Chapter 5

Groundwater management practices and emerging challenges: Lessons from a case study in the Karnataka State of South India

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INTRODUCTION

In the last two decades significant changes have taken place in India in the use of groundwater for irrigation, and currently about 60% of irrigated agriculture depends on groundwater pumping (Shah et al., 2003). Irrigation wells are managed by individual farmers and their management and replacements are made under their own control. Further, there is an increased reliance on groundwater irrigation due to fragmentation of farm land holdings and increasing numbers of marginal/small farmers. This has resulted in systematic changes in land use practices especially in the upland areas (recharge areas of river basins), which were not part of the green revolution during 1950–80. Depletion of water tables, contamination (by fluoride and nitrates) and over-extraction of groundwater have become critical issues in several regions of India. In addition, close to 90% of rural domestic water supply is from groundwater, and in most regions there are very few treatment plants in place for water supply. In the same vein, significant proportions of the water demand in the cities and towns are met from groundwater supplies.

Several regions in India are experiencing rapid development and population increase, and the demand on groundwater for water supply has grown considerably during the last decade, and is expected continue to grow further. Also, during the past few years, India has experienced extreme weather events such as droughts1, floods, and cyclones more frequently. To examine the spatial trends in groundwater level variation, Panda et al. (2007) used Mann-Kendall non-parametric trend analysis of groundwater levels over the ten year period of 1994–2003 in the state of Orissa, to characterize regions undergoing groundwater declines attributed to anthropogenic pressures in spite of recharge occurring after the post-monsoon season. They suggested the need to establish relationships between the groundwater dynamics of the areas having a similar spatial pattern of significant trends, and the weather variables. Hence, there

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1 The severe drought of 1987 spurred the Central Government to conceive its first National Water Policy.
is clearly a need to examine the general trends of local climate variation and analyze the relationship between these trends and groundwater level fluctuations. The impact of land use/land cover changes in certain settings is found to be much stronger than the climate variability and hence there is a need to characterize dominant patterns of climate and land use controls on the groundwater system for developing sustainable groundwater resource programs (Scanlon, 2007).

The geology of central and peninsular India is different and far more complex compared to that of the Indo-Gangetic basin, which consists of extensive alluvial aquifers throughout. Figure 1, showing a map of major aquifers of India, suggests the dominance of basalt and crystalline rock formation in peninsular India. The water-bearing
and conveying properties of these aquifers vary greatly even over small distances, making scientific resource management critical and difficult at the same time (GoI, 1995). Overall, however, the yields (shown in liters/sec in Figure 1) of these aquifers are quite modest and, in fact, much smaller than much of sub-Saharan Africa; yet, there is a heavy and growing dependence on groundwater irrigation even in these regions (Shah, 2007). Figure 2 shows the groundwater potential developed in major river basins of India (World Bank, 2005). The groundwater potential has been estimated using the GEC (1997) methodology. This shows the development taking place in parts of south India and especially in the Cauvery River basin, which is in the crystalline rock formation. This presentation highlights the results of the studies in two districts in Karnataka State and which are part of the Cauvery River basin, which has excessive shortage of water both in the surface and groundwater regimes due to the reasons described above. The presence of strong decadal variations in rainfall such as droughts, along with recent trends of spatio-temporal variations in the anthropogenic effects, provides distinct groundwater signatures in the system at various scales, which are discussed. The current management practices and the baseline of the system are presented.

Figure 2  Proportion of groundwater potential developed in major river basins of India (Source: World Bank, 2005).
improvements needed in the science & technology inputs to manage the system under
the changing hydro-climatic scenario are also outlined.

FROM UNION TO LOCAL POLICY FOR GROUNDWATER

Water is a resource for a wide range of concurrent uses, a resource for development,
and is an environment for a variety of ecosystems, because it is flowing and changing
its physical and biogeochemical state. The law in any country is building a complex
legal system in order to regulate access to water and its uses under the constraints of
social equity and, when it is granted, the right to drinking water. In this study we only
mention the basic legal information required to picture the on-going situation in the
Cauvery River basin.

