Chapter 3
Understanding the dynamics of groundwater resources

The complexity of flow within aquifers may require extensive data and detailed modelling to answer development questions. Even with this, as mentioned above, accurate analysis of the water balance is often complicated by inflows and losses that are difficult to identify, monitor or interpret.

However, relatively simple data, such as specific water levels in a carefully designed network of monitoring wells, can be combined with estimates of rainfall input to provide key indications of groundwater dynamics. Long-term declines in water levels are often indicative of overabstraction conditions. Similarly, stable water levels generally indicate that inflows are in balance with outflows. However, this is not always the case, e.g. where water in confined aquifers is released through compression, water levels may not decline at least initially when overdraft is occurring.

Unless monitoring networks are designed carefully and the data subject to careful analysis, water-level changes can be difficult to interpret. In many cases, declines represent local or regional cones of depression created by the lagged nature of aquifer responses to pumping or changes in inflow, not actual overabstraction. Aquifers can take hundreds of years to equilibrate to changes in extraction and recharge. Similarly, poorly designed monitoring wells often tap multiple aquifers; water levels observed in such wells provide a difficult-to-interpret reading of the pressure in all rather than a clear reading of head changes in any single one. Despite the care required in interpreting water-level changes, wells do provide the best, directly observable data on changes in groundwater conditions. Furthermore, they have a critical advantage in that they relate directly to water access. When water levels fall, whether or not overabstraction is occurring, the cost of pumping increases, shallow wells go dry and groundwater contributions to environmental values (such as the baseflow in streams or wetlands) decline. Furthermore, water-level changes are a key indicator that flow patterns are changing and that low-quality water may be mobilized. For this reason, they can provide advance warning of pollution and quality declines. As a result, water-level changes relate much more directly to ‘what people care about’ than do more abstract descriptions of extraction and recharge or flow dynamics. Based on these considerations, long-term records of water-level changes are probably the single most important piece of data necessary to monitor changes in groundwater availability. However, having such information is only the first step. In addition, there needs to be a clear mechanism to feed the information into formal planning processes. The mechanism also needs to ensure that data are transparently available to the user groups whose consensus would be required for effective action to limit drawdown to commonly acceptable levels.

NATURE AND LIMITATIONS OF AVAILABLE DATA

At the outset of this project, the hope was to locate significant amounts of data on groundwater levels in the focus countries through publicly available sources, particularly the Web sites and databases of the major international groups such as the Global Water Partnership. It was also hoped to locate substantial additional information through contacts in key organizations, e.g. the Central Ground Water Board (CGWB) in India, the IIMI, the IFPRI, the USGS, the British Geological Survey, the World Bank, and FAO. However, despite substantial effort, this search yielded relatively little primary data. In many cases, estimates of extraction and recharge are difficult to interpret from primary data. In others, there are statements such as: *“water levels in key aquifers are declining at rates of 1-3 m/year”*. However, such broad averages hide substantial variation.

In the 1980s, the UNDTCD (now merged into the DESA) compiled a systematic survey of groundwater occurrences on a country-by-country basis under the Water Series publications. This comprehensive work has not been updated, but at the time it represented the only systematic portrait of groundwater occurrences with an indication (where possible) of trends in groundwater resource use.

The degree to which this broad array of information on specific aquifers and aquifer systems and specific scientific themes related to groundwater can be collated to present a coherent ‘state of the art’ on the resource base is questionable. The proliferation of relevant material at country level would overwhelm a global exercise. Moreover, the benefits would be negligible compared with the urgent local problems on which groundwater management has to focus.

Box 3 is illustrative of the challenges that data limitations impose on management. Sources contacted at the World Bank, the IFPRI and the IIMI indicate that groundwater data are highly scattered and that access to much of the data is restricted owing to the confidential nature of many consulting reports. Data are often available in state and local-level groundwater

Box 3: The significance of groundwater data and its uncertainties

The problems of compiling groundwater data and interpreting abstraction records to establish and model the status of an aquifer system are well illustrated by interim reports on the Northwestern Sahara Aquifer System (SASS/OSS, 2001). This massive system covers Algeria, Tunisia and the Libyan Arab Jamahiriya and broadly comprises two super-imposed sandstones: Continental Terminal and Continental Intercalaire. Up to 8 000 borehole records and associated abstraction data from 1950 to 2000 have been compiled and a regional groundwater model constructed (Modflow - the standard finite difference groundwater model). A preliminary analysis of abstraction data indicates a two to threefold increase in pumped volumes throughout the aquifer system beginning in the late 1970s, peaking in 1990 and thereafter showing stabilization or slight decline. Abstraction from the system as a whole is estimated at 80 m^3/s. In 1950, abstraction was estimated at 13 m^3/s and in 1975 had reached 25 m^3/s. The impact on the overall water balance of the system is being refined through the application of a regional hydrogeological model. However, the distribution of boreholes indicates that the generation of drawdown externalities will be very localized. At control-point observation boreholes, there has been a marked lowering of the piezometric surfaces since 1980, with total drawdowns since 1950 typically of the order of 20-40 m in the exploited aquifer blocks. However, the control on abstraction data is variable (in Tunisia abstraction yearbooks have been published since 1973). In general, the levels of uncertainty associated with the data derived from a variety of data sources from the period of record are manifold. The authors of the reports emphasize the fundamental methodological differences that need to be appreciated when dealing with hydrogeological as opposed to hydrological data; specifically piezometric (water pressure head or level) altitude corrections and methods of analysis and validation in relation to hydrogeological time series data. For these reasons, the error terms that need to be attached to any hydrogeological observation are significantly higher than those normally associated with standardized streamflow data. Thus, even where great effort and thought is put into standardizing raw hydrogeological data in preparation for modelling activities, levels of uncertainty will remain high. In this particular case, model results do show a good match with the control observation data and thus provide a broad picture of the aquifer’s evolution as development has proceeded. However, the data and model results would probably be too coarse for the establishment of quantitative pumping rights in specific aquifer blocks.

departments but access often requires formal government permission and fluency in the local language. Furthermore, in many cases, the data are not in digital format. Hence, accessing data is frequently a time-consuming process.

The primary type of publicly available information is that contained in syntheses such as those produced by regional governments and by Postel (1999), Seckler *et al*. (1999), and Shah *et al.* (2000). The following section on China is typical of the results from these syntheses.

GROUNDWATER IN CHINA

"Although it is perhaps the most visible manifestation of water scarcity in China, the drying-up of the Yellow River is only one of many such signs. The Huai River, a smaller river situated between the Yellow and Yangtze rivers, was also drained dry in 1997, and failed to reach the sea for 90 days. Satellite photographs show hundreds of lakes disappearing and local streams going dry in recent years, as water tables fall and springs cease to flow. As water tables have fallen, millions of Chinese farmers are finding their wells pumped dry" (Brown and Halweil, 1998).

