CHAPTER 3
Groundwater for irrigation: productivity gains and the need to manage hydro-environmental risk

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ABSTRACT: The enhancement of agricultural production through of groundwater irrigation is well acknowledged and to this extent has been a success story. However, the precise contribution of groundwater and the physical and socio-economic consequences of this success are not always immediately apparent. A definitive national, regional and global account of the contribution of groundwater irrigation will never be possible because a clear partition between surface and groundwater sources cannot be derived at these scales. Indeed, access to groundwater is instrumental in maintaining the continuum between rainfed and irrigated agriculture but because of sometimes unclear linkages between groundwater and food production, the scope for management of the resource through explicit food production policies is constrained. Three key points emerge: 1) access to groundwater will continue to allow intensification of agricultural production in response changing patterns of demand; 2) the scope for managing agricultural demand for groundwater is limited, particularly where rural communities are trying to break out of poverty; and 3) where aquifers are over-exploited through agricultural use, users are being forced into economic and social transitions – moving off the land or transferring resources or user rights to competing users – municipal and industrial users. The net result will be: 1) a loss of some strategic aquifers; 2) an enhancement of agricultural productivity in relation to overall water use and uptake of conjunctive use; 3) a marked transfer of groundwater from agriculture to other competing users; and 4) substitution of groundwater by imports or alternative sources.

1 INTRODUCTION

1.1 *The apparent success of groundwater irrigation*

In 93 developing countries analysed by FAO (FAO, in press b) irrigated land now occupies 20% of the total arable area but accounts for 40% of all crop production and almost 60% of cereal production. By 2030, agricultural water use in these developing countries is expected to increase by 14%. There should be no surprise here. What is left un-stated is the success of groundwater irrigation in the latter half of the 20th century in achieving this statistic. Much of this paper draws upon a FAO internal paper prepared on groundwater and food security (FAO, in press a) prepared by Marcus and Yarrow Moench and the author, to try to address this issue of understatement and the failure to manage groundwater effectively.

It should also be noted that the implications of accelerated groundwater development were captured as early as the late 1950s in a review entitled Large Scale Groundwater Development (United Nations 1960), and clearly the advent of energised borehole pumping, in particular associated with the essentially private control over the application of groundwater, has resulted in agriculture production gains. Much of this success has occurred as an indirect result hydraulic engineers continuing to promote the expansion of irrigated agriculture through surface command areas. The Indus basin, large schemes such as the 16,000 ha irrigated perimeter of Loukkos, Maroc (FAO 2001b), and many commands in India and China have seen the proliferation of public and private investment in groundwater abstraction, where it has conferred specific water security to producers who would otherwise have to rely on intermittent surface irrigation services. In many cases the advantages of scavenging groundwater (for drainage and crop application) and to provide *ad hoc* solutions to the *tail ender* problem has been an un-intended by-product of surface irrigation schemes and it is essentially anarchic.

That this successful *anarchy* has generated both positive and negative externalities is not in question, but it is the latter that are emphasised in the current popular debates on groundwater management (e.g. Payal 2000). In this sense, groundwater development has become a victim of its own success, but it would be irresponsible to suggest that unfettered access to the resource base should continue. Particular sets of people, and particular environments are impacted by the intensive use of groundwater, and future use needs to be enabled to maintain benefits where systems permit, but controlled if the economic, social and environmental consequences of overuse are intolerable.

In many senses this will become a spatial question. Just where intensification of irrigated agriculture will need to continue and expand and where it has reached limits and will be forced to decline are important questions. The Global Perspectives Studies Unit of FAO released their Summary report *World Agriculture: towards 2015/30* (FAO, in press b) on the basis of expected demand for agricultural produce by the year 2030. The report anticipates a net global expansion of some 45 million ha with significant regional disparity. This reflects a projected annual growth rate of 0.6%, compared with the 1.9% observed in the period 1963–1999. As will be explained below, the precise contribution of groundwater to the observed trend is not possible, but as the global review presented by Shah *et al.* (2000) illustrates, the local impacts of intensive use are keenly felt around the globe and with the exception of urban areas dependant upon groundwater, all these impacts may be related to groundwater used for irrigated agriculture.

1.2 *Food: the key driver*

The linkage between groundwater and food production might appear straightforward. In practice, these links are hard to establish, particularly at a macro scale. A recent review of groundwater and food security (FAO, in press a) concluded that a lack of reliable basic groundwater level data precluded broadcast statements such as those of Lester Brown (Brown & Halweil 1998) and Postel (1999). The FAO study concluded that simply deriving sufficiently precise monitoring borehole hydrographs representative of aquifer behaviour across systems that are known to be heavily exploited (in this case Gujarat and the North China Plain) was not possible.

Therefore assertions that some 10% of the globe's food security could be at threat as water tables decline would presume that a one to one mapping of food production and groundwater decline can be established. While food production trends can be assessed with some measure of accuracy (FAO, in press b) the required level of consistent groundwater data at commensurate scales does not exist, nor is it likely to exist. What does exist are variable sets of groundwater data for specific aquifers where particular problems are encountered, but in the developing world, this may have an inverse relationship with the severity of the problem. Good quality aquifer monitoring data in Pakistan, India or North China is the exception rather than the rule, and the government agencies who are responsible for gathering that data are only too well aware of the low degree of confidence that can be attached to groundwater data and their own capacity to improve it. As a recent report from the Ministry of Water Resources in China (MWR 2001) has noted:

> "Effective management (of groundwater) is highly dependent on appropriate reliable and up-to-date information. Currently there are thousands of local and personal databases storing key technical and licensing data in a very unsatisfactory manner. An absolutely fundamental need for effective groundwater management and protection is a comprehensive, publicly accessible, groundwater database (GDB). The complete lack of a GDB is seriously constraining the formulation and implementation of effective groundwater management throughout China. The inability to access information, which at times is part of institutional secrecy, encourages inaction or incorrect decisions. GDBs are well established in almost every country

where significant groundwater is used. The lack of such a database in China is surprising".

Despite this *unsatisfactory* state of affairs, the seminal analysis of the reliance placed upon groundwater by agriculture, and rural development in general, has been undertaken by Shah (1993). Shah's perspective is that of a political economist and the analysis injected some much needed fresh air into the groundwater management debate. Working on data compiled in India in the 1970s is was clear that the boost to agricultural production conferred by access to groundwater was significant. But Shah's analysis also indicated the complexity of this reliance –the use of informal groundwater markets, the differential caused by land ownership and access to markets, the role of fertiliser subsidies and other inputs. While access to groundwater may be critical, it is not by itself a sufficient explanation of enhanced productivity.

However, the tangible evidence for this is anecdotal at best. FAO's AQUASTAT database, for instance, can only partition in a rough cut the irrigated areas that rely upon groundwater at national level. The attached annex at the end of this chapter is an extract of the current AQUASTAT database presenting –where known– the contribution of groundwater in terms of irrigated hectares. The data exclude Europe and the Pacific where FAO does not have data for the partition between surface and groundwater. But for the rest of the world, it can be seen that some 152 million ha are under surface water control (but excluding spate irrigation) and some 89 million ha under groundwater control. The FAO estimate of total irrigated area (including Europe and the Pacific) is 389 million ha. The global contribution of groundwater is therefore significant and relative significance at regional and country level can be found in the Annex.

Photograph 1. Extensive groundwater irrigation from stratiform aquifers south of Sadah, Yemen.

1.3 *Drivers: post the Green Revolution*

While the intensive use of groundwater to irrigate continues, the pressure to exploit groundwater merely to produce food has eased. Grain surpluses, low farm-gate prices and competition for groundwater from there sectors are much more prevalent. Alternative drivers of groundwater use in rural areas are now coming from competing users such industry and municipalities. Examples range from to coastal cities of Southern California (Los Angeles, San Diego), the upland aquifers of Yemen (Sana'a, Ta'iz), the coastal aquifers of Lebanon, Mauritania and Senegal to the vast North China Plain where municipal demand for groundwater is progressively crowding out irrigated agriculture.

These shifting patterns of demand for groundwater and the different consequences of intensive use (particularly in terms of the quality of the drainage water) from the differing users make the negotiation of agricultural use much more complex and less certain. New levels of risk are apparent and new levels of management required by the competing sectors. Agriculture is in a poor position to maintain its *market share* of both surface and groundwater against higher value users. What is clear is the expected growth in the use of groundwater for precision agriculture where reliance on water is absolute if production contracts are to be met. This can be observed in the relatively humid settings of the Vale of York, United Kingdom, (Forbes-Adam, pers. comm.) and the desert conditions of Saudi Arabia (Abderrahman, this volume). The same reliance is also observable in developing countries (Shah 2001) where widespread rural welfare continues to hinge on access to groundwater.

Thus, in many senses, the era of groundwater development, *per se*, has passed into period of groundwater management (Moench 1994), but as this paper will argue, it is not straightforward technocratic resource management that can be expected to make positive impacts on the status of groundwater and its related productivity (Shah 2001).

1.4 *The management problem*

River basins and surface water irrigation schemes present *neat* arrangements. The resource is naturally integrated at any point in the basin's watercourse and measurements, diversions, storage, abstractions can be easily monitored. The impacts of irrigation abstraction and return flows occur in near real-time and are immediately apparent upstream and downstream through hydraulic continuity. The system is neatly bounded, there are clear solutions of continuity and systems of rights in use are generally clearly established. The same cannot be said for aquifer systems and groundwater development. Aquifer systems are known imperfectly, there are no clear solutions of continuity (Burke 2000 a, b), responses are highly non-linear (geological heterogeneity and anisotropy) and can be lagged over centuries with none of the clear *water year* rhythm observed in surface basins.

Not surprisingly, the actual management systems that have grown up around surface water and groundwater are markedly different. The largely technocratic, vertically integrated basin management model built around surface water schemes and the sets of incentives to surface water managers and users are markedly different from the management *models* and incentives associated with the much more fuzzy, imprecise character of aquifer systems and groundwater use. In addition, while the *client base* for a basin manager would typically consist of a set number of well identified user groups –irrigation schemes, water user associations, municipalities, etc.– the manager of an aquifer system may in practice have millions of individual users with which he/she has to engage.