The administrative subdivision of the Republic of India is hierarchically organized
in States and Territories, divisions, districts, taluks (or tehsil or sub-district, compris-
ing several villages) and (several kinds of) municipalities. The National Water Policy
(Ministry of Water Resources, 2002) is providing general guidelines and orientations
for the sustainable development of water resources at the national level. It covers the
identification of needs and planning issues, institutional mechanisms, definition of
allocation priorities, resource development, governance schemas and economic incen-
tives for an effective enactment of the promoted priorities. Both surface water and
groundwater are considered along with quantity and quality management, offering
the possibility to tie the local application of the water policy to the regional character-
istics of the water cycle regime. Nevertheless the observed uses of the groundwater are
mainly consequences of the legal status of the resource: the Indian Easements Act of
1882 states that ownership of the groundwater accrues to the owner of the land above.
The locally available groundwater was considered as a resource to ease the exploita-
tion of the land. The easements are also restrictive of certain rights like the exclusive
right for a land owner to “enjoy and dispose the same and all products thereof and
accessions thereto”.

From an economic point of view water resources are most often considered as a
natural renewable resource. In some socio-environmental contexts the non-renewable
character can be dominant when considering time scales of uses being much shorter
than the ones for the regeneration of the resource. In such a case the water resource can
be managed as a stock, the optimal exploitation strategy depending on the expected
evolution of the market and socio-economic factors. The evaluation of the water
resource itself is prone to a high degree of uncertainty related to the limited knowledge
of the resource state, and to the dynamics of different time scales and spatial scales.
However the legal regulation of the use of groundwater resources is usually not con-
ceived with consideration for the economic sustainability of the resource exploitation

2 More details about the Indian legal system for water (laws, policy, institutions, organizations,
etc.) can be found for example in Tambe (2007) and in the references therein.
3 Presently the Union counts 28 States and 8 Territories (e.g. Puducherry, in the Cauvery river
basin).
4 See the definition of an easement in Chap. 1 of the Act and the ontologically related definitions
of the land and beneficial enjoyment.
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per se. The adopted policy allows any land owner to freely withdraw and exploit the resource for their own purpose and benefit; for example for crop production, the economics of market adds some degree of control without any need for direct intervention by state or public authorities. Indeed at the State level, water policy and management is most often dominated by the promotion of sectoral interests, an approach that tends to stress the concurrence of the various water uses and potentially fuels conflicts.

The Model Bill to regulate and control the development and management of groundwater of 2005 – or in short the Ground Water Act (Ministry of Water Resource, 2005) – recognizes the over-exploitation of groundwater and the related degradation of the environment (Chap. III of the Act). It is conceived as a model made available for prompting new regulations at the level of States and Territories. The succeeding versions (most recently 1992, 1996, 2005) of the Model Bill have received rather marginal attention until today. Several measures are proposed in order to promote a sustainable development of the groundwater resources, among which is the establishment of a Ground Water Authority with given powers and competencies. Interestingly this Model Bill is not considering groundwater in its dynamic relationship with surface water. The accounting for groundwater as a component of a larger water system is indirect, the Authority ensuring that the exploitation of the groundwater resource is not exceeding the “natural replenishment to the aquifers” (Chap. II, sub-section 5(5)). It is also recognized that the capability to undertake any action for the conservation or sustainability of the resource must rely on some survey system and database. In any case, any regulation considered at this level of governance is drawing a legal framework rather than enforcing actual decisions and policy-based actions. The legislation and regulations are often given in the form of “incentives”, and such “soft” law does not really need to be enforced (in a sociological sense). The Bill is a kind of template for the State Government to design their own policy (in a way similar to the “Directives” in the European Union). It is the responsibility then for each State to define and implement a policy adapted to the environmental context and socio-economical pressures found on its own territory.

Both the legal and the economic visions of groundwater management have been encouraging the intensive exploitation of groundwater for the development of rural areas, and also for water supply. In cities like Bangalore or Mysore any land owner, even of a small parcel, can dig a well and extract the groundwater for any use (even for private economical exploitation of the resource). Both visions also consider separately the surface water, the groundwater, and the rainfall contribution characterized by a strong inter-annual variability related to monsoon dynamics. More specifically let us consider the Cauvery, an inter-state river shared by the States of Kerala and Karnataka in the west, Tamil Nadu States, and the Puducherry Union Territory with the Coromandel Coast along the Bay of Bengal. With rapid economic development, the sharing of water resources has been the cause of a water dispute since the 1990s mainly between Karnataka and Tamil Nadu, the historical agreement of 1882 and 1924 signed between the Madras Presidency and the Princely State of Mysore being recurrently contested after Independence (Anand, 2004). Anchored in the Indian Constitution, the Inter-State Water Disputes Act (1956) is providing the legal dispositions required for the Central Government to create a Tribunal for the adjudication of the water dispute (after listening to the various stakeholders and parties). The verdict mainly consists in allocating yearly volumes of surface water to each State, with the proper operational
monitoring system. Apart from the many socio-political criticisms that have been formulated when the verdict was published in 2007, a simple “scientific view” notices that (a) once again only one component of the water cycle is considered (the surface water in this case) though it is known that the over-use of groundwater has a negative impact on the surface water availability (conversely the reduction of surface flows and streams negatively impact the replenishment of the groundwater) and (b) an analysis of the historical time series of rainfall and river flow shows that statistically the (legal) allocated water volume is likely not to be available every year for each State in the future.