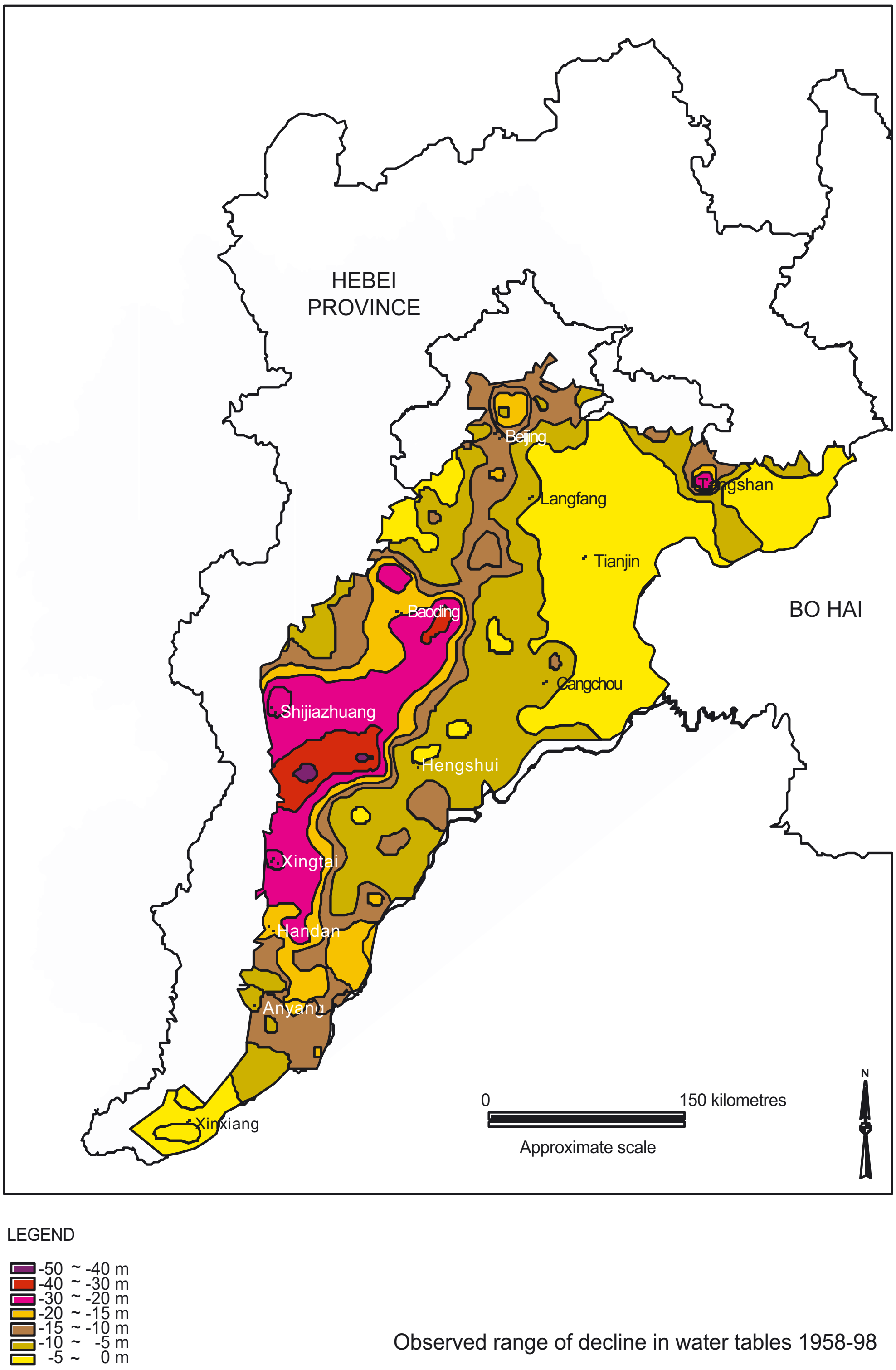
The above syntheses of China's data paints a picture of a country facing a serious water and population imbalance. Compounding the problem of falling groundwater levels (Figures 2a and 2b) is the country's huge population and its rapid urbanization as people leave the countryside to seek higher incomes in the industrial sector. This, in concert with population increases (by 2010 China's population is expected to grow by another 126 million), suggests a precarious future for the country's food security. The country's growing affluence compounds the issue as more affluent people consume larger quantities of livestock products (Brown and Halweil, 1998). China's cities are facing severe water shortages as demands for modern amenities grow and as consumption patterns change. Since 1965, the water table under Beijing has fallen by nearly 59 m, dropping 2.5 m in 1999 alone. Competition for water has usually seen farmers lose out to the much more profitable industrial sector. While figures may be imprecise, they do point to the drastic shortage China is facing and the direct implications for grain production. Falling groundwater levels could imply dire consequences for China's food security. China could be forced to import as much as 370 million tonnes of grain per year to feed its population in 2025 (above), with consequent steep increases in cereal prices and disruption of the world market. The country's vast size, growing population, and increasing affluence point to the critical need to make accurate assessments of China's patterns of grain production and water demand. Although the above analysis may be compelling, its accuracy is limited by the available data. National assessments of water demand in China (e.g. IWHR, 1998) have tended to overproject water demand. Moreover, such assessments obscure local aquifer dynamics where points of competition may be intense and shortfalls in supply apparent, but taken together do not necessarily permit a conclusion at macro-level or point to a national structural gap in groundwater availability.

Problems in accessing groundwater data

The problem of accurate assessment is illustrated in a report by the Ministry of Water Resources (MWR, 2001) on a water sector strategy for north China, specifically the Hai, Huai and Yellow (3-H) river basins. According to this report, the scale of abstraction for urban and rural use in the Hai basin has grown over the past 40 years, but projections of withdrawals in relation to available resources have changed considerably over time (Table 1).