Therefore the transaction costs of applying *cross-sectoral integrated water resources management* in a classic sense, (which may be prohibitively high in many developed river basins, (United Nations 1999)) can be expected to several orders of magnitude higher –if cross-sectoral integrated water resource management remains the objective. On the face of it, this does not auger well for progressive conjunctive use management as a means to reconcile competing surface and groundwater demands. Despite this, progress in applying conjunctive use –whether by design or accident– and the use of extensive informal water markets both in and around surface and groundwater irrigation schemes demonstrate the ability of irrigation end-users to adapt, often in the face of contradictory signals and incentive structures established by higher order *managers*. As to whether this *de facto* arrangement offers more or less equity and/or more or less economic *efficiency* is debatable. Where regulation is weak or absent –which is the usual case for groundwater– the opportunity for the richer members of a groundwater user group to capture through technology or access to land will always be there. Having said that, it is also possible to observe enhanced equity and efficiency through the myriad of small water, energy and pumping transactions that occur amongst groundwater irrigation user groups –as documented by Shah (2001) largely to break away from conventional command and control irrigation management systems.

Because of sometimes unclear linkages between groundwater and food production, the scope for management of the resource has been constrained. The broader question that remains –is given the levels of uncertainty associated with groundwater information (the pin-cushion problem)– is groundwater amenable to the same types of management approaches associated with surface water irrigation (e.g. irrigation management transfer) and does it sit well within the frame of so called *integrated water resource management*? It is important to resolve this question since the aquifers that are being intensively used can be expected to be in arid and semi-arid zones where surface water sources alternatives are scarce or unavailable and drawdown and pollution externalities can be expected to impact users within and without the zone of groundwater use. Therefore solutions that require some sort of *integrated* or consensual and expert management –such as conjunctive use– will become imperative. However, requests to individual users to give up private opportunity for the sake of basin or aquifer wide efficiencies and equity is likely to be resisted particularly if the access to groundwater is the principal means to build assets and break out of poverty (Moench, this volume).

Photograph 2. An array of groundwater users and managers in Kordofan, Sudan.

The scope for addressing such management problems in irrigated is also conditioned by the need to serve several policy *masters*. Irrigated agriculture is a key component of many national agriculture strategies, but is also expected to conform to water and environmental policy initiatives. That management of groundwater use for irrigation should be part of a national and regional commitment to integrated water resource management is not disputed, but precisely how and through which policy instruments it is effected is often remains a murky subject.

2 KEY DEFINITIONS AND ISSUES

2.1 *Groundwater overdraft, over-abstraction and over-exploitation*

There is continuing confusion over terms to describe and define levels of groundwater withdrawals and the impacts that these have on particular aquifers. *Overdraft* or *over-abstraction* generally refers to withdrawal of groundwater that results in significant long term declines in groundwater levels. It does not necessarily imply that the abstraction exceeds recharge. *Over-exploitation* on the other hand could be taken to imply a combination of impacts brought about by withdrawal and disposal (injected or percolated).

There also remains a confusion in the usage of *over-abstraction* and *groundwater mining*. The latter only refers to the depletion of a stock of non-renewable groundwater that will not be replaced, leaving the aquifer de-watered indefinitely. Clearly, the planned mining of an aquifer is a strategic water resource management option if the full physical, social and economic implications are understood and accounted for over time (Schiffler 1998). However, the replenishment by down-ward percolation of meteoric water shows high inter-annual variability and is a complex physical process that is difficult to evaluate (Lerner *et al.* 1990, Simmers *et al.* 1992). Therefore, over-abstraction should not be defined in terms of an annual balance of recharge and abstraction, but needs to be evaluated on an inter-annual basis, since the limit between the non-renewable stock and the stock that is replenished by contemporary recharge from surface percolation is usually unknown. But what really matters to decision makers and well users is the overall reliability and productivity of a well (in terms of water levels, volumes and water quality) during a given time period. Therefore, if a well taps a particular aquifer, what is its sustainable rate of exploitation given variable periods of recharge and drought? The answer to this question is not trivial, and requires a certain level of precision in understanding the dynamics of the physical system, but the only real management indicator for a community of groundwater users is the maximum admissible drawdown they are prepared to accept.

2.2 *Food security*

The main generally available indicator used to monitor food security is, according to technical documents prepared for the World Food Summit in 1996: "*per capita* food consumption, measured at the national level by the average dietary energy supply in Calories on the basis of national food balance sheets and food supplies as national averages" (FAO 1996). In line with this, we follow the definition in the FAO database of terminology that: "Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life". This definition does not focus on food production and physical availability alone but also includes the critical dimension of access to available food supplies. Under the definition, food security often depends more on the ability of populations to purchase, rather than produce, food because global and national food distribution systems now frequently negate the impact of local production problems on the availability of food in the market. As a result, the question of whether or not people have access to sufficient food when groundwater problems disrupt agricultural production depends heavily on whether or not local they have access to a diverse array of alternative income sources or reserve capital so that food can be purchased. It also depends on wider factors such as transportation systems and the ability of countries to purchase and distribute food available on global markets. All this implies that analysis of groundwater availability/reliability on a project or regional basis is *by itself* a poor indicator of the vulnerability of populations to food insecurity.

The above said, in many cases access to water –particularly highly reliable groundwater sources– does play an important role in food security. Access to reliable sources of water reduces the production risk and farm incomes at both micro (farm) and aggregate (regional) levels will be buffered from the effects of precipitation variability, drought or general water scarcity conditions. As a result, access to reliable groundwater supplies can ensure the income flow needed to purchase food as well as playing a central role in food production. Furthermore, particularly in remote locations within developing countries income sources other than irrigated agriculture are not available to rural populations. As a result, there can be a direct link between access to water and household or regional food security. This link is, however, highly dependent on the specific situation –there is no inherent direct link between water and food security. While access to water is important in many situations, in other situations irrigated agriculture is only one out of many income sources or available livelihood strategies. Consequently, while falling water levels, irrigation system deterioration, droughts or other direct indicators of water scarcity can serve as signals warning that food security may be threatened, the actual degree of threat will depend on a wide variety of context specific factors. Water scarcity measures are warning signals but do not, on their own, indicate the emergence of food insecurity.

Water availability and reliability are closely linked to food security, but the water-food security equation is partial and the linkages are neither linear nor transparent, certainly not to the extent suggested by Postel (1999) who indicated that some 10% of the world's food production could be threatened by falling groundwater levels. The full equation is a function of the interaction between water access, production economics and the wider network of entitlements water users and others have within society. It can not be assumed that a one to one relationship exists between access to reliable water supplies for irrigated agriculture and food security.

2.3 *Water use efficiency and water productivity: groundwater and surface water distinctions*

Water use *efficiency* describes the efficacy of the transport process from the source to the crop and is a dimensionless unit (simply, input over output). Since, in most cases, the groundwater source is very near the point of application to the crop, it comes as no surprise that groundwater sources can demonstrate much greater systemic efficiencies over surface sources. The conveyance losses associated with surface water distribution systems do not apply. However, the mode of in-field application for surface and groundwater systems can be exactly the same –flood irrigation from groundwater is common throughout much of Asia. Combined with the flexible, on-demand nature of groundwater, the technical efficiency advantage of groundwater is clear. But these comparisons can be artificial –in many cases choosing between surface and groundwater sources is simply not an option.

Photograph 3. Flood irrigation from groundwater with subsidised pumping in Baluchistan.

In terms of irrigation practice, making efficiency gains is important at all scales if pressures are to be reduced on environmental flows and downstream/downgradient users. Irrigation is not in a position to foreclose on other users. It is simplistic to assume that at basin level, irrigation efficiency is not significant (Seckler 1996) since irrespective of the impact across a particular basin or catchment system, it is the immediate deprivation of opportunity that may count. By the same token, it should also be appreciated that seeking efficiencies involves specific groups of water users and managers at the various levels –this is not the case for productivity, which can be defined and applied at a range of levels. However, there may be no incentives for direct users making efficiency gains if upstream managers cannot ensure conveyance efficiency. With groundwater, this may not apply since the incentive is generally internalised entirely by the user.

Water *productivity* can be defined as the efficiency with which the crop uses water to produce biomass and yield expressed in kg/m^3. In practice this involves a suite of potential definitions. At a recent workshop on water productivity organized by IWMI in Waduwa, Sri Lanka, twenty-one papers were presented that demonstrated a range of assumptions and definitions of water productivity. All the papers expressed productivity as a relationship of output per unit of water; however, most definitions did not satisfactorily identify the units of output or the specific flows of water that produced them. A first attempt at synthesizing the working group's discussions, and focuses on three types of output resulting from water use: 1) biomass in agriculture and natural vegetation; 2) nutritional content of various forms of food produced with water; and 3) economic value created by water use in different sectors, i.e. agriculture, fisheries, livestock, and indeed non-agricultural or non-food uses. As a result, productivity estimates that are appropriate at one scale may provide very little meaningful information at the next scale up. From physically quantifiable measures of water productivity at the plant, field and watercourse scales, the exercise is increasingly less capable of providing verifiable estimates of productivity that are comparable across contexts. The notion of *value* defined in societal preference terms (difficult to reduce to simple monetary terms) increasingly gains importance.

A framework for water use efficiency and water productivity is offered by Smith (2001) and includes irrigation efficiency, rainfall efficiency, soil water use efficiency and crop water use efficiency leading to a measure of water productivity. The best opportunity to increase water productivity is provided in raising crop water productivity, as reflected in the FAO prognosis (FAO, in press b), which foresee a 35% increase in irrigated cereal yield. Present yield levels under irrigation are below potential and considerable scope exists to raise yields while maintaining or even reducing present levels of water use. This can be obtained in the first place through a further increase in yield by the introduction of high yielding varieties combined with optimal inputs to sustainable levels of fertility and pest control and in particular the provision of a secure and optimal water supply. Micro irrigation is the irrigation where such secure levels of water and fertility supply can be achieved.

Agricultural research has over the past decades ensured a steady increase in yield levels through a highly effective plant genetic selection programme. New microbiology and biotechnological developments can be expected to promote further growth in yield levels and productivity. Yields under optimal water supply are likely to increase but also there is potential to increase yields under reduced water supply and to limit the adverse effects of water stress (Smith 2001).