Starting from a survey of the current situation, the 2007 Report of the Expert Group on “ground water management and ownership” (Planning Commission, 2007) has analyzed the state of the art in groundwater management, governance and ownership, and proposed several measures for improving the sustainability of this resource, which is central to many economic activities and dimensions of social life. On one hand such proposals are bound by many constraints, related in rural areas to the economic capacities of small producers to pay any kind of tax or pay for the electricity for operating pumps, the size of the parcels and irrigation infrastructures, etc. On the other hand, the negative impacts on the environment of an overexploitation of the groundwater should be prevented, and projects aiming at producing new water resources (e.g. rainwater harvesting and aquifer recharge) or at its sparing use (improving productivity of irrigated agriculture, etc.) are to be developed, as well as the control of the resource use (through the registration of existing wells, permits to dig new wells, systems for surface and groundwater survey, etc.). Every State Government can promote such initiatives through new regulations that try to anticipate the future socio-economic development and growth of the country. Karnataka State is implementing the various tools of its water policy, the objectives of which are mainly to guarantee a minimum daily amount of drinking water to everyone, to develop irrigation, to improve performance of all water projects and of irrigated agriculture, to harness the hydropower potential and to provide a legislative, administrative and infrastructural environment, which will ensure fair, just and equitable distribution and utilization of the water resources (GoK, 2002).

However the political will to design and enforce new water policy orientations scalable to the socio-environmental problems to be solved at the level of the Union is questionable (Narasimhan, 2008). As noticed previously for other legal texts, the groundwater is not really considered as one component of a larger system including interactions with surface waters and the rainfall regime. Today, scientific knowledge is not used as a possible basis for the design of an integrated water policy (and rule making), nor for its implementation.

THE SOCIO-ENVIRONMENTAL CONTEXT IN THE KABINI RIVER BASIN

The current studies in hydrology provide a lot of useful information for the management and sustainability of the groundwater resource. They can also provide the basis for an integrated scientific approach to the larger problem of water governance. Let us
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illustrate our ideas with the analysis of the groundwater in the Kabini River (drainage area \( \sim 10,000 \text{ km}^2 \)), a tributary of Cauvery River. The Cauvery River basin covers one-third of the area of Karnataka. Karnataka, a state in the south-west of India, has a total land area of 191,791 km\(^2\) and a population of approximately 53 million, giving a population density of 276 people per km\(^2\) (DES, 2001). The state is enclosed by mountain ranges along much of the western, eastern and southern regions with peaks reaching 1,500 meters above sea level. Annual average precipitation ranges between 500 and 3500 mm. Rainfall is lowest in the eastern regions of the state and increases in the western areas, reaching its maximum over the coastal zone. Karnataka is one of the more developed states in India and with a human development index (HDI) of 0.650 in 2001 ranks seventh in the country. The HDI improved by 20 percent over the 1991 figure of 0.541. Karnataka is predominantly an agricultural state with more than 70 percent of the major agriculture area under rainfed conditions. Recurrent droughts, soil erosion, erratic rainfall, and groundwater depletion have impacted the potential agricultural productivity significantly. Rainfed areas are often prone to these multiple risks; therefore, efficient and sustainable use of natural resources has become a basic need for rural economic development.