Figure 2a

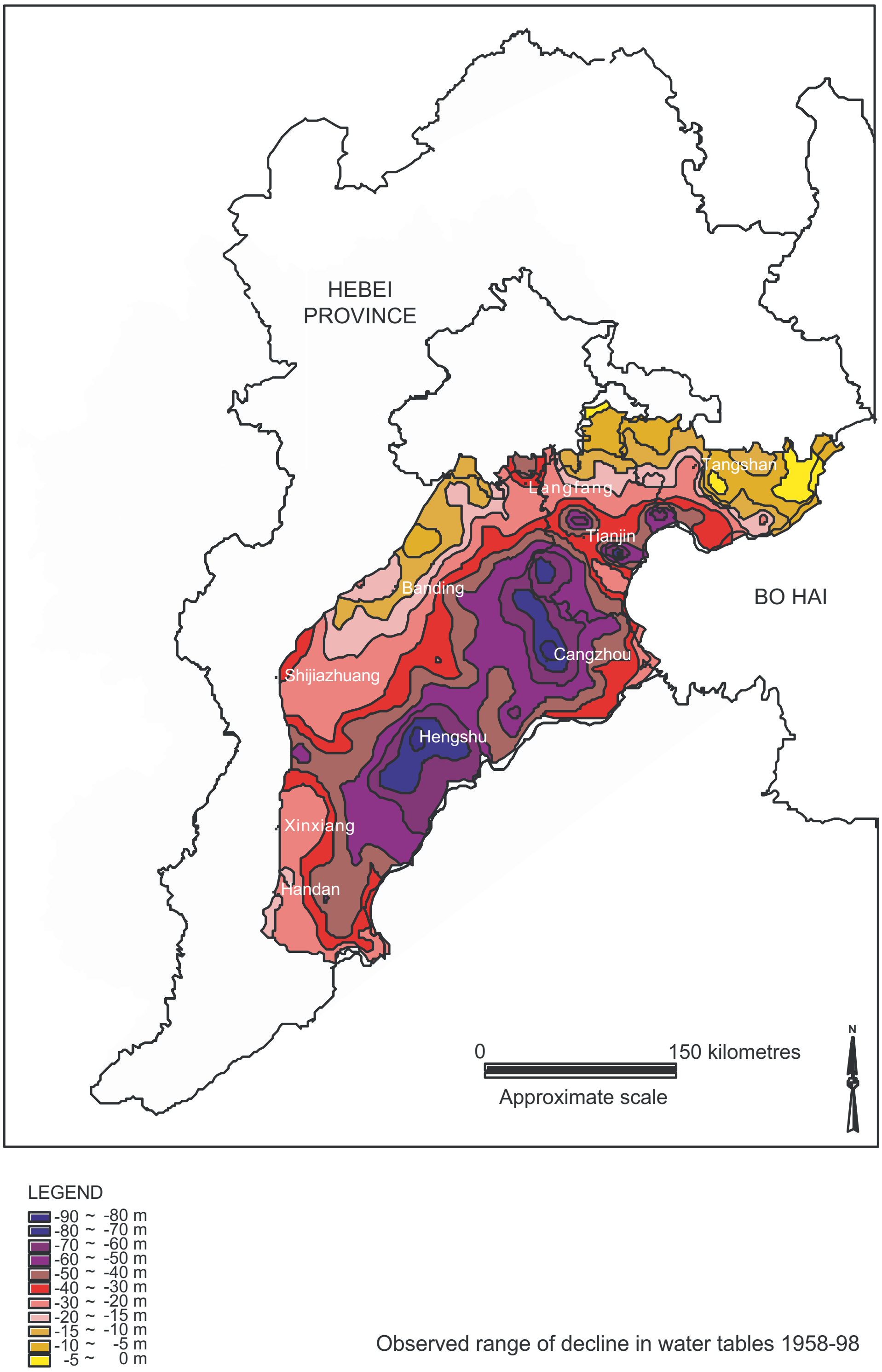
Difference between shallow groundwater levels in 1958 and 1998 in the Hai Basin Plains in northern China



Source: Agenda for Water Sector Strategy for North China. Ministry of Water Resources, World Bank and AUSAID, 2001.

Figure 2b

Difference between deep groundwater levels in 1958 and 1998 in the Hai Basin Plains in northern China



Source: Agenda for Water Sector Strategy for North China. Ministry of Water Resources, World Bank and AUSAID, 2001.

Table 1
Withdrawals for the 3-H basins, 1980, 1998 and projections

	1980	1998	2000	2010	2020	2050
			(1 000 million m^3)			
Non-agriculture						
IPPDI (1992)	19.7	36.2	46.9			
UNESCAP (1997)				45.0	75.7	
IWHR, NIHWR (1999)			46.9	67.5		
IWHR (1999)					74.2	87.6
IWHR action programme studies			39.9	54.0	68.4	88.7
World Bank			37.3	43.1	52.7	59.1
Agriculture						
IPPDI (1992)	106.4	102.5	128.7			
UNESCAP (1997)				125.9	129.1	
IWHR, NIHWR (1999)			116.5	118.3		
IWHR (1999)					109.5	106.5
Penman/FAO approach			141.1	141.0	138.1	140.1
Total						
IPPDI (1992)	126.1	138.7	175.6			
UNESCAP (1997)				170.9	204.8	
IWHR, NIHWR (1999)			163.4 1	85.8		
IWHR (1999)					183.7	194.1

Notes: Sources in table: IPPDI, China's water resources development, 1992. UNESCAP, China: water resources and their use, 1997. NIHWR, IWHR, China water supply and demand in 21st century, 1999. IWHR, Strategic options for the water sector, 1999. IWHR, Industrial and domestic water demand forecasts, project working paper, 1999.
Source: MWR (2001).

The report goes on to emphasize that: *"The two most striking aspects of these results are (a) they all exceed likely future water supply capacity .… by a wide margin, and (b) each successive projection resulted in lower future demands than its predecessors. For example, IPPDI (probably writing in the early 1980s) projected demand to total 175.6 Bcm for the entire 3-H region in 2000. The United Nations Economic and Social Commission for Asia Pacific (UNESCAP), based on analysis done by NIHWR about 1996, reduced this to 170.9 Bcm. IWHR, working on the Action Program in 1999, came up with 163.4 Bcm. The years beyond 2000, where estimated, show similar trends. The Australian Consultant, using an entirely different approach, came up with lower numbers still. ... the 3-H region has probably hit a "brick wall" supply constraint, which in the absence of alternative water supplies, will constrain withdrawals to something near 140 Bcm per year"* (MWR, 2001).

Syntheses such as the above were developed in large part by collecting information from a mix of raw water-production data from provincial authorities and related reports in the consulting, international development and scientific literature. Moving beyond them to tease out the specific groundwater abstraction data would require access to primary sources. This is complex. The same report quoted above states that: *"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.”*

Nonetheless, the report does give a summary of groundwater resources and use in the 3-H basins. However, in view of the data problems emphasized in the report, it is not clear whether the summary is any different in its accuracy (or relevance to management in specific locations) from any of the preceding summaries.

Implications for food security

Even with free access to primary data, substantial questions exist regarding the extent to which a clear understanding of emerging groundwater overabstraction concerns and their implications for economic development or food security would emerge. The MWR (2001) report notes: *“There is hardly a sector in which water does not play an important role, and given its scarcity it may therefore appear very surprising that there is so little correlation between growth and water conditions. But analogy with other poorly endowed countries and regions in East Asia and elsewhere suggests that neither land nor water constraints need be decisive. Rather, it is a question of how well a country or region adapts to its resource endowment that determines whether land and water constraints impact seriously on economic development. ... In this sense, natural resources are no different from the other factors that help determine comparative advantage, and alarmist conclusions to the contrary are very misleading. It is the conclusion of this report that economic growth in the 3-H region ... including agricultural growth, can be sustained and that water may not impede this growth provided immediate attention is directed to finding real solutions to current water pollution and water scarcity problems.”*