2.4 *Agricultural productivity and groundwater*

The most direct and tangible link between groundwater conditions and food security has to do with water availability to meet crop requirements. Water availability in an aggregate sense is, however, close to meaningless since crop production is heavily dependent on seasonal and interannual fluctuations in availability including timing in relation to crop growth stages. Many crops are highly vulnerable to moisture stress at critical points in plant growth and yields can be substantially reduced even if adequate water supplies are available following periods of shortage (Perry & Narayanamurthy 1998). Water stress at the flowering stage of maize, for example, can reduce yields by 60%, even if water is adequate during all the rest of the crop season (Seckler & Amarasinghe 1999). Similar impacts on onions, tomatoes and rice have also been documented (FAO irrigation and drainage series, 24, 33, 56, Meinzen-Dick 1996). In addition to the direct impact of water availability on crop growth, assured supplies are a major factor inducing investment in other inputs to production such as labour, fertilisers, improved seeds and pesticides (Kahnert & Levine 1989, Ahmad 2001). As a result, as the reliability of irrigation water supplies increases there is multiplier effect on yields. Taken with the inherent flexibility of groundwater abstraction (on-demand, just-in-time), these characteristics of groundwater will continue to make its intensive use high attractive both to small-holders seeking to build an asset base and to commercial concerns –such as winter wheat production in Zambia which is totally dependant upon groundwater.

The evolution of the groundwater phenomenon in agriculture is revealing. Expansion of irrigation was the *lead* input driving yield increases during the Green Revolution of the 1960s-70s and subsequent decades. As the most reliable source of irrigation water –a source that can generally be tapped when and in the amounts needed– groundwater played a particularly major role. As Repetto (1994) comments: "The Green Revolution has often been called a wheat revolution; it might also be called a tube-well revolution". However, this turn-around concentrated on high value crops (with high crop water demands) and with ability to pay for pumping energy costs.

Yields in groundwater-irrigated areas are higher –often double– compared to those in canal irrigated areas (Shah 1993, Meinzen-Dick 1996). In India, groundwater irrigated area accounts of roughly 50% of the total irrigated area and, according to some estimates, as much as 70%–80% of total agricultural production may, in one form or another, be dependent on groundwater (Dains & Pawar 1987). Similar patterns are present in other countries as well. In North China's Henan province, China's largest, roughly 2 million ha or 52% of irrigated landsare served by tube wells (Lunzhang 1994). Parts of Mexico –including some of the most productive agricultural areas– are also heavily dependent on groundwater. The role of groundwater is equally important in industrialized countries. Barraqué (1997), for example, estimates that: "Irrigation uses 80% of all water in Spain and 20% of that water comes from underground… The 20%, however, produces more than 40% of the cumulated economic value of Spanish crops". Recent findings from Andalucía indicate that irrigated agriculture from groundwater is economically over five times more productive (in terms of €/m^3) and generates more than three times the employment in comparison to surface irrigated agriculture (Hernández-Mora *et al.* 2001).

Photograph 4. Localised groundwater irrigation from alluvial aquifers in Southern Yemen.

The role of groundwater is not just through higher yields in normal water years. In an analysis of wheat cropping in the Negev desert, Tsur estimated the *stabilization value* –that is the value associated with the *reliability* of the water supply– as opposed to just the value of the volume available of groundwater development as "more than twice the benefit due to the increase in water supply" (Tsur 1990). In Southern California where surface water supplies are less variable than the Negev, the stabilization value in agriculture is, in some cases, as much as 50% of the total value of groundwater (Tsur 1993). During the early 1990s drought in California, economic impacts were minimal largely because farmers were able to shift from unreliable surface supplies to groundwater (Gleick & Nash 1991). The value associated with the flexibility of pumped groundwater supplies has been a further boost to agricultural productivity since it has allowed intensification and diversification of agricultural production in surface irrigation schemes that are otherwise notoriously inflexible. This is particularly the case in Asia (Facon, pers. comm.)

The presence of groundwater irrigation alone cannot, however, be given full credit for the increased yields documented around the world. Instead it needs to be seen as part of a complementary and mutually reinforcing set of inputs. Groundwater availability enables farmers to invest in complimentary inputs that, in combination, substantially increased crop yields. As Ahmad points out, "the response of crop to fertilizer is higher where supply of irrigation water is assured compared to rainfed conditions" (Ahmad 2001). It is the reliability and flexibility of groundwater that allows farmers to take the risk of investing in fertilizer, but which also substantially increases their crop productivity. Fertilizer use in Pakistan is, for example, highest in areas supplied by both canals and tubewells and thus having a highly assured supply of irrigation water. The total nutrient application in these areas is 420 kg/ha compared to 29 kg/ha in rainfed areas (Nisar & Chaudhry 2000, cited in Ahmad 2001). For cereal production in developing marketing economies Pinstrup-Anderson *et al.* (1999) estimated that the contribution of fertilizer was 55%–57% of the rise in average yield per hectare and 30% of the total increase in production (Ahmad 2001). These observations point to the dependency of crop yields on interactions within a dynamic agricultural system and the difficulty of isolating a single factor as the primary factor contributing to increased production.

The above said, available information clearly indicates the critical role groundwater has played in agricultural production over recent decades. The relationship between assured supplies of irrigation water, increasing yields and food production is now under stress. According to Rosegrant & Ringler (1999): "The growth rate in irrigated area declined from 2.16% per year during 1967–82 to 1.46% in 1982–93. The decline was slower in developing countries, from 2.04% to 1.71% annually during the same periods". Yield increase rates are also declining and projections indicate that this will continue over coming decades (Rosegrant & Ringler 1999, FAO, in press b). Furthermore, in some local areas such as Sri Lanka and in the rice-wheat system of India, Nepal, Pakistan and Bangladesh, yields have been stagnant for a number of years (Amarasinghe *et al.* 1999, Ladha *et al.* 2000).

Although stresses on water resources are clearly increasing and there is a logical link between water scarcity and yield stagnation, *causal relationships between emerging water problems, yields and food production vulnerability are far from proven*. According to Ladha *et al.* (2000), where yield stagnation is concerned:

> "There is some evidence of declining partial or total factor productivity… The causes for the stagnation or decline are not well known, and may include changes in biochemical and physical composition of soil organic matter (SOM), a gradual decline in the supply of soil nutrients causing nutrient (macro and micro) imbalances due to inappropriate fertilizer applications, a scarcity of surface water and groundwater as well as poor water quality (salinity), and the buildup of pests, especially weeds such as *Phalaris minor*".

Furthermore, as Seckler & Amarasinghe (1999) note: "It is very difficult to project crop yields… The international dataset does not distinguish between yields on irrigated and rain-fed area: they are just lumped together in average yields". Water is only one factor affecting crop yields. Data available at the global level don't actually allow much insight into the relationship between yields on irrigated and rainfed lands –to say nothing of yields on areas irrigated by groundwater much less areas where groundwater depletion is occurring. Recent evaluations of the implications of water scarcity on food security range from the optimistic to the pessimistic. Lester Brown, for example, contends that primarily because of impending water shortages in northern China, the country will have to import as much as 210–370 million tons of grain per year to feed its population in 2025. It is claimed that this massive increase in imports could cause steeply increasing cereal prices and disruption of the world market (Seckler *et al*. 1999). At the other end of the spectrum, analyses undertaken by both FAO and IFPRI indicate that yield increases –rather than increases in the area under cultivation– will be the dominant factor underpinning growth in cereal production over coming decades and that, in aggregate, these production increases will be sufficient to meet demand. (Rosegrant & Ringler 1999, FAO, in press b). The FAO report goes so far as to state that: "The overall lesson of the historical experience, which is probably also valid for the future, seems to be that the production system has so far had the capability of responding flexibly to meet increases in demand within reasonable limits".

3 PATTERNS AND INTENSITY OF GROUNDWATER ABSTRACTION FOR IRRIGATION

3.1 *Introduction*

This paper attempts to examine the use of groundwater for irrigation exclusively. In practice, groundwater abstraction devices are used to supply other domestic and productive uses by local populations as well as supplement existing surface water irrigation. However, the predominant use of abstracted water in most regions of the world is, and will remain, for irrigated agriculture. This places a particular responsibility upon the irrigated sub-sector to account for its use and for resource managers to enable equitable systems of allocation as socio-economic conditions and patterns of consumption change. There is very little evidence to suggest that such policy and regulatory shifts are occurring as a result of planned state interventions, rather that shifts in groundwater use and patterns of agricultural production are occurring as hydrogeological limits are reached (depletion or migration of low quality water) and limits to pumping (excessive capital and energy costs) become apparent (Moench 1996, FAO, in press a). Indeed the scope to regulate a way out of intensive groundwater abstraction and conserve strategic groundwater resources in many developing countries is severely limited in (Burke & Moench 2000). Instead, it is possible to observe a multitude of little groundwater *crises* all over the world which require specific management solutions that may have little do with traditional or *integrated* water resource management (FAO, in press a) designed by river basin managers.

3.2 *Pattern of groundwater abstraction for irrigation*

The specific pattern of groundwater abstraction for irrigation has not been mapped consistently at any national regional or global scale. The same is true of hydrogeological mapping and groundwater occurrences. It should be noted that the only comprehensive global compilation of groundwater information was carried out by UNDTCD in the 1980s and published by the United Nations (1983–1990) as the Natural Resource/Water Series 12–27 by the then Department of Technical Cooperation and Development (now folded into UNDESA). Some standardization of national hydrogeological mapping has occurred since then based on the UNESCO legend.

Comprehensive mapping of irrigated areas across the globe does not exist. On of the earliest compilations was for Africa (FAO 1987) which presents a 1:10,000,000 map and detailed memoir. This initiative has been updated by FAO (2001a) with the release on CD-ROM of an *Atlas of Water Resources and Irrigation in Africa*. Here all the major African river basins are broken down into the principle sub-basins and the irrigation demand applied in the respective sub-basins on the basis of assumed crop water requirements. This analysis does allows sub-basin irrigation demands to be compared with lumped water balances.

Other examples include the Irrigation Map of India (1:5,000,000) which provides is a national map for India (Central Board of Irrigation and Power 1994) The map provides a breakdown by State of net sown area and irrigated area (for 1998–99) together with inventories of existing and *under construction* projects, *tubewells* and *other wells*. The map indicates the predominance of groundwater irrigation in the states of Bihar, Haryana, Punjab and Uttar Pradesh. For the 1988–89 data from the Ministry of Agriculture, there is a declared national inventory of 3.64 million ha irrigated by *tubewells* (public or private not stated) and 8.93 million ha irrigated *other wells*. This is broadly in line with estimates of numbers of wells produced by the Central Groundwater Board.