The Kabini River basin comprises the climatic and the geomorphological gradient forming on the edge of the rifted continental passive margin of the Karnataka Plateau in Peninsular India (Gunnell and Bourgeon, 1997). The West-East geomorphologic gradient is associated with a climatic gradient induced by the Western Ghâts, which form a barrier to the monsoon winds coming from the Indian Ocean and moving north east. A steep decline of the mean annual rainfall is recorded along the inland region, from 5000 mm/yr to 700 mm/yr (Pascal, 1982). The dynamics of the south-western monsoon cause a rapid change in the spatiotemporal pattern of precipitation in the Kabini basin (Figure 3). The rainfall patterns also exhibit climatic trends as well as a strong inter-annual variability, like the extreme 1990 and 2002 droughts in this region (droughts recorded all across India in 1982, 1985, 1986, and 1987, based on Parthasarathy et al., 1994).

The development of groundwater development exhibits characteristic patterns in the Mysore and Chamarajanagar districts of Karnataka State. The sub-humid and semi-arid zones in the Kabini River basin form the two administrative districts (Mysore and Chamarajanagar) in the Karnataka state (Figure 3) and the landscape in this region is composed of shallow regolith and outcropping tors/inselbergs. Two major dams exist on the Cauvery and Kabini rivers, which irrigate large areas especially in the Mysore district (a total geographical area of 6577 km\(^2\)) in the region between these two rivers. The south part of the Kabini River system in the Chamarajanagar district (a total geographical area of 5686 km\(^2\)) has relatively lower irrigation from surface water systems and comprises about 22,000 irrigation wells, based on the census prepared by the Department of Minor Irrigation, Karnataka state in the year 2005. Typical statistics of Gundlupet Taluk in the Chamarajanagar district is given in Table 1. Conspicuous changes in the agriculture have occurred in the semi-arid zone of the Kabini basin moving from agriculturally low water-consuming rainfed crops (sorghum and millet), to intensive agriculture (with increased double cropping), highly dependent on irrigation resulting in higher water demand and consumption. Large areas in the uplands in the districts of the lower Kabini River basin (located in Karnataka state) are under groundwater irrigation (Figure 4a). Currently, groundwater is extensively
Figure 3  The Kabini river basin showing major drainage network and reservoirs along with spatial variation of annual rainfall (thin light black lines). Also shown are two administrative districts in the Karnataka state (Mysore and Chamarajanagar) in the basin. The dots show groundwater monitoring stations in these two districts.

Table 1  Statistics of Gundlupet Taluk in Chamarajanagar district, Karnataka.

<table>
<thead>
<tr>
<th>Gundlupet Taluk</th>
<th>2001</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographical coordinates</td>
<td>11° 49′ N  76° 45′ E</td>
<td></td>
</tr>
<tr>
<td>Population</td>
<td>1,027,015,247</td>
<td>1,147,995,904</td>
</tr>
<tr>
<td>Households</td>
<td>45231</td>
<td>50559</td>
</tr>
<tr>
<td>Average number of people/household</td>
<td>4.7</td>
<td>4.7</td>
</tr>
<tr>
<td>Area</td>
<td>1406 km²</td>
<td>1406 km²</td>
</tr>
<tr>
<td>Forested area</td>
<td>449 km²</td>
<td>449 km²</td>
</tr>
<tr>
<td>Rainfall</td>
<td>693 mm</td>
<td>771 mm</td>
</tr>
<tr>
<td>Bore wells</td>
<td>6000</td>
<td>10000</td>
</tr>
<tr>
<td>Households/bore well</td>
<td>7.5</td>
<td>5.0</td>
</tr>
<tr>
<td>Population/bore well</td>
<td>35</td>
<td>24</td>
</tr>
</tbody>
</table>

1Projected based on annual all-Indian growth rate of 1.47%.

used for perennial crops such as sugarcane and banana. The areas irrigated by canals, tanks, and groundwater (bore & dug wells) in the various taluks of Chamarajanagar and Mysore districts, which are in the semi-arid region of the basin, are shown (in Figure 4b). The canal network fed by the Kabini, Nugu and KRS dams provides irrigation in large areas in the taluks of Mysore district. Paddy and sugarcane are grown
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(a) (b)

Figure 4  Groundwater development in the two districts of Mysore and Chamarajanagar in Karnataka State (Department of Economics and Statistics, 2001) (a) Mode of irrigation (numbers show total cropped area and irrigated area respectively), (b) Type of crop irrigated (numbers show dug and bore wells in 2001, and their increase between 1995 and 2001).

in these commands. However, in the Chamarajanagar district groundwater forms the main source of irrigation. Perennial crops represent a high percentage of the total cultivated area in taluks having canal and tank irrigation in the Mysore district. Traditionally crops are grown during two seasons, one during the June–October season (period of south–west monsoon), which is referred to as Kharif crop, and the other during the November–February season (dry period) and is referred to as Rabi crop. The Rabi crop is mainly cultivated by irrigation. In the taluks of Chamarajanagar, Kharif crops are the main crops and also interestingly groundwater irrigation is mainly used for Kharif crops with certain areas having perennial crops and plantations. The number of bore wells increased approximately 3 times in the Chamarajanagar district between 1992 and 2002, while in the Mysore district they increased about 5–6 times.