However, the concluding chapter of the report (on proposed action plans) reports the following contrasting comment: *“The very serious and largely irreversible falling groundwater levels throughout the North China Plain demands a major program of groundwater management planning to reduce groundwater use to sustainable levels. The groundwater management strategy proposed will require a huge effort, however the consequences of not doing it will have major long term implications, such as effectively destroying the groundwater dependent agricultural base, massive subsidence and sea water intrusion, virtual elimination of groundwater as a water source for many cities and countless households and the loss of “insurance” water for future generations.”*

The above comments highlight a basic tension in the MWR report that is also present in debates on the relationship between water availability and food security in many other regions. Groundwater overabstraction in the 3-H region is substantial and could lead to reductions in food production. However, even under a severe drought, any reduction in irrigated area would almost certainly occur gradually because water levels are declining at different rates in different locations and water availability varies widely in different parts of the aquifer. This gradual decline could be offset by China’s plans to import water from other areas. It could also be offset by a gradual increase in food purchases from global grain markets. Such purchases might in turn encourage more production in other parts of the world and could lead to a broad redistribution of production to areas with greater comparative advantage for irrigated agriculture. At least in the short term, the main threat to food security would occur if groundwater depletion occurred in conjunction with a wide variety of other factors that limited China’s ability to adapt. For example, severe food security problems could arise if an extended and severe drought occurred in areas suffering from overdraft and if access to global markets were constrained by war, economic conditions or sudden increases in demand from other countries in addition to China.

Once again, the point is that groundwater overdraft is likely to become a major source of food insecurity primarily if it occurs in conjunction with other factors that limit China's ability to adapt.

The viability of groundwater management

In addition to uncertainty over the implications of groundwater overabstraction for food security, the way towards management 'solutions' is not clear. For example, the MWR (2001) report advocates a set of regulatory measures predicated upon identification and planning of sustainable yields and the coordinated compliance of millions of groundwater users. As it states: "*The fundamental objective proposed is to reduce groundwater use to sustainable levels by 2015.*" A broad range of technical, institutional and management actions are required to achieve this goal.

"*The key actions required are:*

- *All significant groundwater usage areas be defined as Groundwater Management Units and the Sustainable Yield be determined.*
- *Groundwater management plans be prepared and implemented as per the program described herein.*
- *Allocation licensing be linked with the sustainable yield assessment.*
- *Allocation licensing be only undertaken by one department.*
- *Licensing of well construction drillers.*
- *A National Groundwater Data Base be developed.*
- *A groundwater pollution prevention strategy be prepared.*
- *The Ministry of Water Resources should review the adequacy of regulations required to implement the groundwater management reforms proposed herein.*
- *The introduction of realistic groundwater prices.*
- *A major education program about groundwater processes and the need for groundwater management.*"

Despite the above recommendations, the report does not address in detail the viability of the management actions it advocates. However, it does hint at the probable complexities when it states in the case of shallow aquifers that: "*In principle, shallow wells should be regulated and charged for in a comparable manner to deep wells, but in practice regulation of dispersed small wells may be difficult and farmers may resist resource charges. Unsustainable use results in well interference, higher pumping costs, reductions in over-year storage and other adverse externality effects (of which mobilization of arsenic and other minerals may be the most damaging). Nevertheless exploitation of shallow aquifers tends ultimately to be self-regulating as farmers adjust conjunctive use of rainfall, surface supplies and groundwater to whatever combination of resources is available to them. This may not result in a theoretical "optimum" but in practice can be an acceptable compromise.*"

More indications of the probable challenges are contained in a recent study of the Hauihe basin (United Nations, 1999). The report emphasizes that, even with centuries of experience in hydraulic management and the proliferation of voluminous hydraulic regulation, surface water management in the Hauihe basin is effectively anarchic and that implementation of sensible water policies and law remains blocked by the economic self-interest of riparian provinces.

Given the fragmented database in the 3-H region, the technical viability of some key recommendations (such as assessment of sustainable yields) is unclear. As the situation in the Hauihe basin illustrates, the social and political viability of most of the other core recommendations may also be open to question. Where surface-water management is, for a combination of social and political reasons, effectively anarchic, there is little reason to expect that management will be more effective in the groundwater case. Hints of the political complexity of groundwater management are also evident in the contradictory objectives evident at numerous places in the report. For example, in relation to the tension over groundwater allocation to different sectors, the MWR report states: "*From a macroeconomic view, the vastly higher economic values of water generated by the urban and industrial sectors should not be sacrificed for increased agricultural production. The ability of China's industrial sector to generate trade surpluses easily offsets foreseeable reductions in agricultural output that may arise from irrigation water shortages. However, three-fourths of China's population is rural and depend on agriculture for two-thirds of their incomes. Protecting and increasing these incomes and maintaining growth in agricultural production is a national concern, and one that depends in part on more and better irrigation.*"

Overall, the emergence of major overabstraction problems contrasted with uncertainties regarding their real extent, the issue of what can be done (in terms of implementing regulation) and the implications of leaving problems unaddressed generates substantial tension in debates on approaches to groundwater.

The circumstances in northern China illustrate the complexity inherent in any evaluation of the implications of groundwater overabstraction for regional food security. Questions start with basic information and data on groundwater conditions and then move upwards through the implications of water availability for agriculture and economic development before approaching the food security equation. Questions also depend on the viability of management. A key starting point in investigating this chain rests on groundwater data, on the degree to which emerging groundwater problems are understood and their implications open to interpretation.

GROUNDWATER MONITORING IN INDIA

In India, the groundwater data issue has been examined in detail and there exists a national organization dedicated to the collection and analysis of groundwater data. The case of India is illustrative of the inherent data problems facing any global evaluation of groundwater conditions.

India maintains extensive networks of wells for monitoring groundwater levels and water quality. The CGWB operates a network of about 10 000 monitoring wells nationwide. Groundwater entities attached to various state-level departments operate other networks. Water is a state matter under India's constitution but the central government provides much of the financing for groundwater development. In consequence, there is substantial competition for control over funding and the interpretation of groundwater data. This situation complicates scientific evaluation of groundwater conditions.

Historically, most of CGWB-maintained wells were open dug wells (generally used for drinking-water). However, a substantial number of isolated piezometers have been installed over the past five years and the number is increasing. Aside from a limited selection of piezometers and key wells that are monitored more frequently, most wells in the CGWB network are monitored four times a year, including once before and once after the monsoon.

Groundwater data collection and monitoring by organizations at state level is relatively similar in design to the CGWB network but varies substantially in relation to the attention given to it. Some states have developed extensive groundwater departments attached to major line organizations such as the Public Health Engineering Department. Other states maintain small units as adjuncts to marginally related mining or geology organizations. Most states monitor a network of 1 500-2 000 wells although some have many more (Rajasthan monitors more than 6 000 wells). Groundwater levels in state networks are generally monitored twice a year, before and after the monsoon. As with the CGWB, state monitoring networks are dominated by open dug wells supplemented by a small number of piezometers. Some are moving to strengthen their networks through the installation of piezometers (Rajasthan being a prime example). However, most of these piezometer networks are only a few years old.