Currently, the University of Kassel in Germany (Döll & Siebert 1999) has developed a methodology for mapping irrigated areas at continental level and produced the first global digital map of irrigated areas on the basis of cartographic information and, among other sources, FAO AQUASTAT statistics: (http://www.fao.org/ag/AGL/aglw/Aquastat/aquastat.htm). This map has a resolution of 0.5 degree and was developed "for the purpose of global modelling of water use and crop production". While the compilation which was done at the level of 5 minute raster polygons (approx. 10 km at the equator) was overdue, the 0.5 degree of resolution of the mapping product itself is too coarse to be of use in determining abstraction across large stratiform aquifers.

With these limitations in mind, the Water Development Division of Food and Agriculture Organization of the United Nations and the Center for Environmental Systems Research, University of Kassel, Germany (http://www.usf.uni-kassel.de/usf), are currently co-operating in the development of a global irrigation mapping facility. The mapping facility will develop global GIS coverage of irrigated areas and to make it available to users in the international community. The methodology developed to produce this first version of global map of irrigated areas will be used as starting point to develop an improved global map of irrigated areas with a spatial resolution of 5 minutes and the data collected through the AQUASTAT surveys will be used to improve the overall quality and resolution of the information.

While these data sets can (or soon can) be downloaded, the required appreciation of physical details of most exploited aquifer systems and the points of abstraction will have to continue to be sought through compilations of geological mapping, raw groundwater data and consultant's reports and groundwater modelling exercises. This will never be compiled globally so that only systemic analysis of specific aquifer systems will remain the only credible level of analysis.

3.3 *Intensity of groundwater abstraction for irrigation*

Despite the problems with the spatial resolution, the current University of Kassel mapping does provide some indication of intensity of irrigation at 5 degree cell resolution (Döll & Siebert 1999). For Asia and China this does reveal the scope of an intensive irrigation (broadly, anything above 25% of the area in each 5 minute cell equipped for irrigation based on 1995 FAO data) in:

- The Punjab and Uttar Pradesh.
- The lower Indus in Pakistan.
- The North China Plain –the 3H basin (Huanghe, Huaihe and Haihe River Plain), and the lower Yangste basin.

With the exception of the lower Yangtse basin, the bulk of the productive irrigation in these areas could be accounted for by groundwater irrigation, but the picture and the story is more complex. The work of the IWMI Tata Programme on groundwater recharge in Uttar Pradesh (http://www.cgiar.org/iwmi/groundwater), for instance has highlighted the mix of old drainage canals, more recent irrigation canals and tubewells in the command areas of the western Indo-Gangetic Plain and how conjunctive use has emerged as an essentially opportunistic response to unreliable surface water irrigation.

In the Indus, the SCARP vertical drainage programme effectively developed into a fresh groundwater irrigation programme. In China, the complex story of groundwater depletion by irrigated agriculture, competition from municipalities and saline intrusion needs detailed, local examination as offered by Adams *et al.* (1994).

Groundwater development in the North China Plain has been critical but is essentially out of control (MWR 2001). With the planning of the south-north transfer from the Yangtse basin, the incentives for managing demand for groundwater would appear limited.

In general, it is possible to observe a continuum of water control across irrigated landscapes, from groundwater in-filling and supplementing surface sources in humid and subhumid zones to providing the sole source of irrigation water in arid zones. At all scales, this results in a mosaic of irrigation styles. This makes impossible both a clear partition between surface and groundwater sources and the identification of a groundwater use *density* field.

3.4 *Scale of groundwater abstraction for irrigation*

In theory, the volumes of groundwater abstracted for irrigation could be obtained by taking the FAO AQUASTAT groundwater irrigation areas and applying an average crop use requirement. But this partition would be highly artificial would be meaningless. First the average weighting of crop use would grossly distort actual use, second the mix of surface and groundwater use in any reported scheme is not known. Even if schemes are reported in national or state/provincial figures as *surface* in these intensive areas, field experience has confirmed the prominent role private investment in wells, tubewells and pumps to supplement or substitute unreliable deliveries of surface water.

In short, it is not possible to obtain a quantitative picture of groundwater withdrawals. Even if it were, it is not volumes that are critical. It is the groundwater levels that count (Burke & Moench 2000).

3.5 *A macro picture of the future*

The concern that the reliance groundwater irrigation is threatening global food security is somewhat over-played. Land irrigated by groundwater is going in and out of production incrementally as agricultural systems and markets respond to natural resource limits. The possibility that a shortfall in China's grain requirements would suddenly, at a stroke, soak up the international market in traded grain is remote. The aquifer depletion that is going in North China at the moment will not suddenly reach a groundwater recovery limit all over China at the same time.

This does not prevent a global concern with the role of irrigation in meeting food requirements (World Bank, in press). Again, this type of global analysis reveals little of the inherent tensions and opportunities that are experienced with groundwater irrigation at local scales.

Photograph 5. Drilling for centre pivot irrigation to produce fodder crops on the Batinah coast, Oman.

4 THE CONSEQUENCES: HYDRO-ENVIRONMENTAL IMPACTS AND RISK MANAGEMENT FOR IRRIGATED AGRICULTURE

4.1 *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 today, 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. The nature of the *crisis* is so 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 either operate well below design capacities (which usually says something about the inherent variability of water resource base or competition from upstream users) or 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 has been by more specific regional assessments (e.g. 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 and in so doing, who is exposed to risk and what risk management procedures are in place.

4.2 *The range of drawdown externalities*

The impacts of over-abstraction and water level declines have been reported widely. It is sufficient to note here that over-abstraction can lead to a wide array of social, economic and environmental consequences including:

- Critical changes in patterns of groundwater flow to and from adjacent aquifer systems.
- Declines in stream base flows, wetlands, etc… with consequent damage to ecosystems and downstream users.
- Increased pumping costs and energy usage;
- Land subsidence and damage to surface infrastructure.
- Reduction in access to water for drinking, irrigation and other uses particularly for the poor.
- Increases in the vulnerability of agriculture (and by implication food security) and other uses to climate change or natural climatic fluctuations as the economically accessible buffer stock of groundwater declines.

Yemen presents particularly dramatic evidence of the consequences of over-abstraction. According to the recent Water Resource Assessment of Yemen: "…almost all important groundwater systems in Yemen are being over-exploited at alarming rates… Worst-case predictions made in 1985 on possible depletion of the Wajid sandstone aquifer of the Sadha Plain… have unfortunately come true and groundwater levels have declined on average some 40 metres in only nine years" (WRAY-35 1995). High quality water available in shallow aquifers near Sana'a, Yemen's capital, is expected to be depleted within a few years. This contrasts with rising water levels due to sewage infiltration under the city itself.

As mentioned above, the scale and rate of groundwater abstraction are directly related to the massive expansion in pumping capacity that has occurred over the past five decades in many parts of the world. The number of diesel and electrical pumps in India jumped, as previously noted, from 87,000 in 1950 to 12.58 million in

1990 (CGWB 1995) and an estimated 20 million now.

The impacts of long term abstraction are readily apparent in regions where spring and seepage zones disappear or users have to dig or drill deeper to chase a locally falling phreatic or piezometric head. In addition the aquifer systems themselves are vulnerable to abstraction in many complex, and often not immediately apparent, ways. As in most discussions concerning groundwater over-abstraction, these statistics focus on rates of water level decline and the degree to which estimates of extraction exceed estimates of replenishment. Although the provenance of the replenishment, whether recharge from the surface or leakage from adjacent aquifers is rarely known with any precision. Sustainability is implicitly defined as a level at which draft and recharge are balanced –the *sustainable yield* of an aquifer– and this assumes that a steady state can be achieved in which water levels are stabilised. This narrow focus is often misleading. Pumping will induce water level declines regardless of whether or not the *sustained yield* of an aquifer has been exceeded. These initial water level declines can have major social, economic and environmental impacts long before sustainability of the groundwater resource base is threatened in any quantitative sense.

4.3 *Waterlogging induced by irrigation*

Pakistan and India contain some of the most extensively documented cases of irrigation-induced waterlogging and salinization. Even there, however, it is difficult to evaluate the extent of problems based on available figures. In India, the total area affected by waterlogging due to both groundwater rises and poorly controlled irrigation was estimated in 1990 at 8.5 million ha by the Ministry of Agriculture (Vaidyanathan 1994). In contrast, estimates made by the Central Water Commission for 1990, which considered only areas affected by groundwater rises, totalled 1.6 million ha (Vaidyanathan 1994). Regardless of the actual extent, waterlogging problems represent a major surface and groundwater management challenge, and one that cannot be addressed in the absence of an integrated approach that incorporates surface water imports and use as well as groundwater. Large areas in Pakistan face similar problems. Rising water levels in the command of surface irrigation systems have fundamental implications for the sustainability of social objectives that are groundwater dependent. In the case of food security, estimates indicate that irrigation-induced salinity and waterlogging reduce crop yields in Pakistan and Egypt by 30% (World Bank 1994). In India, the problem is serious enough to threaten growth of the agricultural economy (Joshi *et al.* 1995). The impact of waterlogging and salinization on farmers and regional economies can be insidious. In the initial years, the introduction of irrigation often causes a dynamic transformation of regional and household economies. Farmers shift to high yielding varieties of grain and are able to grow valuable market crops. Wealth is created. As the water table rises, however, the *bubble economy* based on unsustainable water management practices slowly deflates. Land and the unsaturated zone of the soil, once salinised, are difficult and expensive to reclaim. Ultimately, many farm families –and regional economies– may be worse off than before the introduction of irrigation unless sustainable and affordable methods of remediation are found. Some progress with bio-drainage on moderately salinised land has been reported from the Punjab (IWASRI 1994) and it is hoped that this can be taken to scale.

4.4 *Generation of pollution externalities by agriculture*

The scope and scale of pollution externalities arising from agricultural use and return of groundwater plus associated land practices (application of fertilisers, pesticides and herbicides) have been realised only recently. For example, the Stockholm POPs convention (http://www.chem.unep.ch/pops), which makes provision for removal of stockpiles and mitigation measures for the *dirty dozen* organic compounds, has only just been ratified. In developed economies –the European Union is an example, the recognition and regulation of non-point sources of pollution from agricultural practice has been established for some time. However, distinguishing these sources from point sources associated with industrial or agro-processing point sources has proved controversial and resistance from small but powerful farming lobbies in Europe can be expected to slow the implementation of regulation.