The typical land use and land cover details pertaining to one sub-basin (the Gundal sub-basin of ∼1000 km²) located in the Mysore and Chamarajanagar districts is shown in Figure 5a. The land use map was obtained for the year 2002 using multi-season imagery of IRS 1C (LISS III sensor). The vegetation in the Gundal sub-basin is characterized by agricultural activity. Main traditional crops in the Kharif season are finger millet and pulses, whereas paddy is grown in the command areas of tanks and canal command areas (Northern part of the sub-basin). The Kabini and Nugu canal commands satisfy most of the irrigation requirements in the discharge area of the sub-basin. During the last two decades, the major source of water for irrigation in the rest of the sub-basin has been groundwater. As a result of increased irrigation by bore wells, irrigated crops like sugarcane and cash crops replaced traditional rainfed crops. It may be observed from Figure 5a that substantial double crop areas (Kharif and Rabi) exist not only in the discharge zone but also in the recharge areas of the sub-basin. The double crop areas in the recharge zone are managed by groundwater pumping. It may be noted that sustained pumping for both Kharif and Rabi crops in these zones are possible due to the good yields in these areas, which are correlated to the presence of several lineaments and structural control of groundwater in these parts (Sekhar et al.,
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Figure 5  (a) Land use and land cover map from multi-season imagery of IRS-1C of Gundal basin with bore wells in villages in 2002, (b) Annual groundwater pumping for 2001, estimated using well yield, number of wells, crop and electrical units consumed, by village.

2004). Figure 5b shows the village-wise annual groundwater pumping map created for 2002 combining the data for the number of wells in a village, yield of the wells, and the energy consumption of the irrigation wells with the agricultural data of crops in this region. The same approach is used for computing the pumping at a smaller time scale of one month in a year for using it as input for modelling the groundwater dynamics as illustrated in the next section.

SOURCE SEPARATION IN THE GROUNDWATER RESOURCE SPACE-TIME VARIABILITY

Figure 6 shows the time series of a few selected groundwater levels in these two districts during 1977–2007 along with the spatial mean monthly groundwater levels. The mean
monthly groundwater levels are obtained using 65 selected groundwater observation wells monitored by the Department of Mines and Geology, Karnataka State. The spatial distribution of these stations is shown in Figure 3. The series shows the strong effect on the groundwater system of the extreme droughts nation-wide in India in 1990 and 2002. The groundwater levels declined monotonically during the drought period of 1984–1990. However, the mean level recovered back to normal due to higher rainfall in the period 1991–1994. Further during the drought period of 2002–2004, the
groundwater levels declined more sharply than during the much longer drought period of 1984–1990, indicating a strong anthropogenic forcing on the groundwater system. The higher rainfall in the period 2006–2007 helped to reset back the groundwater levels but during the later years they exhibited large seasonal fluctuations. Clearly, the observed groundwater level fluctuations might not only reflect an influence of the space-time distribution patterns of rainfall, but also interactions with surface waters and land use (Panda et al., 2007). To assess the spatial correlation of these patterns, the groundwater level series in the two districts are subjected to empirical orthogonal function (EOF) analysis. EOF is now a classical approach in geophysics that has already been used in several contexts such as the analysis of spatio-temporal patterns in Sahelian vegetation (Jarlan et al., 2005) or soil moisture (Jawson and Niemann 2006). The central idea of EOFs is to reduce the dimensionality of a data set in which there are a large number of interrelated variables, while retaining as much as possible the variation present in the data set. EOF analysis can decompose space-time datasets into a series of spatial patterns of underlying orthogonal modes (ranked by decreasing value of the data-explained variances) and associated time series that indicate the importance of each spatial pattern at each time. This reduction is achieved by transforming to a new set of variables, the principal components, which are uncorrelated, and which are ordered so that the first few retain most of the variation present in all of the original variables. The rainfall and the groundwater level data sets used here are with a monthly sampling frequency. The rainfall data are transformed into cumulative rainfall departures (hereafter CRD; Xu and van Tonder, 2001). Before proceeding to the statistical analysis of the data set, we apply the following pre-processing to the raw data. Each time series is centered (removal of the time average).

