labour force (World Bank, 1997). It is apparent on the evidence of current investments that priorities in irrigated agriculture outweigh other infrastructure interventions. Maintaining a bank of soil resources and flow of water resources to support food production to a population growing at some 3.0% per annum has become an imperative for Pakistan. The bulk of this productivity is associated with the Indus basin in which land is being progressively lost to the pernicious combination of waterlogging and salinisation. As the World Bank (1997) notes, "Waterlogging and salinity are the principal threats to the sustainability of irrigated agriculture in Pakistan: 37.6 percent of the Gross Commanded Area (GCA) is waterlogged, of which 15 percent is severely waterlogged and 14 percent of the surface is saline..."

With almost 14 million ha, the Indus Basin Irrigation System (IBIS) is the largest contiguous irrigation system in the world (FAO, 1997). It consists of an extensive network of barrages, canals and watercourses. The total length of the canals is about 61,000 km with communal watercourses, farm channels, and field ditches covering another 1.6 million km. The Indus basin was developed through surface irrigation under British colonial rule in the late 19th century but the threat to the system of saline accumulation in irrigated soils without adequate drainage was recognised by the original design engineers. Their warnings were not heeded, water tables rose and high evaporation rates encouraged salt accumulation in the upper soil horizons. The environmental and economic impacts and the institutional and engineering issues are now manifold (World Bank, 1994).

The Indus basin is filled with thick alluvial sediments deposited by the Indus river and its five main tributaries: Jhelum, Chenab, Ravi, Sutlej and Beas, forming a thick set (300–500 m) of unconfined and leaky aquifers. Before the introduction of a weir-controlled canal irrigation system, the groundwater table was relatively deep (averaging 30 m) under most of the Indus Plain. As a result of the additional recharge introduced by irrigation, the water table started rising at a rate of 15–75 cm/year. The level of the water table before and after the introduction of the large canal networks in the upper part of the basin rose 20–30 m over a period of 80–100 years.

The quality of groundwater is related to recharge styles of the aquifer units and pre-existing geological conditions. In general, water from shallow wells located near sources of recharge is of good quality. Along the rivers and in the upper reaches of the doabs, where rainfall is a major source of recharge and maximum canal supply is available.

groundwater usually contains less than 1000 ppm (parts per million) of dissolved solids. The physical and chemical environment in which groundwater is found and is evolving in the Indus basin is complex, particularly in the shallow horizons that have experienced recent groundwater recovery and quality changes. Relatively fresh groundwater occurs side by side with saline groundwater or under or overlain with saline groundwater. This requires a high degree of operational knowledge in the management of groundwater to ensure its sustainability in terms of quantity and quality. It would have been reasonable to assume that the identification of hydrogeological processes and the establishment of a good sedimentological framework to explain and quantify the groundwater occurrences and the rate of aquifer replenishment and depletion would have driven good management practices.

In fact, the management responses have exacerbated the problem. Public tubewell development started in the 1960s through Salinity Control and Reclamation Projects (SCARPs). Since drainage projects alone generally have a low economic rate of return, priority has been given to locating SCARPs in areas of usable quality groundwater. As a result, 90% of the SCARP tubewells and 95% of pumped groundwater is from fresh groundwater zones. In effect SCARPs have evolved into groundwater supply projects in which drainage is a by-product. In addition, the capacity by the private sector to develop good quality groundwater (which was not appreciated in the early planning stages) was triggered by the SCARP development. Indeed, the recently launched National Drainage Programme (World Bank, 1997) proposes removing subsidies from public tubewells in fresh groundwater areas. As a result, the salt balances of the Indus and its associated sub-basins have been disrupted as the hydro-chemical systems have become progressively closed and the supplemental generation of salt through waterlogging had further exacerbated the positive salt balance. The Indus is effectively a saline sink with minimal flushing and outflow. This applies to the Indus Plain as much as to basins in the Northwest Frontier Province (NWFP) and Baluchistan, which are also in danger of becoming closed sub-systems. More recent attempts to tackle the problem locally through biological drainage have met with some success but have had to rely on the flexible initiative of local farmers and farmer groups (IWASRI, 1994), rather than on large scale infrastructural drainage initiatives. The interesting feature of this initiative is the willingness of farmers cultivating moderately salinised soils to initiate biological drainage (largely with Eucalyptus trees) with the bare minimum of grant assistance and technical co-operation. This is not a criticism of the highly centralised Water and Power Development Authority (WAPDA) or the provincial level Irrigation Development Authorities (PIDAs) in Pakistan, rather an illustration of what potential there is for remediation of damaged landscapes and reclamation of essential agricultural productivity by spreading risk—not concentrating it.