The combination of these externalities is now resulting in sharp competition for groundwater quantity and quality within and between economic sectors.

In many developing countries, agricultural chemical use has, at least until recently, remained low in comparison to levels in industrialised countries. This may no longer be the case, particularly in countries such as India and China, where irrigation is extensive. Concerns over groundwater pollution from agricultural chemicals were raised as a major issue in India a little over two decades ago (Chaturvedi 1976), but few data were available. At that time, the level of agricultural chemical use was very low. By 1991, however, fertiliser use per hectare of agricultural land was 60% *higher* than in the USA (Repetto 1994, emphasis in original). At present no agency in India has a systematic programme for monitoring potential non-point sources of pollution. Fragmentary data indicating the potential extent of agricultural pollution problems are, however, available. In Gujarat, for example, maps prepared by the Central Groundwater Board (CGWB) show nitrate concentrations exceeding 45 mg/L (the maximum for drinking recommended by the World Health Organization) in over 370 sample sites scattered across the state (Phadtare 1988). How much of this is strictly related to agricultural pollution and how much to domestic or other sources is unknown.

Aside from non-point-source considerations, it is important to recognise that nitrate and other nutrient pollution in groundwater is often related to agricultural practices other than the use of chemical fertilisers. Any location where animal wastes are concentrated, such as feed lots or poultry farms, can release high levels of nutrients into groundwater. In addition to nutrients, pesticides and herbicides are other major sources of groundwater pollution related to agriculture. In some circumstances, soils can absorb or immobilise a large fraction of such agricultural chemicals. Many pesticides and herbicides, however, break down slowly under aquifer conditions and as a result, can persist over long time periods. In any case, groundwater pollution data are generally scarce and chemical analysis of water samples needs to be specific to detect their presence.

The dispersed nature of sources of pollutants is a core challenge facing both monitoring and control of groundwater pollution related to agriculture. Unlike industry or municipal sewage systems, agricultural pollutants are dispersed over large land areas. While return flows in drainage canals can be monitored, it is difficult to determine the extent of direct seepage of pollutants through soils and into the groundwater until contaminant concentrations in groundwater become significant.

4.5 *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 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 arbitrary 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 USA 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 & 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 not operated equitably and/or have induced local waterlogging. 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 is 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.

4.6 *Implications for food security*

The groundwater data and analytical issues highlighted in the proceeding sections place major limitations on the analysis of relationships between water and food security. Improving estimates of groundwater availability for irrigation beyond the initial calculations made by Postel, Seckler and Shah, would require a major initiative to collect primary groundwater data and the associated information essential to interpret it correctly from widely dispersed locations. In addition to the relatively straightforward process of locating data sources and documents, this would require substantial effort to obtain approval from governments in order to obtain access to primary data.

Compilation of available primary data on groundwater from country sources would substantially improve understanding of water level trends in the agricultural areas that supply much of the world's food production. This would enable evaluation of probable changes in the economics of groundwater extraction and changes in access to groundwater for poor and marginal groups or those dependent on specific technologies –such as dug wells. This type of information would have tremendous utility for evaluating the distributional and economic impacts likely to occur as development proceeds and water-levels decline. It would not, however, resolve the inherent problems of data quality and the short period of record that are often encountered due to the relatively recent establishment of groundwater monitoring networks. Similarly, questions related to other key components of the water balance equation –extraction rates, leakage between aquifers, evapotranspiration by native vegetation as well as crops, etc.– would not be resolved. As a result, while the data should enable improvements in over-abstraction estimates, they would not resolve many of the major modelling issues and would probably not enable accurate estimates of groundwater over-abstraction at a global or regional level. These types of uncertainties would be magnified if taken a step further and used as inputs for analysis of global food production. The parallels to debates over climate change are worth noting here. According to Rosenzweig & Hillel (1995):

> "The uncertainty inherent in predictions is a very important feature of climate change impact studies… Other uncertainties derive from the fast pace and unpredictable directions of future social, economic, political and technical changes. The world of the coming century will be different in many ways; unforeseeable developments in other sectors may change the way in which agriculture responds to climate change".
>
> "An even more challenging task is to estimate the probability of coincidental events that might happen in conjunction with global warming, spanning the range between low probability catastrophic events (called surprises) and higher probability gradual changes in climate and associated environmental effects. A seemingly small change in one variable –for example, rainfall– may trigger a major unsuspected change in another; for example droughts or floods might possibly disrupt the transport of grain on rivers. Moreover, one surprise may than lead to another in a cascade, since biophysical and social systems are interconnected".

Given the status of the groundwater database and the inherent unknowns in the models used to predict the impacts of development, the above comments apply equally well to estimates of the impacts of groundwater level change on global food production and security. While improvements in access to primary data on groundwater would improve models of food production and food security, the predictive value of such models will remain limited by data quality issues, incomplete understanding of systems and ongoing processes of climate, demographic, economic and agricultural change. The utility of this type of analysis is, as a result, uncertain. In the climate change case, Rosenzweig & Hillel (1995) advocate courses of action that respond to this uncertainty and increase resilience: "Identifying potential surprises and communicating them to the public and policy makers may help to build the resilience that is needed to anticipate and mitigate harmful effects in a timely fashion". Similar courses of action appear appropriate in the debate over groundwater over-abstraction and food security.

The above discussion suggests that, rather than attempting to analyse the *macro* implications of water availability or, more specifically, groundwater problems for food production or access on an aggregate level, it will be more productive to focus on a broad array of early warning indicators that can be used to trigger responses to food security concerns as they emerge at specific points of time in specific local contexts. Food security problems emerge due to a confluence of hydrologic, climatic, economic and social factors. Analysis could, as a result, focus on developing indices of food security vulnerability that combine an array of long and short-term physical, economic and social indicators. Groundwater conditions and availability would be among the more important water availability indicators that would need to go into this. They would need, however, to be combined with other indicators that reflect, for example, drought probabilities, general economic conditions (availability of alternative sources of work), global food availability and transport capacity, and so on. Such indices could be used to trigger proactive responses to emerging food security problems before they reach a critical level and thus reduce the need for *post facto* relief programs. The role of analysis would, thus, shift away from efforts to quantitatively predict the impact of groundwater depletion on aggregate food production and would focus instead on the development of more localized early warning indicators.

Placing greater emphasis on indicators of food security vulnerability does not reduce the importance of groundwater management. While data limitations and other factors restrict our ability to quantify with any degree of confidence whether or not groundwater over-abstraction and falling water levels have major implications for aggregate food production and access, we do know that it could. We also know that water level changes have major implications for poverty, environmental values, health and regional economies *whether or not* global food security is at risk. The critical importance of responding to groundwater problems in locations where they are clearly evident should, as a result, not be underestimated.

4.7 *Implications for water management*

On the basis of current practices, the obvious conclusion might be that there is no effective system of groundwater management. It is a rare exception when wells are closed down and capped off to prevent abstraction, or limits set on pumping durations or volumes. It is not such a rare exception to observe local, consensual enforcement of pumping limits. For example, it is possible to observe locally agreed controls and policing on pumping for irrigated agriculture in Eritrea and Yemen when pumped groundwater is rationed during dry season. These arrangements are *customary*, but have only been occasioned by the advent of cheap motorised pumps.

It is the pattern of groundwater use that serves as a starting point. For example, the patterns and management of groundwater and aquifer use in urban areas can be clearly distinguished from those patterns observed in rural areas. Two quite distinct styles of use exhibiting (and requiring) quite distinct management solutions for the each setting. In many arid and semi-arid urban areas, local aquifers are often the water resource of last resort and also the ultimate pollution sink –a rather schizophrenic circumstance– but the range of services provided by underlying aquifer systems are usually much more complex that those demanded by adjacent rural dwellers. Understandably, the systems of rights in use are markedly different. Rural users anticipate access direct abstraction from local aquifers (irrespective of their legal or customary status) while many urban dwellers and businesses anticipate municipal services derived from groundwater resources without any sense of real engagement with (or right in use) the resource.

These variable patterns of use and the varied services that aquifer systems provide do not amount to any clear aggregate picture or status of groundwater, nor do they present an opportunity for systematic management response. In this respect the situation is fuzzy. Despite the highly technical work that is carried out and presented in the hydrogeological literature, the status of knowledge of the aquifer systems is often limited at the level at which a management response is required. Highly detailed studies in contaminant transport are carried out in high value settings (usually because regulatory systems are enforced), but accurate and reliable monitoring and regulation in the crucial aquifers of Northern India (FAO, in press a), Baluchistan, for example, are not available. Even if they were, would such data provide an effective tool for regulation or furnish a clear message for the education of users and the basis for behavioural change?

One major concern is the fact that issues outlined above are a symptom of current water management as a whole. In general, these management practices continue to ignore the integrity of groundwater systems even in arid regions where groundwater is the *lender of last resort* and particularly with large sedimentary aquifer systems, which are de-coupled from contemporary recharge and are effectively non-renewable. In addition, the varying *scales* at which groundwater systems occur and are developed or exploited pose particular management challenges beyond those of conventional surface water or river basin management. Therefore a clear articulation of the specific guiding principles in groundwater development and criteria for evaluating policy responses to groundwater depletion and degradation is warranted. Such principles may have very little to do with the more conventionally espoused principles of *integrated water resource management* which are generally predicated on hydraulic control and regulation over river basins. This *engineering hydrology* focus on water management continues to colour water resource management styles, which remain largely centralised and technocratic, even in circumstances where the reliance on groundwater is profound. Such examples can be found in Namibia, where some 60% of bulk water is furnished by groundwater, yet the institutional arrangements and investments have been concerned with the development of intermittent surface flows.

5 OPPORTUNITIES FOR IMPROVING GROUNDWATER MANAGEMENT

5.1 *Introduction: gaps in management*

As human development becomes more susceptible to climatic variability and spatial variability in drought, groundwater acts as the primary buffer against the impact of this variability. Consequently three major gaps in groundwater management have emerged, each of which have significant implications for sustainable development.

1. The inability to cope with the acceleration of degradation of aquifer systems by over-abstraction, and effective resource depletion through quality changes (pollution, salinity).
2. The lack of both professional and public awareness about the sustainable use of groundwater resources generally. In particular, the lack of coherent planning frameworks to guide all scales of groundwater development and the consequent lack of appropriate policy responses and institutional development to prevent and attenuate degradation to groundwater systems.
3. The failure to resolve groundwater management through increased marginal costs, competition between sectoral uses and environmental externalities.