Until recently, data collection by both the state organizations and the CGWB was organized on the basis of blocks, local-level administrative units between the *panchayat* (local government) level and the major districts into which each state is subdivided. Recently, some states have transferred the focus of groundwater data collection and monitoring to hydrological units. For example, Maharashtra conducts monitoring on a watershed basis, while Rajasthan uses ‘hydrologic potential’ units. Recent revisions in groundwater evaluation methodologies by the Ground Water Resource Estimation Committee (GWREC) recognize the importance of hydrological units and recommend that monitoring and evaluation be based on watersheds (GWREC, 1997). Regardless of the base unit, groundwater conditions in most states are reported on the basis of administrative blocks. This reflects the core reason why groundwater monitoring was initiated: its role in guiding the allocation of groundwater development financing.

Analytical methods and the role of groundwater data in development finance

Groundwater development in India was initiated on a large scale in the 1950s and 1960s as a core strategy to address famine and increase agricultural production. The spread of groundwater irrigation was achieved primarily through government credit and subsidies to farmers for wells, through extension of the electricity network into rural areas and through power subsidies for both diesel and electricity. Subsidies and credit guarantees for new wells are provided through the National Bank for Agriculture and Rural Development. These are targeted to local banks at the block level in rural areas. In order to target available financing as efficiently as possible and avoid financing where groundwater resources are limited, funds are allocated on the basis of groundwater availability estimates.

Availability is defined as the balance between recharge and extraction. Estimates of this balance are defined as the ‘level of development’, equal to the ‘net yearly draft’ divided by the ‘utilizable resource for irrigation’ (GWREC, 1997). The GWREC categorizes areas for the purpose of financing as ‘safe’ (level of development less than 70 percent with no significant long-term decline in water levels), ‘semi-critical’ (level of development between 70 and 90 percent and with no significant long-term decline in water levels) and ‘critical’ (level of development between 90 and 100 percent with declines in water levels, or more than 100 percent and no declines in water level). Areas where the level of development exceeds 100 percent and both pre- and post-monsoon water levels show long-term declines are classified as overexploited.

In general, financing for groundwater development is open in areas where development estimates are below 70 percent, somewhat restricted in critical areas, and highly restricted in overexploited areas. Local surveys are required in critical areas before the financing of any further groundwater development. For overexploited areas, the GWREC (1997) recommends

Plate 7
A groundwater recharge message in Gujurat, India
[M. Moench]

that “*there should be intensive monitoring and evaluation and future ground water development be linked with water conservation measures*” (Plate 7).

Recharge estimation

The estimated level of development plays a central role in the allocation of funding. The recharge component of this is estimated using the ‘water-table fluctuation method’. The core principle is that water-level changes between the pre- and post-monsoon readings (generally a rise) are multiplied by the estimated specific yield of the regional formation and by the area of the evaluation unit (watershed or block) in order to estimate the volume of water recharged during the monsoon. This value is normalized to reflect the nature of the rainfall year, and corrections are made to account for recharge during the non-monsoon period and other inflows. Finally, a percentage of the estimated water is reserved for drinking. The remainder is classified as the net resource available for irrigation. Extraction estimates are based on well surveys and estimated pumping hours (GWREC, 1997). In most states, the above method has been applied to estimate groundwater availability in administrative blocks regardless of the nature of the hydrological units involved. Water-level fluctuations in the 5-10 monitoring wells in each block, together with rainfall (used in normalizing fluctuation measurements), represent the only direct measurements. The remainder of the estimate depends on assumptions derived from other studies regarding the specific yields, pumping hours and other factors applicable to the area.

Estimates of gross recharge based on water-table fluctuations contain large scientific uncertainties. First, the water-table fluctuation approach assumes that resource availability can be calculated on the basis of changes in saturated storage. Particularly in hard-rock areas, changes in storage in the vadose (unsaturated) zone may be the primary factor determining actual water availability (Narasimhan, 1990). Second, estimating changes in saturated storage requires accurate assessments of specific yields from pumping tests. Most analytical methods for interpreting pumping tests were devised for borewells in alluvial aquifers with relatively simple geometric configurations. They do not apply to the large-diameter wells and complex, heterogeneous, hydrological conditions typical of the hard-rock aquifers extending throughout most of peninsular India. As Narasimhan (1990) states: “indiscriminate fitting of hydraulic test data to available mathematical solutions will but yield pseudo hydraulic parameters that are physically meaningless.” Therefore, one of the key parameters necessary for estimating recharge using water-table fluctuations may be impossible to calculate in many areas.

Abstraction estimation

Abstraction estimates represent the 'second half' of the equation for estimating the level of development. Moench (1994) argues that these probably contain more inherent uncertainties than do the recharge estimates. In India, groundwater abstraction is estimated using a combination of well census figures, average well commands, crop areas, water duties, well yields, and pumping hours. The GWREC (1997) recommended calculating abstraction by multiplying the average area irrigated by each well by the average annual irrigation depth. In practice, the precise method used to calculate extraction varies in different states and localities.

Regardless of method, there is substantial uncertainty in the basic data underlying extraction estimates. In Gujarat, the 1986-87 census of minor irrigation was conducted in a drought year when many wells were dry. It is the only comprehensive source on well numbers. If one takes the number of wells counted as functioning in 1987 as the basis for estimating extraction (as was done in the 1992 assessment), then the state's net area irrigated from groundwater is about 1.7 million ha. However, the total number of wells present is much higher than the number functioning during the 1987 drought. If all the wells were included when estimating irrigated area, then the total would be about 3.5 million ha. As the official 1992 estimate of the total area that can potentially be irrigated from groundwater is 2.9 million ha, the difference between the two well counts is a difference between 59 and 121 percent development. Similar problems are also present with crop water duties. These are generally estimated using data from experimental farms. The number of irrigations used on experimental farms and in farmer's fields can vary by a factor of three or more (Goldman, 1988).

Given problems in the available data, most groundwater experts working in government departments consider abstraction estimates to be less reliable than recharge estimates. Accurate estimation of each of the components used for calculating draft would require substantial surveys for which the groundwater departments lack sufficient resources. As a result, hydrologists working for state and central organizations often state that they adjust abstraction figures to represent what they think is happening.

Methodological improvements

The 1997 GWREC report contains several important methodological improvements over the water-level fluctuation methodology adopted in 1984. The new methodology recommends that evaluations be done on the basis of watersheds rather than administrative blocks and incorporates consideration of long-term water-level trends. The earlier approach did not utilize water-level trends in the definition of critical and overexploited areas. Instead, it focused on the estimated 'level of development' within administrative blocks as the sole measure.

However, major methodological issues remain. All of the inherent data issues in estimating recharge using water-level fluctuations remain. Groundwater abstraction volumes are also highly uncertain. The report states that abstraction is not to be estimated "based on (a) electric power consumption from pumpsets, (b) statistics of area irrigated by ground water and the associated crop water requirements, and (c) use of remote sensing data to obtain seasonal data on area of different irrigated crops in non-command areas, where only ground water irrigation is used." The report goes on to indicate that: "In view of the uncertainties in the estimation of ground water draft by any of these methods, it is clearly desirable to use more than one method for draft estimation to enable a cross check." As power for groundwater pumping is unmetered in most areas and many wells are diesel, the first method is of limited usefulness at present.