a. **EOF analysis of rainfall and groundwater levels**

The CRD data were built using four series of the grid averaged (1° long. by 1° lat.) rainfall (1951–2004) provided by the Indian Meteorological Department for this region. Most of their signal variances are explained by the first two modes, which show (Figure 7: only time-dependent modes are plotted) decadal patterns of monsoon (cycles repeating once every 10 years) and a longer climatic cycle of 20 years (e.g. 1959–1979). Tiwari and Rao (2004) observed statistically significant signals indicating 22 year cycles (Solar cycles) when analysing the rainfall of the whole of India. The first two EOF modes explain 51.5% (n = 1) and 35.0% (n = 2) of CRD data set variance. When considering the space-dependent modes (not plotted here), we see that the first mode (Figure 7a) represents the cycles of rainfall patterns in the semi-arid region while the second mode (Figure 7b) represents the humid region. The modes capture the intra-annual behaviour of mono-modal rainfall in the humid zone (mode 2) and the bi-modal rainfall in the semi-arid zone (mode 1). Further, EOF analysis is performed using the data at 45 rain gauges monitored by the WRDO, Karnataka State in the Kabini basin and then compared with the results obtained using the grid averaged data of IMD. Figures 7c and 7d show that EOF modes for the data of 45 rain gauges during the period 1977–2007 have similar patterns as of the EOF modes of the grid-averaged data for the same period from a much larger region. This indicates that the rainfall patterns in the study region are similar to that of the larger south Indian region. The groundwater level data, built using 65 piezometer data (1976–2004) in the semi-arid region provided by
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Figure 7  EOF analysis of cumulative rainfall (monthly) departure. Results of grid averaged data of IMD corresponding to the region of Kabini river basin: (a) first and (b) second mode. 51.5 and 35 are percentage explained variances for the first and second time modes respectively; (c) and (d) Results of comparison between the grid averaged data of 31 points corresponding to south India and 46 rain gauge stations located in the Kabini river basin.

the Department of Mines and Geology of Karnataka state, were used. The first two time modes capturing the groundwater dynamics are shown in Figure 8. The first time mode (Figure 8a, capturing 24% explained variance (EV) of the groundwater level data) shows that there is no trend during the low rainfall period of 1980–1990, while showing an increasing trend during 1990–2004. The second mode (Figure 8b; 23% EV)
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Figure 8 EOF analysis of groundwater levels in the Kabini river basin. Results of first and second temporal modes are given in (a) & (b) respectively. 24.4 and 23 are percentage explained variances for the first and second time modes respectively. Results of contributions of first and second spatial modes are given in (c) & (d) respectively. (e) Results of joint EOF analysis of groundwater levels and cumulative rainfall departure. (f) Distribution of pumping wells in villages.
on the other hand captures the patterns of the groundwater level, which are similar to
the CRD observed during this period. The first and second spatial modes are shown in
Figures 8c and 8d respectively. The local amplitude to be attributed to the first ground-
water level time-mode (Figure 8a) is given by the first space-mode shown in Figure 8c
(see the range of amplitudes in the legend). We see that this first mode mainly captures
the coherent dynamics of the piezometers located along the river and canal regions
(larger amplitudes in Figure 8c). The larger amplitudes corresponding to the second
time-mode (Figure 8b) are spatially distributed as shown in Figure 8d. The piezometers
located away from the river and canal system and in the upland regions capture these
patterns of the dominant climatic signals. The upland region between the Cauvery and
Kabini rivers and the upland region to the south of the Kabini basin has these patterns.
The mean monthly groundwater levels shown in Figure 6 have a similar dynamics.