These specific concerns hinge upon the central issue of awareness, which relates as much to the groundwater related environmental concerns in industrialised countries as it does to the peri-urban communities in developing countries who are continually thrown back onto locally available groundwater sources. In this sense, groundwater management regimes may be expected to encompass a set of economics, regulatory, and ethical levers that are pushed by markets, regulators/state institutions and user associations. Effective institutional approaches need to be aware of these socio-economic realities surrounding groundwater use and appreciate the inherent risks associated with development and the level of uncertainty (plus limitations in data quality) and the range of social pressures.

5.2 *Filling the gaps*

Are there practical approaches for responding to groundwater problems or their socio-economic impacts that are absent in current management styles? In general it is possible to observe the following characteristics of current groundwater *governance*.

- Lack of data and scientific understanding limit the ability of society to predict aquifer functioning or to develop realistic rights systems.
- Rights systems are difficult to design or implement and in most situations for a variety of technical and economic reasons.
- Social acceptance of private rights may be problematic.
- Aquifer management is politically complex because it would require active modification of established use patterns.
- Finally, the dynamic nature of both socio-economic globalisation and global climate change makes management complex –people are increasingly mobile and often have little incentive to participate in long-term management initiatives.

Under these circumstances, groundwater management may be most realistic when applied in a limited manner to *strategic* aquifers –those that have a particularly high value in relation to key uses (such as domestic supply)– for which a social consensus supporting management exists. Arguably, this has happened in the case of the Qa'Disi aquifer in Southern Jordan and the sister aquifers in Saudi Arabia, but these bright spots are few and far between. Reference has already been made to the recharge initiatives in India (Shah 2000). Here a *thin and wide* approach to resource management may ultimately prove more successful that a *thick and deep* approach to aquifer management, such as the technocratic initiatives to aquifer recharge that have been observed along the Batiah coast in Oman and the Quetta basin in Baluchistan. In any event, the impacts of groundwater management approaches do require specific monitoring and evaluation periods to make an accurate assessment of success in terms of aquifer response alone, and it is doubtful if enough time has elapsed to allow such an assessment of the various initiatives and to identify clear *bright spots*.

These considerations apart, focusing management on strategic aquifers would also allow society to concentrate the required scientific, monitoring, and enforcement tools on relatively small areas. In addition, any current users displaced by management could be absorbed far more easily than if management were attempted over larger areas. The design of implementation strategies to successfully initiate and then propagate across the area of concern will be key and the recharge movement observed by Shah (2000) will deserve attention where it is clear that such viability may have more to do with social structures than the technical feasibility of conservation and regulation.

To start address gaps in management it is important to recognise that institutional innovation or adaptation in groundwater management will need to be much more sensitive to the range of influences and management instruments. A diagnostic to develop such adaptations will need to cover:

- Macro-economic policies.
- Sector policies.
- Rights systems.
- Institutions and capacities.
- Regulatory frameworks.
- Public involvement.

Against the *soft* institutional strategies, it is possible to define sets of technical options that relate directly to groundwater. Arguably, these options present expanded opportunities to manage groundwater, but again would have to be applied strategically in circumstances that are amenable –where uptake of technical strategies will succeed. Such technical options include:

- Conjunctive Management (conjunctive use and ASR).
- Conservation enhancement and protection.
- Water harvesting and supply enhancement.
- Irrigation efficiency improvement and demand management.

Implementing a suite of institutional and technical strategies and implementing them at the required scale to make an impact –to conserve or re-allocate groundwater resources.

6 CONCLUSIONS

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 allowed groundwater irrigation to take up opportunities in the continuum between rain-fed and full control irrigation –it has filled in– but has also sheltered the end user from natural hydrological risk. The imperative for in-field irrigation efficiency has been partially removed since the physical and economic management of the resource is often determined by command area authorities or, in the case of 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, 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.

Groundwater will continue to be used intensively and some expansion of irrigated agriculture can be expected to develop new groundwater sources, particularly as markets for agricultural produce change. This will happen in parallel with:

- Land going out of irrigated production due to physical depletion and migration of low quality water, economic depletion (where the costs of pumping become excessive), waterlogging and salinisation.
- Groundwater transfers out of agriculture (as is happening in the Western USA).

The net result is likely to be:

- A loss of some strategic aquifers.
- An enhancement of agricultural productivity in relation to overall water use (taking basin water budgets as a whole) and uptake of conjunctive use.
- A marked transfer of groundwater from agriculture to other competing users.
- Substitution of groundwater by imports or alternative sources.

All these shifts will be incremental –so that the scenario proposed by Brown (1999), for instance, is unlikely to occur. This is one of the continued advantages of groundwater. The impacts of intensive use are incremental, so to is recovery if systems can be relaxed. Having said this, it is always sobering to consider that with over 100 years of development in the Ogallala aquifer, a collective agreement to co-manage a common property aquifer can only attenuate the rate of decline, not reverse it (White & Kromm 1995).

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ANNEX

IRRIGATION AREAS FROM AQUASTAT

Country	PHYSICAL AREA	POPULATION (1)			WATER RESOURCES (2)	
	Total area (1000 ha) FAOSTAT 1999	Total population (1000 inh) 2000 FAOSTAT	Rural population (1000 inh) 2000 FAOSTAT	Urban population (1000 inh) 2000 FAOSTAT	Average precipitation 61-90 (mm/yr) IPCC	Internal renewable water resources (km3/yr) AQUASTAT
Algeria	238174	30291	12033	18258	89	13.90
Angola	124670	13134	8643	4492	1010	184.00
Botswana	58173	1541	767	774	416	2.90
Burundi	2783	6356	5787	570	1218	3.60
Cameroon	47544	14876	7599	7277	1604	273.00
Cape Verde	403	427	162	265	423	0.30
Central African Republic	62298	3717	2186	1531	1343	141.00
Chad	128400	7885	6010	1876	322	15.00
Comoros	223	706	471	235	1754	1.20
Congo, Republic of	34200	3018	1131	1888	1646	222.00
Benin	11262	6272	3621	2651	1039	10.30
Egypt	100145	67884	37195	30690	51	1.80
Equatorial Guinea	2805	457	236	220	2156	26.00
Djibouti	2320	632	105	527	221	0.30
Gabon	26767	1230	229	1001	1831	164.00
Gambia	1130	1303	880	423	836	3.00
Ghana	23854	19306	11901	7405	1187	30.30
Guinea	24586	8154	5482	2672	1651	226.00
Cote d'Ivoire	32246	16013	8590	7423	1348	76.70
Kenya	58037	30669	20517	10152	693	20.20
Lesotho	3035	2035	1466	569	788	5.23
Liberia	11137	2913	1605	1308	2391	200.00
Libyan Arab Jamahiriya	175954	5290	654	4636	56	0.60
Madagascar	58704	15970	11241	4729	1513	337.00
Malawi	11848	11308	8490	2819	1181	16.14
Mali	124019	11351	7941	3410	282	60.00
Mauritania	102552	2665	1126	1538	92	0.40
Mauritius	204	1161	682	479	2041	2.21
Morocco	44655	29878	13119	16759	346	29.00
Mozambique	80159	18292	10934	7358	1032	99.00
Namibia	82429	1757	1214	542	285	6.16
Niger	126700	10832	8604	2228	151	3.50
Nigeria	92377	113862	63775	50086	1150	221.00
Guinea-Bissau	3612	1199	914	285	1577	16.00
Eritrea	11760	3659	2973	686	384	2.80
Zimbabwe	39076	12627	8168	4459	692	14.10
Reunion	251	721	210	511	2051	5.00
Rwanda	2634	7609	7141	468	1212	5.20
Saint Helena	31	6	2	4	763	-
Sao Tome and Principe	96	138	73	65	2169	2.18
Senegal	19672	9421	4951	4469	687	26.40
Seychelles	45	80	29	51	1970	-
Sierra Leone	7174	4405	2791	1614	2526	160.00
Somalia	63766	8778	6365	2413	282	6.00
South Africa	122104	43309	21503	21806	495	44.80
Sudan	250581	31095	19863	11232	417	30.00
Swaziland	1736	925	681	244	788	2.64
Tanzania	94509	35119	23571	11548	1071	82.00
Togo	5679	4527	3021	1506	1168	11.50
Tunisia	16361	9459	3261	6198	313	4.15
Uganda	24104	23300	20002	3298	1180	39.00
Burkina Faso	27400	11535	9405	2130	748	12.50
Ethiopia	110430	62908	51805	11102	848	110.00
Congo, Dem Republic of	234486	50948	35521	15427	1543	900.00
Zambia	75261	10421	6293	4128	1020	80.20
Africa sub-total	**3,004,561**	**793,374**	**492,939**	**300,435**		**3,950.21**

WATER USE		IRRIGATION		SOURCE OF IRRIGATION WATER (3)		
Agricultural water withdrawal in 1998 (km3/yr) AQUASTAT	Agricultural water withdrawal as percentage of total withdrawal AQUASTAT	Year of irrigation data	Total irrigation (ha) AQUASTAT	Area irrigated with surface water (%) AQUASTAT	Area irrigated with groundwater (%) AQUASTAT	Area irrigated with groundwater (ha) AQUASTAT
3.94	69	1992	445500	-	-	-
0.21	65	1974	75000	100.0	0.0	0
0.06	50	1992	1381	44.3	55.7	769
0.19	84	1985	14400	-	-	-
0.73	74	1987	20970	-	-	-
0.02	88	1988	2779	-	-	-
0.001	5	1987	135	100.0	0.0	0
0.19	85	1988	14020	-	-	-
-	-	1987	130	-	-	-
0.004	10	1993	217	-	-	-
0.19	80	1994	9786	99.6	0.4	39
54.00	88	1993	3246000	95.4	4.5	146070
0.001	10	-	-	-	-	-
0.01	88	1989	674	0.0	100.0	674
0.05	48	1987	3150	-	-	-
0.02	92	1991	1670	-	-	-
0.25	64	1994	6374	100.0	0.0	0
1.36	93	1994	15541	100.0	0.0	0
0.60	72	1994	47750	100.0	0.0	0
1.01	68	1992	66610	99.0	1.0	666
0.01	31	1994	2722	-	-	-
0.06	54	1987	100	-	-	-
5.13	90	1990	470000	-	-	-
14.31	99	1992	1087000	-	-	-
0.81	86	1992	28000	100.0	0.1	14
6.87	99	1994	78620	97.4	2.6	2044
1.50	92	1994	49200	90.4	9.6	4723
0.37	82	1995	17500	88.0	12.0	2100
11.36	93	1989	1093200	68.3	31.1	339985
0.55	89	1993	106710	-	-	-
0.17	68	1992	6142	85.6	14.4	884
2.08	96	1989	66480	-	-	-
5.51	77	1991	219621	-	-	-
0.10	90	1994	5110	88.3	11.7	598
0.30	-	1993	12494	-	-	-
2.24	90	1993	116577	-	-	-
-	-	1998	12000	-	-	-
0.02	33	1993	2000	-	-	-
-	-	-	-	-	-	-
-	-	1991	9700	100.0	0.0	0
1.43	93	1994	71400	-	-	-
-	-	-	-	-	-	-
0.34	89	1992	1000	-	-	-
3.28	99	1984	50000	-	-	-
10.03	73	1994	1270000	82.0	18.0	228600
36.07	97	1995	1900000	96.0	4.0	76000
0.75	97	1990	67400	-	-	-
1.79	94	1993	150000	-	-	-
0.08	53	1990	2008	98.1	1.9	38
2.23	87	1991	355000	37.3	60.7	215485
0.12	59	1987	5550	-	-	-
0.69	90	1992	15430	-	-	-
2.47	89	1994	189556	-	-	-
0.11	29	1995	10000	100.0	0.0	0
1.32	77	1992	46400	94.6	5.4	2506
174.94			**11,489,007**			**1,021,196**