Statistics on crop water requirements and irrigated areas have the same inherent issues mentioned by Moench (1994). The use of remote sensing information might improve area estimates but would not improve crop water use estimates.

Beyond the methodological issues, many states are raising questions with regard to implementation of the recommended methodologies. Such questions have made it impossible for the CGWB to issue any updated national evaluation of groundwater resource conditions.

The only relatively recent and publicly available report (CGWB, 1995) is based on data from as early as 1989-1990 and was compiled using the older estimation methodology that neglected long-term water-level trends.

Data collection and quality

The above methodology and its utilization as a key tool have been the major factor driving groundwater data collection in the past 20 years. Because ‘level of development’ was the main criteria for allocating groundwater development financing, the focus of groundwater monitoring was to collect the water-level fluctuation data necessary to drive the methodology. Furthermore, arid states such as Rajasthan and Gujarat, which depend heavily on groundwater, had a strong incentive to generate their own data as a tool in the debates with the central government over development finance. As a result of this dynamic, pre- and post-monsoon water levels are available as the core data set with state groundwater organizations and the CGWB.

Although some wells have been monitored since the mid-1970s, most of the monitoring began in the 1980s after the GWREC report. Staff from the CGWB and state groundwater organizations take measurements manually. Most of the wells selected are dug wells because tubewells are often blocked by pumps. Where possible, wells used for drinking-water rather than irrigation have been selected. This selection rests on the assumptions that drinking uses will result in less extraction and that the well will provide a more accurate measure of water-table conditions than more heavily utilized wells. However, many state networks contain a significant number of irrigation wells where use levels may be high. This is also true of the CGWB network (although this network contains a significant number of piezometers).

Data from the national and state networks are currently being compiled electronically and as part of the Hydrology Project, which is supported by the World Bank. This project covers most states. Although the data are in electronic format, they are not readily available to the public. There are also substantial questions regarding the reliability of data, particularly those from some of the state networks (Moench, 1994). In addition to the usual problems with any form of data collection, the role that data play in determining financial allocations for groundwater development creates a major structural dynamic that can affect their quality. For example, in Gujarat, water levels recorded in the original logbooks were corrected as many as four times from the original measurement. The then chief hydrologist of the state explained this as corrections for staff errors explaining that the water level cannot fall during the monsoon, hence data that indicate otherwise must be errors. However, under the water-table fluctuation methodology, water-level declines during the monsoon would reduce the estimated recharge and could shift the status of a block into the restricted critical or overexploited categories. As a result, there are incentives to manipulate the outcome of groundwater availability estimates and these appear to have affected the quality of basic data at least in the above case. Moench (1994) discusses this issue in detail. However, the main point is that there are significant non-technical factors that may have affected the quality of some of the core water-level data.

Variability

Data quality issues are compounded by the large seasonal and interannual variability in water-level trends and hydrological conditions encountered within physiographic regions. Administrative blocks often contain a wide variety of geological formations and hydrological units. In many cases, monitoring wells have not been selected to represent these units but to ensure a reasonable distribution of monitoring points within a given administrative block. As a result, it is difficult to relate monitoring data to specific aquifers or hydrological units.

The lack of good hydrogeological information may be one factor explaining the high degree of variability in water-level trends observed in monitoring wells within relatively small areas. For example, water-level trends within regions often display substantially different hydrographs. For example, maps of ten-year changes in water levels made by the Ground Water Department in Rajasthan indicate broad declines of from 1 m to more than 10 m between 1984 and 1987 (Rathore and Mathur, 1999). A review of the actual data on which this map was prepared indicates that field conditions are more complex. For example, in Jaipur, one of the districts most affected by overabstraction, monitoring wells show highly varied trends and both the rate and extent of decline depend on the time-period selected. Water-level trends are rising in some blocks, while the extent to which water levels are falling is less clear in others. This probably does not invalidate the general picture indicated in the Ground Water Department's map, but it does highlight the large variation present at local levels even within areas where overabstraction levels are reported to be high. This variation complicates estimation of the impacts of overabstraction on water access and thus on food production and security.

In addition to variation in groundwater conditions, there is substantial variability in precipitation, the main source of recharge. This is particularly true in arid areas. As Pisharote (1992) notes for the district of Kutch in Gujarat, half the annual rainfall typically occurs in a period of 2-3 hours in the monsoon season. There are generally 8-10 rainy days in the year and rain actually falls for an annual average of 12-15 hours. Under these conditions, rainfall is highly located and runoff is intense and lasts for brief periods. Rainfall also varies significantly from year to year and location to location. As a result, long periods of record would be required to develop accurate estimates of rainfall, runoff and recharge. This is not a minor concern. As discussed in Box 1, rainfall increases in the High Plains occurred over nearly 20 years and provided an ultimately unfounded proof for many regarding that model's validity. Reisner (1986) reports a similar situation where water of the Colorado River, the United States of America, was allocated between states based on an average annual flow estimate of 17.5 million acre-feet (21 577 500 000 m^3). However, the period of record happened to include some of the wettest years in the Colorado basin's history. The water allocation agreement did settle disputes temporarily but, as subsequent records indicate, only temporarily as "the average annual flow of the Colorado River was nowhere near 17.5 million acre-feet." (Reisner, 1986).

The potential for problems similar to those above is high in the case of groundwater in India. Groundwater monitoring data in India span a few decades at most. Given the wide range of hydrological units involved, the high variability of the hydrological cycle in arid areas and the short periods of record, such data must be interpreted with caution. This is particularly true with 'level of development' estimates as they are derived by combining a wide variety of information, all of which is subject to substantial regional, seasonal and long-term variation. Furthermore, extraction and recharge estimates do not reflect directly the factor that has the greatest influence on access to water, i.e. water levels. Users may not care about the theoretical balance between extraction and recharge but they do care about water being available in the wells, and this availability is a direct function of water-level fluctuations, not the longer-term balance between extraction and recharge.

Water-level fluctuations

Hydrographs for locations in Gujarat illustrate some of the water-level conditions encountered through monitoring open dug wells in hard-rock areas. In Gordhanpur, monitoring between August 1981 and August 2000 indicated a water-level decline of about 2 m in a 20-year period (Figure 3). However, the main information this hydrograph conveys concerns daily fluctuation rather than long-term change in average levels. During dry periods, e.g. 1986-88, water levels often fell more than 20 m below ground level. However, they approached the ground surface at other times. The water-level observations reflect a rapid aquifer response to changes in conditions, presumably rainfall and extraction. The declining trend line may be an artefact of the period of data collection rather than an actual trend. This may also be the case for the Jhalod hydrograph (Figure 4), where the trend line is increasing and fluctuations are significant.