A joint EOF analysis of CRD time series from 46 rain gauges and that of 65
groundwater level monitoring stations was performed. Figure 8e shows the spatial
mode corresponding to this analysis, which brings out the stations where the ground-
water levels and cumulative rainfall departures are not similar. A comparison of these
results with the well inventory data set of various villages in Fig. 8f indicates that spatial
patterns as observed in Figure 8e are similar. The EOF analysis provides time modes,
which capture spatial mean patterns of the groundwater levels, and it is observed that
they are following the decadal cycles in annual rainfall. The higher rainfall during
one cycle is able to help in bringing up the groundwater levels, which have declined
during the lower rainfall cycle. This means that management strategies of augmenting
groundwater recharge are likely to help that much better, if practiced during the peri-
ods of higher rainfall cycle. Further the spatial modes help in identifying clearly the
regions affected by groundwater pumping or anthropogenic activities. This will help in
classifying areas from a large region that need to be selected for appropriate treatment
under management plans.

b. Groundwater modeling for assessing climatic and
land use effects

The groundwater dynamics of the Gundal sub-basin were modeled using a ground-
water model based on the CRD method. It is a lumped model and estimates
the groundwater balance components based on the observed water level fluctuations. The details of the method are described in Xu & Beekman (2003) and Javeed
(2010). The results of this method are compared with another lumped model of Park
and Parker (2008) and found to be similar (Sat Kumar et al., 2010). The model was
used to estimate the groundwater budget in the Gundal sub-basin comprising a small
number of monitoring stations. As discussed earlier, the Gundal sub-basin is illustrated
here as it is located in the southern part of the Kabini River basin and in the semi-arid
zone where groundwater abstractions are higher, and is also the upland region away
from the main Kabini river and canal system. The monthly cumulative rainfall and
groundwater levels for one of the monitoring stations in the Therkanambi watershed
(an area of about 80 km²) in this sub-basin are shown in Figure 9a. The groundwater
dynamics are very similar to the rainfall patterns capturing the long term cycles. The
model is calibrated over the period of 1979–1990 (Figure 9b) for the groundwater
recharge and discharge parameters. Using these parameters, the model is used in the
Figure 9 (a) Groundwater levels and cumulative rainfall departure for Therakanambi watershed: Simulation of groundwater dynamics using CRD model (b) without pumping & (c) with pumping; (d) Rainfall-recharge; (e) Discharge (underflow) with respect to depth to groundwater; (f) Comparison of pumping estimated from field data and model simulations; (g) Annual variation of recharge, groundwater discharge & pumping (draft) in mm.
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The simulation framework during 1991–2007 using the rainfall as the model forcing. The groundwater level simulations capture the measured patterns but fail to match the levels during 2000–2007. Clearly, not considering the effect of pumping shows a poor model response in the later period. In the next step, the model is simulated by choosing suitable pumping such that a good performance between simulations and measurements results during 2000–2007 (Figure 9c). The pumping simulated using the model is compared with the field estimates obtained based on the crop statistics, number of wells operating, the yields and the number of hours of pumping (Figure 9f). These estimates are made for each of the villages in the watershed and aggregated for comparison with the model simulations. Clearly the trends of groundwater pumping are similar but it is observed that there is a lag between model simulations and field estimate. The differences may be due to the scale of averaging the field estimates. The model used here not only provides the recharge but also the groundwater discharge. A plot of annual recharge and rainfall is shown in Figure 9d and the groundwater discharge (underflow) with depth to the groundwater level is shown in Figure 9e. The temporal variations of annual groundwater balances simulated using the model, are shown in Figure 9g. During the period 1979–1990, the imbalances of annual groundwater recharge and discharge result in the groundwater storage changes. In the later periods the groundwater discharge plus the pumping are balanced by recharge. The higher pumping in the later years results in reduced groundwater discharge. The groundwater discharge forms the underflow from the watershed and relates to the base flow to the stream and tank system of the Gundal River, which drains into the Kabini River. Table 2 shows the typical estimate of averaged groundwater draft (276 mm) in a year in the groundwater irrigated areas in the south region of the Gundal sub-basin. The average draft computed for this entire region combining the irrigated and non-irrigated areas is also given (26 mm), which is one order of magnitude lower than the irrigated areas in the total cropped area and significantly smaller, as shown in Figure 2a, for the Gundlupet Taluk. As the recharge is 53 mm, the groundwater irrigated areas are pumping groundwater five times the rate of the recharge. However, when averaged over the entire taluk scale, the groundwater development does not show the same ratio with regard to pumping and recharge. The current practice in India is to compute both groundwater draft and recharge at the Taluk scale in hectare-meter (HaM) units. Following this approach, the net groundwater draft due to irrigation averaged over the Gundlupet Taluk is 3640 HaM whereas the net draft from the irrigated area of 75 km² alone is 2070 HaM. The recharge for the Gundlupet Taluk is 7420 HaM, while for the irrigated area is 398 HaM.