Country	PHYSICAL AREA	POPULATION (1)			WATER RESOURCES (2)	
	Total area (1000 ha) FAOSTAT 1999	Total population (1000 inh) 2000 FAOSTAT	Rural population (1000 inh) 2000 FAOSTAT	Urban population (1000 inh) 2000 FAOSTAT	Average precipitation 61-90 (mm/yr) IPCC	Internal renewable water resources (km3/yr) AQUASTAT
Armenia	2980	3787	1137	2649	562	9.07
Afghanistan	65209	21765	17003	4762	327	55.00
Bahrain	69	640	50	590	83	0.004
Bangladesh	14400	137439	103743	33696	2666	105.00
Bhutan	4700	2085	1936	149	1667	95.00
Brunei Darussalam	577	328	91	237	2722	8.50
Myanmar	67658	47749	34529	13220	2091	880.60
Sri Lanka	6561	18924	14466	4458	1712	50.00
Cyprus	925	784	339	445	498	0.78
Azerbaijan	8660	8041	3436	4605	447	8.12
Georgia	6970	5262	2068	3194	1026	58.13
Gaza Strip (Palestine)	38	1077	59	1018	-	0.05
India	328726	1008937	721998	286939	1083	1260.54
Indonesia	190457	212092	125266	86826	2702	2838.00
Iran, Islamic Rep of	163319	70330	27002	43328	228	128.50
Iraq	43832	22946	5320	17626	216	35.20
Israel	2106	6040	533	5507	435	0.75
Kazakhstan	272490	16172	7044	9128	250	75.42
Japan	37780	127096	27007	100089	1668	430.00
Jordan	8921	4913	1268	3645	111	0.68
Kyrgyzstan	19990	4921	3284	1637	381	46.45
Cambodia	18104	13104	11018	2086	1904	120.57
Korea, Dem People's Rep	12054	22268	8854	13414	1404	67.00
Korea, Republic of	9926	46740	8471	38269	1062	64.85
Kuwait	1782	1914	46	1869	121	0.00
Laos	23680	5279	4040	1239	1834	190.42
Lebanon	1040	3496	359	3137	661	4.80
Malaysia	32975	22218	9461	12757	2875	580.00
Maldives	30	291	215	76	1972	0.03
Mongolia	156650	2533	925	1609	241	34.80
Nepal	14718	23043	20304	2738	1321	198.20
Pakistan	79610	141256	88929	52327	304	248.00
Papua New Guinea	46284	4809	3972	837	3142	801.00
Philippines	30000	75653	31307	44346	2348	479.00
East Timor	1487	737	682	55	-	-
Qatar	1100	565	42	523	74	0.05
Saudi Arabia	214969	20346	2901	17445	-	2.40
Singapore	62	4018	0	4018	2497	0.60
Tajikistan	14310	6087	4411	1676	491	66.30
Syrian Arab Republic	18518	16189	7371	8818	318	7.00
Turkmenistan	48810	4737	2616	2122	161	1.36
Thailand	51312	62806	49250	13556	1622	210.00
Oman	21246	2538	406	2132	125	0.99
Turkey	77482	66668	16446	50222	593	227.00
United Arab Emirates	8360	2606	367	2239	78	0.15
Uzbekistan	44740	24881	15705	9175	206	16.34
Viet Nam	33169	78137	62722	15415	1821	366.50
Yemen	52797	18349	13814	4535	167	4.10
China	959805	1282437	865951	416487	627	2879.40
Asia sub-total	**3,221,388**	**3,675,033**	**2,328,164**	**1,346,870**		**12,656.64**

WATER USE		IRRIGATION		SOURCE OF IRRIGATION WATER (3)		
Agricultural water withdrawal in 1998 (km3/yr) AQUASTAT	Agricultural water withdrawal as percentage of total withdrawal AQUASTAT	Year of irrigation data	Total irrigation (ha) AQUASTAT	Area irrigated with surface water (%) AQUASTAT	Area irrigated with groundwater (%) AQUASTAT	Area irrigated with groundwater (ha) AQUASTAT
1.94	66	1995	285649	88.0	12.0	34278
22.84	99	1967	2385740	84.6	15.4	367404
0.17	62	1994	3165	0.0	86.4	2735
70.20	97	1995	3751045	30.8	69.2	2595723
0.40	98	1995	38734	100.0	0.0	0
-	-	1995	1000	100.0	0.0	0
27.86	99	1995	1555416	96.5	3.5	54440
11.74	97	1995	570000	99.8	0.2	1140
0.17	75	1994	39545	48.2	51.3	20287
11.65	70	1995	1453318	93.0	7.0	101732
2.13	60	1996	437500	100.0	0.0	0
-	-	1998	12000	-	-	-
580.81	94	1993	50101000	40.5	53.0	26553530
75.60	94	1996	4427922	99.0	1.0	44279
66.78	92	1993	7264194	49.9	50.1	3639361
39.38	92	1990	3525000	93.8	6.2	218550
1.31	77	-	-	-	-	-
28.41	82	1993	2313100	90.0	8.0	185048
56.03	63	1993	3128079	100.0	16.0	500493
0.76	76	1991	64300	39.7	54.6	35108
9.45	94	1994	1077100	99.0	1.0	10771
4.00	99	1993	269461	100.0	0.0	0
4.96	57	1995	1460000	86.0	14.0	204400
8.99	51	1996	888795	94.9	5.1	45329
0.20	48	1994	4770	0.0	61.0	2910
2.59	94	1995	155394	100.0	0.0	0
1.06	72	1993	87500	54.3	45.7	39988
5.60	65	1994	362600	92.0	8.0	29008
0.00	0	-	-	-	-	-
0.23	53	1993	57300	-	-	-
9.82	98	1994	1134334	73.9	12.4	140657
161.84	97	1990	14327000	66.0	34.0	4871180
0.001	2	-	-	-	-	-
21.01	76	1993	1550000	90.2	9.8	151900
-	-	-	-	-	-	-
0.21	74	1993	12520	0.0	94.2	11794
15.42	90	1992	1608000	3.2	95.6	1537891
-	-	-	-	-	-	-
10.96	92	1994	719200	87.0	9.0	64728
18.96	96	1993	1013273	39.8	60.2	609990
24.04	98	1994	1744100	98.0	2.0	34882
79.29	96	1995	5003724	99.8	0.2	10007
1.23	94	1993	61550	0.0	100.0	61550
27.11	76	1994	4070746	83.5	16.5	671673
1.53	69	1995	66682	0.0	100.0	66682
54.37	94	1994	4280600	94.0	6.0	256836
48.62	87	1994	3000000	-	-	-
6.19	96	1994	383200	0.0	100.0	383200
414.76	78	-	-	-	-	-
1,930.73			**124,694,556**			**43,559,483**

Country	PHYSICAL AREA	POPULATION (1)			WATER RESOURCES (2)	
	Total area (1000 ha) FAOSTAT 1999	Total population (1000 inh) 2000 FAOSTAT	Rural population (1000 inh) 2000 FAOSTAT	Urban population (1000 inh) 2000 FAOSTAT	Average precipitation 61-90 (mm/yr) IPCC	Internal renewable water resources (km3/yr) AQUASTAT
Albania	2875	3134	1832	1302	996	26.90
Austria	8386	8080	2856	5224	1110	55.00
Belgium - Luxembourg	3312	10686	310	10376	-	13.00
Bulgaria	11091	7949	2419	5530	608	21.00
Denmark	4309	5320	781	4539	703	6.00
Belarus	20760	10187	2939	7248	618	37.20
Estonia	4510	1393	438	955	626	12.71
Finland	33815	5172	1693	3479	537	107.00
France	55150	59238	14475	44763	867	178.50
Germany	35703	82017	10219	71798	700	107.00
Bosnia and Herzegovina	5113	3977	2269	1708	1028	35.50
Greece	13196	10610	4234	6376	652	58.00
Hungary	9303	9968	3589	6378	589	6.00
Croatia	5654	4654	1967	2686	1113	37.70
Iceland	10300	279	21	258	978	170.00
Ireland	7027	3803	1559	2244	1118	49.00
Italy	30134	57530	18988	38542	832	182.50
Latvia	6460	2421	751	1670	641	16.74
Lithuania	6520	3696	1167	2529	656	15.56
Malta	32	390	37	353	383	0.05
Moldova, Republic of	3385	4295	2313	1983	553	1.00
Netherlands	4153	15864	1686	14177	778	11.00
Macedonia, The Fmr Yug Rp	2571	2034	773	1261	619	5.40
Norway	32388	4469	1097	3372	1120	382.00
Czech Rep	7887	10272	2598	7674	677	13.15
Poland	32325	38605	13296	25310	600	53.60
Portugal	9198	10016	3562	6453	855	38.00
Romania	23839	22438	9836	12602	637	42.30
Russian Federation	1707540	145491	32471	113020	460	4312.70
Yugoslavia, Fed Rep of	10217	10552	5047	5505	795	44.00
Slovenia	2025	1988	987	1001	1162	18.67
Slovakia	4901	5399	2299	3100	824	12.60
Spain	50599	39910	8931	30979	636	111.20
Sweden	44996	8842	1475	7367	624	171.00
Switzerland	4129	7170	2313	4857	1537	40.40
United Kingdom	24291	59634	6371	53263	1220	145.00
Ukraine	60370	49568	15856	33712	565	53.10
Europe sub-total	**2,298,464**	**727,051**	**183,455**	**543,594**		**6,590.48**