The trend in the Junagadh hydrograph (Figure 5) indicates a decline of about 3 m in the period 1970-2000. However, the hydrograph indicates that water levels return to within 3-7 m of the ground surface in most years. In 1975-76 and in 1986-88, water levels fell to more than 20 m below ground level. This suggests that the aquifer was responding rapidly to drought or short-term increases in extraction. The hydrograph also suggests that the magnitude of annual fluctuations in water level has increased in the past decade, but the data are not conclusive. However, such a pattern would be consistent with that expected in hard-rock areas as development increases. Well discharges typically increase linearly with increases in the width and number of fractures and, reflecting declines in fracture width and spacing, decrease linearly with increases in depth to the static water level (Basak *et al.*, 1993). Therefore, the magnitude of fluctuations is likely to increase as well depth increases, regardless of whether or not recharge increases.

The hydrographs in Figures 3, 4 and 5 are all from open dug wells where use may be a factor in the water levels observed on any given day. Continuous monitoring in isolated

FIGURE 3
Hydrograph of Gordhanpur (41J3A02)

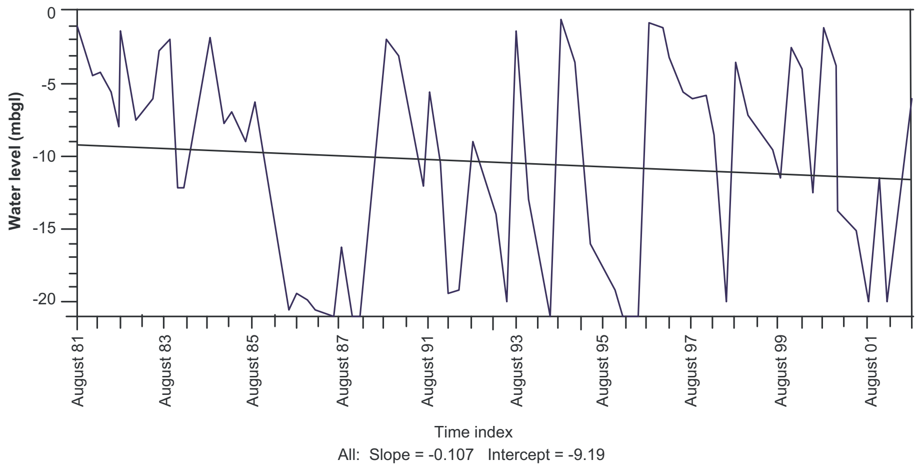


Figure 4
Hydrograph of Jhalod (4614A01)

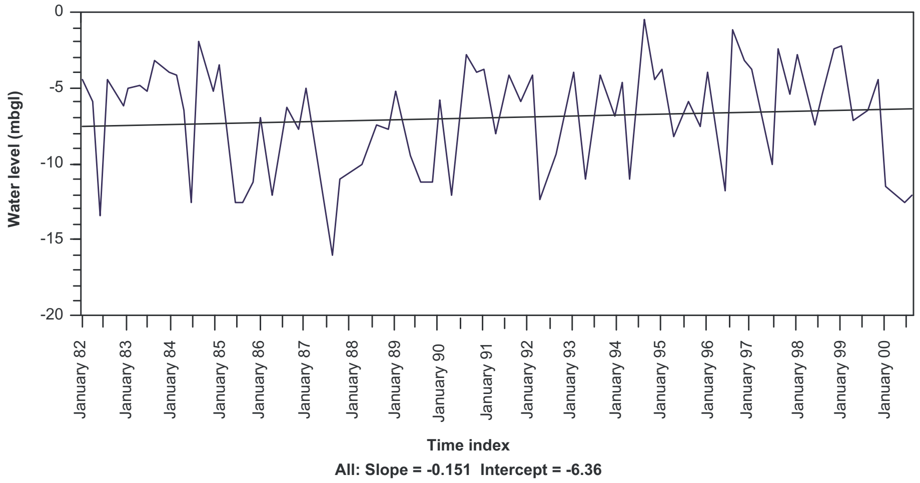
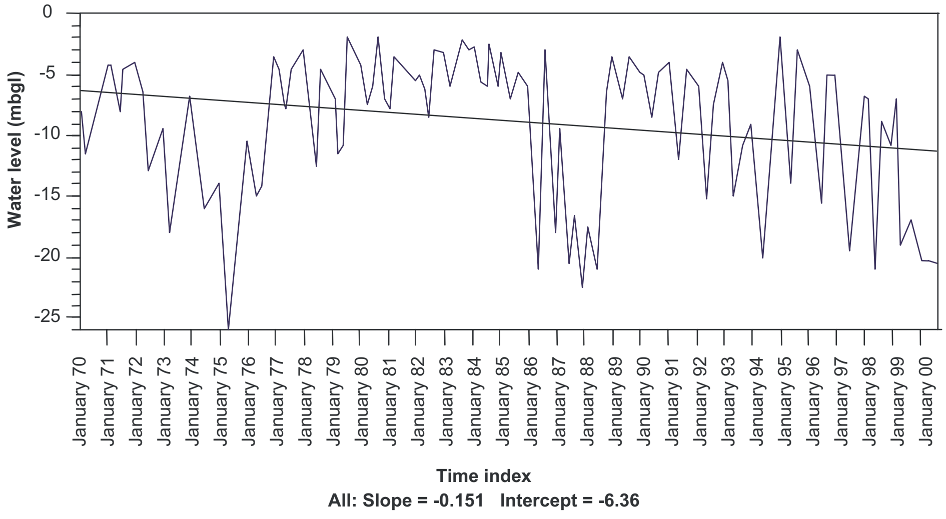


Figure 5
Hydrograph of Junagadh



piezometers typically shows much less fluctuation and might display the long-term water-level trends observed in adjacent dug wells. This suggests that the water-table fluctuation method contains inherent sources of error in hard-rock areas. Because permeabilities in hard rocks are often very low (dependent on whether or not wells intersect major fracture zones), water-level fluctuations in dug wells could indicate little concerning actual changes in regional storage. Instead, they would be dominated by recent use, and fluctuations would reflect changes in storage within the well itself (as with a cistern) rather than in the surrounding area as a whole.

Speculation of the above type is difficult to resolve within the limitations of available data. As water levels are monitored only four times a year (and often only twice a year), data documenting the fluctuations necessary to relate water-level changes to extraction and recharge events are lacking. However, it is important to recognize that fluctuations of the type shown in Figures 2, 3 and 4 have much more significant implications for the actual water availability experienced by farmers. Under these circumstances, the value of annual or even interannual aquifer water balances is limited.

Dug wells are often only 10-20 m deep. If fluctuations such as those observed in Junagadh, Jhalod and Gordhanpur are common, wells will frequently go dry irrespective of whether estimates indicate the presence of overabstraction or whether long-term water-level changes show declines. In many areas, farmers complain about water-level declines and the drying out of wells, but estimates of the 'level of development' (and long-term water-level trends) indicate little problem. This may be the primary factor underlying conflicting views of scarcity and availability. In many cases, water-level fluctuations, including seasonal ones, may have more significant implications for water availability than lumped estimates of recharge and extraction.