5.2. *Dryland salinity in the Murray–Darling basin, Australia*

The example of the Murray–Darling Basin in south-eastern Australia illustrates how the equilibrium in soil–water systems can break down through piecemeal as opposed to engineered interference with the hydrological cycle. The problem is also pervasive in Western Australia (George et al. 1997), but has had most economic impact in the Murray–Darling.

In the headwaters of the Murray–Darling Basin large areas of natural forest and scrub have been cleared since European settlement and replaced with grass or crops. This resulted in a significant increase in aquifer recharge, causing water tables to rise to a new equilibrium depth at a shallower level. The response to land clearing typically occurs within a few years, with farmers noting increased yields from wells and even the development of artesian conditions in some valley floor bores. Local streams also develop higher baseflows. An unforeseen side effect of the new equilibrium has been the saturation of salt-bearing clays in many valleys and an increased flux of groundwater through these clays as the groundwater system responds to the increased recharge. The increased flux of groundwater leads to destabilisation of the clays and to the accumulation of salts in the shallow soil. Vegetation becomes stressed by the salt accumulation and dies. The result is rapid sheet and gully erosion over areas associated with groundwater discharge. The erosion products have led to increased turbidity and salt loads in the streams that drain these areas (Acworth et al., 1997).

The impacts of the development of dryland salinity in the headwaters of many streams in the Murray–Darling Basin is a major concern of the Murray–Darling Basin Authority who have the task of managing water quality and quantity in the extensive irrigation areas lower down the catchment. But while the public involvement with the dryland salinity hazard in Australia is well developed through 'Saltwatch' and 'Landcare' programmes, the damage has been profound and illustrates how broad-brush policy approaches to land development need to be tested and researched well before implementation is taken to scale.

6. Conclusions

The examples given above do not in themselves tell us anything new about irrigated agriculture and agricultural production, but they do indicate how many important food production systems have been sheltered from hydrological reality and the inherent limits of land and soil–water systems. In some cases, the damage is fundamental and cannot be reversed. Political and socio-economic pressures to develop irrigated agriculture, even in systems that are already stressed and degraded, remain. Global markets in food grains will only offer a marginal solution in the short term, at least until traded volumes of grain and distribution infrastructure improve significantly, particularly in China and the rest of Asia.

In this regard it is interesting to note the case in the High Plains of the USA where even into the 1970s farming communities had no idea about the age and provenance of the groundwater they were pumping or the potential for sophisticated application of water. As Kromm and White (1992) observe, it is now too late to expect the current pattern of agriculture to be maintained. The contingency that deep groundwater offered has been foregone. Although farmers are inherently conservative, it is also possible to observe, in the case of India, how individual farmers are capable of spreading risk when the managers of the resources (for both surface water and power) fail to provide a reliable service.

It is also interesting to note that the companion papers in this issue highlight the issues with soil fertility in Africa, where long periods of sub-aerial erosion and weathering have depleted the mix of soil nutrients in the upper horizons. Yet the older erosion surfaces of sub-Saharan Africa are often cited as the land units with the most potential for irrigated agriculture (FAO, 1997). This is also hinted at in the companion paper prepared by Koohafkan (this issue). While the latter paper necessarily takes a global perspective, there is so much local conditioning of risk due to the spatial and temporal variability of soils and hydrology, that generalisations mask the root causes of degradation. These have largely to do with a failure to recognise the broad hydro-environmental risk associated with the modification of landscape processes.

Where it might have been expected that technology would allow more sustainable development, it could be argued that engineering efficiency has only deferred the problem, made food producers insensitive to risk, and worsened the environmental condition of the water and land systems. The relevant question to ask in the 21st century is: who takes the risk and who takes the liability for land and water systems that will become increasingly modified?

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