WATER USE		IRRIGATION		SOURCE OF IRRIGATION WATER (3)		
Agricultural water withdrawal in 1998 (km3/yr) AQUASTAT	Agricultural water withdrawal as percentage of total withdrawal AQUASTAT	Year of irrigation data	Total irrigation (ha) AQUASTAT	Area irrigated with surface water (%) AQUASTAT	Area irrigated with groundwater (%) AQUASTAT	Area irrigated with groundwater (ha) AQUASTAT
1.00	95	1998	340000	-	-	-
0.02	1	1998	4000	-	-	-
0.11	1	1998	40000	-	-	-
1.97	15	1998	800000	-	-	-
0.55	45	1998	476000	-	-	-
0.84	32	1993	131000	-	-	-
0.008	5	1995	3680	100.0	0.0	0
0.07	3	1998	64000	-	-	-
3.56	10	1998	2000000	-	-	-
9.31	20	1998	485000	-	-	-
-	-	1998	2000	-	-	-
6.12	77	1998	1422000	-	-	-
2.45	36	1998	210000	-	-	-
-	-	1998	3000	-	-	-
0.0002	0.1	-	-	-	-	-
0.0002	0	-	-	-	-	-
20.00	47	1998	2698000	-	-	-
0.04	13	1995	20000	100.0	0.0	0
0.02	8	1995	9247	-	0.0	0
0.01	22	1990	763	0.0	63.3	483
0.76	26	1994	312000	100.0	0.0	0
2.69	34	1998	565000	-	-	-
-	-	1998	55000	-	-	-
0.23	11	1998	127000	-	-	-
0.06	2	1998	24000	-	-	-
1.35	11	1998	100000	-	-	-
3.60	49	1998	632000	-	-	-
14.23	57	1998	2880000	-	-	-
13.83	18	1990	6124000	-	-	-
-	-	1998	57000	-	-	-
-	-	1998	2000	-	-	-
-	-	1998	174000	-	-	-
24.22	68	1998	3640000	-	-	-
0.26	9	1998	115000	-	-	-
0.05	4	1998	25000	-	-	-
0.28	2	1998	108000	-	-	-
20.00	52	1994	2605000	100.0	0.0	0
127.65			**26,253,690**			**483**

Country	PHYSICAL AREA	POPULATION (1)			WATER RESOURCES (2)	
	Total area (1000 ha) FAOSTAT 1999	Total population (1000 inh) 2000 FAOSTAT	Rural population (1000 inh) 2000 FAOSTAT	Urban population (1000 inh) 2000 FAOSTAT	Average precipitation 61-90 (mm/yr) IPCC	Internal renewable water resources (km3/yr) AQUASTAT
Antigua and Barbuda	44	65	41	24	2420	0.05
Bahamas	1388	304	35	269	1292	0.02
Barbados	43	267	134	134	2066	0.08
Bermuda	5	63	0	63	1507	-
Aruba	19	101	-	-	-	-
Belize	2296	226	103	123	2191	16.00
Canada	997061	30757	7040	23717	537	2850.00
Costa Rica	5110	4024	2099	1925	2926	112.40
Cuba	11086	11199	2765	8435	1335	38.12
Dominica	75	71	20	50	3436	-
Dominican Republic	4873	8373	2926	5446	1410	21.00
El Salvador	2104	6278	3350	2928	1724	17.77
Greenland	34170	56	10	46	585	603.00
Grenada	34	94	58	36	1535	-
Guadeloupe	171	428	1	427	247	-
Guatemala	10889	11385	6870	4515	2712	109.20
Haiti	2775	8142	5236	2907	1440	13.01
Honduras	11209	6417	3033	3384	1976	95.93
Jamaica	1099	2576	1131	1445	2051	9.40
Martinique	110	383	19	364	2631	-
Mexico	195820	98872	25326	73546	752	409.00
Nicaragua	13000	5071	2225	2847	2391	189.74
Panama	7552	2856	1249	1606	2692	147.42
Puerto Rico	895	3915	970	2944	2054	3.40
Saint Kitts Nevis	36	38	25	13	2133	0.02
Saint Lucia	62	148	92	56	2301	-
Saint Vincent/Grenadines	39	113	52	62	1583	-
Trinidad and Tobago	513	1294	336	959	1787	-
United States of America	962909	283230	64553	218678	736	2818.40
N & C America sub-total	**2,265,387**	**486,746**	**129,699**	**356,949**		**7,453.97**
Australia	774122	19138	2931	16207	534	492.00
Solomon Islands	2890	447	360	88	3028	44.70
Fiji Islands	1827	814	411	402	2592	28.55
French Polynesia	400	233	110	123	-	-
Guam	55	155	94	61	-	-
New Caledonia	1858	215	49	166	1498	-
New Zealand	27053	3778	536	3242	1732	327.00
Tonga	75	99	62	37	1966	-
Samoa	284	159	124	34	2992	-
Oceania sub-total	**808,564**	**25,038**	**4,677**	**20,360**		**892.25**

WATER USE		IRRIGATION		SOURCE OF IRRIGATION WATER (3)		
Agricultural water withdrawal in 1998 (km3/yr) AQUASTAT	Agricultural water withdrawal as percentage of total withdrawal AQUASTAT	Year of irrigation data	Total irrigation (ha) AQUASTAT	Area irrigated with surface water (%) AQUASTAT	Area irrigated with groundwater (%) AQUASTAT	Area irrigated with groundwater (ha) AQUASTAT
0.001	20	1997	130	-	-	-
-	-	-	-	-	-	-
0.02	24	1997	1000	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
0.0002	0.2	1997	3000	-	-	-
5.41	12	1998	720000	-	-	-
1.39	55	1997	103084	83.0	17.0	17524
5.64	69	1997	788799	50.0	50.0	394400
0.00	0	-	-	-	-	-
2.16	69	1999	269710	78.0	22.0	59336
0.72	65	1997	44993	97.0	3.0	1350
-	-	-	-	-	-	-
-	-	1997	219	-	-	-
-	-	-	-	-	-	-
1.61	84	1997	129803	94.0	6.0	7788
0.93	94	1991	91502	-	-	-
0.66	83	1997	73210	-	-	-
0.20	50	1997	25214	-	-	-
-	-	-	-	-	-	-
60.34	78	1997	6256032	66.0	27.0	1689129
1.08	84	1997	61365	30.0	70.0	42956
0.23	32	1997	34626	99.0	1.0	346
-	-	-	-	-	-	-
-	-	1997	18	-	-	-
-	-	1997	297	-	-	-
0.00	0	-	-	-	-	-
0.02	6	1981	3600	-	-	-
209.43	44	1998	21400000	-	-	-
289.84			**30,006,602**			**2,212,828**
6.70	41	1998	2400000	-	-	-
-	-	-	-	-	-	-
0.05	82	1998	3000	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
0.89	44	1998	285000	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
7.64			**2,688,000**			**-**

Country	PHYSICAL AREA	POPULATION (1)			WATER RESOURCES (2)	
	Total area (1000 ha) FAOSTAT 1999	Total population (1000 inh) 2000 FAOSTAT	Rural population (1000 inh) 2000 FAOSTAT	Urban population (1000 inh) 2000 FAOSTAT	Average precipitation 61-90 (mm/yr) IPCC	Internal renewable water resources (km3/yr) AQUASTAT
Argentina	278040	37032	3733	33299	591	276.00
Bolivia	109858	8329	3126	5203	1146	303.53
Brazil	854740	170406	31901	138506	1783	5418.00
Chile	75663	15211	2181	13030	716	884.00
Colombia	113891	42105	10991	31113	2612	2112.00
Ecuador	28356	12646	4384	8262	2087	432.00
French Guiana	9000	165	36	129	2895	134.00
Guyana	21497	761	470	291	2387	241.00
Paraguay	40675	5496	2420	3077	1130	94.00
Peru	128522	25662	6988	18674	1493	1616.00
Suriname	16327	417	108	309	2331	88.00
Uruguay	17622	3337	292	3045	1265	59.00
Venezuela	91205	24170	3160	21010	1875	722.45
South America sub-total	**1,785,396**	**345,737**	**69,790**	**275,948**		**12,379.98**

Note
(-) No data available.
(1) The sum of the urban and rural population may deviate to the total population due to rounding.
(2) The internal renewable water resources is the sum of the average annual flow of rivers and recharge of groundwater generated from endogenous precipitation and does not include incoming flow originating outside the country.
(3) The sum of the percentage of irrigation area irrigated with groundwater and surface water does not add up to 100 % when nonconventional sources are used for irrigation. For Japan the sum exceeds 100 % due to supplementary irrigation on land supplied by surface water.

WATER USE		IRRIGATION		SOURCE OF IRRIGATION WATER (3)		
Agricultural water withdrawal in 1998 (km3/yr) AQUASTAT	Agricultural water withdrawal as percentage of total withdrawal AQUASTAT	Year of irrigation data	Total irrigation (ha) AQUASTAT	Area irrigated with surface water (%) AQUASTAT	Area irrigated with groundwater (%) AQUASTAT	Area irrigated with groundwater (ha) AQUASTAT
21.52	75	1988	1550233	74.0	26.0	403061
1.12	88	1999	128239	93.0	7.0	8977
36.12	63	1998	2870204	81.0	19.0	545339
7.97	71	1996	1900000	97.0	3.0	57000
4.92	47	1992	900000	-	-	-
13.96	82	1997	863370	99.0	1.0	8634
-	-	-	-	-	-	-
1.60	99	1991	150134	-	-	-
0.35	79	1997	67000	-	-	-
16.42	86	1998	1195228	89.0	11.0	131475
0.62	93	1998	51180	100.0	0.0	0
3.03	98	1998	181200	96.0	4.0	7248
3.94	64	1989	570219	98.0	2.0	11404
111.57			**10,427,007**			**1,173,137**