Implications

Despite recent methodological improvements, estimates of the 'level of development' (i.e. extraction and recharge estimates) almost certainly remain unreliable. In the case of recharge estimates, this is due to their dependence on aquifer parameters, such as specific yield (which varies considerably between locations), data quality concerns and uncertainties in what was being measured (actual changes in water levels or localized drawdown). Major uncertainties are also inherent in extraction estimates because these depend on limited surveys and the results of experimental farm research (often significantly different from actual use by farmers). Moench (1991; 1994) discusses these and other uncertainties inherent in the water-level fluctuation approach in detail.

Although the new methodology outlined in the 1997 GWREC report incorporates evaluation of water-level trends, it does not eliminate many uncertainties. Data quality concerns remain major as does the short period of record for most of the monitoring network. Furthermore, in hard-rock areas, water-level fluctuations may be as or more important in relation to the actual amount of water available in wells at any given time than longer-term water-level trends. Water scarcity may be severe during droughts or on a seasonal basis even where long-term trends are absent and water-balance estimates indicate substantial resources are available for development.

Resolving the above uncertainties would require long-term data on water levels that capture seasonal fluctuations. Such data are currently unavailable and could take decades to collect. Despite their limitations, water-level data in the databases maintained by state groundwater organizations and by the CGWB would probably be sufficient to give a broad picture of water-level changes over recent decades. However, accessing this data would require government permission to utilize the database developed by the Hydrology Project. It would also require visits to state groundwater organizations not involved in the Hydrology Project. In addition, as the process of data entry from states is ongoing, visits to state groundwater organizations and CGWB offices in those states involved in the Hydrology Project would also be required in order to confirm that all relevant data are incorporated in the database. Finally, even with sufficient resources to visit all the relevant departments, there may remain extensive clearance processes that impede access to the data.

Evaluation summary

The following sections summarize the key issues relating to the evaluation of groundwater conditions in India.

Data

The available groundwater database contains a wide array of inherent limitations including:

- Short period of record with regard to water-level trends.
- Limited monitoring within the year eliminates the ability to analyse the magnitude and extent of seasonal water-level fluctuations.
- Technical questions regarding data quality (e.g. monitoring in dug wells that may be subject to heavy use).
- Non-technical factors affecting data quality (e.g. pressures to modify data to influence the allocation of funds).
- Limited information on the hydrogeological context and formations in which data are collected.
- Insufficient monitoring to capture the regional and seasonal variation in groundwater throughout India.

Analysis

The water-table fluctuation method used to evaluate extraction and recharge has inherent limitations. While such a water balance approach represents a logical, physically based construct, many parameters are subject to substantial (and generally unevaluated) uncertainty, and key processes (such as lateral inflows and outflows) are not captured. Equally, it is good practice to test a range of methods for testing water balances. Experience in other locations indicates that substantial uncertainty often remains in water-balance estimates. This is the case with the San Luis Valley of southern Colorado, the United States of America, where decades of detailed monitoring have been combined with the application of physically based hydrogeological models constructed as a result of intense legal debates over water management. Therefore, the accuracy of water-balance estimates generated using the water-table fluctuation method is almost certainly poor. Computation of confidence intervals for extraction-recharge estimates would provide a useful insight into the statistical accuracy of estimates.

Relationship to water availability

Water-balance estimates often provide little insight into whether or not water users in a given region already face or are likely to face actual problems of water scarcity. However, in many cases the only official data on groundwater availability at a national level is assessed through water-balance estimates.

Data access

Available basic data on water levels and water-level fluctuations are generally inaccessible. Access to core water-level monitoring data compiled by the Hydrology Project and in state government departments is complicated and requires a substantial process of approvals.

Politics

Groundwater information plays an important role in development financing and other politically sensitive decisions. The data are politically sensitive and analyses are subject to pressure (Moench, 1994). As a result, objective evaluation of the extent of groundwater depletion is problematic.

CONCLUSIONS ON GROUNDWATER DATA AND ANALYSIS

The issues identified above highlight the substantial uncertainties inherent in estimating the areas affected by water-level declines and overabstraction. These uncertainties apply to situations in developing countries and in many industrialized countries.

Most data contained in general reports are highly aggregated and processed. As in the case of the estimates produced by the CGWB and state governments in India, such processing generally involves a wide array of assumptions. It is also frequently dependent on other types of information (such as extraction estimates) where results depend heavily on assumptions and estimation techniques. Periods of record for groundwater data are generally short, and data-quality concerns are often present. In combination, such factors make water-level change and overabstraction assessments based on publicly available information problematic. This is not just a concern for groundwater but is a common feature in many water-resource evaluations. As one author comments: "*The data on the water balance and productivity of water for irrigation systems at basin, system and farm level are scarce… wherever such data are reported the method of derivation is not described….The inadequacy of data make it difficult to analyse productivity at system and basin level*" (FAO, 2002).

Available groundwater information indicates that water-level declines are occurring in key agricultural areas and that some aquifers are almost certainly experiencing high levels of overabstraction. However, the extent of areas where water levels are declining over the long-term is not possible to determine from the information accessed through this review.

Apart from data, the largest source of uncertainty relates to the assumptions underlying the interpretations of groundwater conditions. Distributed-hydrogeological and water-balance models can be a powerful tool for interpreting water-availability issues provided that the storage and abstraction volumes are known and understood with some degree of scientific confidence. As the examples in Boxes 1 and 2 illustrate, models can generate misleading results where key hydrodynamic processes are unknown or misinterpreted. Without detailed hydrogeological studies, it is generally impossible to determine key parameters such as permeability, storage and transmissivity. Equally, evapotranspiration from native vegetation or shallow groundwater tables is rarely evaluated but can represent a major portion of the water balance. Even 'known' portions of the water balance (e.g. crop water use) are often subject to substantial uncertainty because of the difference between conditions on experimental farms and field conditions. Crude water-balance estimates developed in the absence of detailed hydrogeological information may well contain errors as major as those in the models of Himalayan deforestation or agriculturally induced climate change discussed above.

The above comments are not intended to denigrate modelling efforts. Detailed hydrogeological models and water-balance estimates are useful tools for organizing understanding of physical data and interpreting the impacts of use or management changes. When properly developed (calibrated and validated) with suitably precise data, they can also become powerful predictive tools. However, data requirements and the fundamental parameters (permeability, storage, transmissivity and leakage) needed to structure hydrogeological models and define confidence limits are lacking in many analyses of groundwater availability, particularly in developing countries. As a result, regional extraction-recharge estimates provide little insight into actual groundwater conditions. In the absence of long-term data relating water-level changes to specific aquifers, it is impossible to quantify the impact that current patterns of groundwater extraction are likely to have on water availability in key agricultural areas. Groundwater scarcity is emerging in some areas, but the size of those areas and the severity of the threat to irrigation water supplies remain unclear.