The results clearly indicate that groundwater budgets made at a larger scale are not so useful for targeting management decisions at the scale of a village, for example. One possible approach is highlighted here that can be used to achieve groundwater storage changes for a year, by using the above modeling results combined with village scale data sets of groundwater levels and pumping. This is demonstrated for the Therakanambi watershed discussed above for the year 2008. Through the model results it is possible to obtain the recharge-rainfall and discharge-depth relationships as discussed earlier, which are applicable for a region. The groundwater levels in a large number of wells in this watershed are measured a few times in a year to obtain the mean depth of the groundwater level in each village of this watershed. Using the groundwater discharge with depth to groundwater level (Figure 9E), the annual groundwater discharge is
Table 2 Groundwater statistics of southern region of Gundal sub-basin.

<table>
<thead>
<tr>
<th>Part of Gundal basin in Gundlupet Taluk</th>
<th>Groundwater statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of wells</td>
<td>8000</td>
</tr>
<tr>
<td>Yield/well</td>
<td>( \sim 2 \text{ l/s} = 7.2 \text{ m}^3/\text{h} )</td>
</tr>
<tr>
<td>Total hours of pumping/year</td>
<td>360 h (3 months) mainly Kharif</td>
</tr>
<tr>
<td>Groundwater pumped/year</td>
<td>0.021 \text{ km}^3</td>
</tr>
<tr>
<td>Area irrigated by wells</td>
<td>75 \text{ km}^2</td>
</tr>
<tr>
<td>Total area</td>
<td>800 \text{ km}^2</td>
</tr>
<tr>
<td>Draft (in irrigated areas)</td>
<td>276 mm</td>
</tr>
<tr>
<td>Draft (averaged in total area)</td>
<td>26 mm</td>
</tr>
<tr>
<td>Rainfall</td>
<td>771 mm</td>
</tr>
<tr>
<td>Recharge</td>
<td>53 mm</td>
</tr>
</tbody>
</table>

estimated for each of the villages. Using the recharge-rainfall relationship (Figure 9d), the annual recharge is estimated for each of the villages for the year 2008. The average yields (in liters per second) are obtained in several wells in each of these villages through field surveys. This is combined with state-organized data collection of electrical energy consumed at each well combined with number of hours of electrical supply, and yielded the spatial and temporal dynamics of the groundwater pumping in a village. Details of the field campaign and data collected are presented in Javeed (2010). Based on this the annual groundwater pumping in each village is estimated. The annual groundwater storage change is computed for each village based on the estimated balance components of recharge, groundwater discharge (underflow) and the pumping for the year 2008. The positive values of groundwater storage change indicate that annual recharge is higher than the sum of groundwater pumping and groundwater discharge in a village. By spatially distributing the groundwater budget through such an approach it is feasible to identify villages with negative groundwater storage change and target them for applying management decisions. The results are shown for each village of Therakanambi watershed in Figure 10. The figure also presents the scale at which current annual recharge and annual groundwater pumping are estimated in the Karnataka state.

**CHALLENGES & GAPS**

Ensuring resource sustainability and equitable access of groundwater for both irrigation and drinking water in rural areas (close to 90% of rural domestic water supply is from groundwater) is a vast and complex task, involving many dimensions, such as questions of inter-sectoral competition (especially with irrigation), interface with other programs and policies such as watershed development, intra-community inequities, and capacity-building for various agencies involved. Tied to these socio-political dimensions are the scientific and technological dimensions of the problem. These cover four major aspects, given below.

- **Understanding micro-level groundwater hydrology**: The science of groundwater hydrology in India has, however, focused largely on irrigation-relevant variables and scales, and on exploitation rather than sustainable use. Groundwater data are
still often inaccessible or unavailable at the right scale (Arghyam, 2008). The enormous variety of geological, climatic and soil hydraulic conditions in the country remains only partially understood. There are substantial gaps in basic information on groundwater availability and agricultural use. In general, however, agricultural
groundwater use appears to be substantially underestimated in most published figures (Giordano and Villholth, 2007).

Several towns and cities in Karnataka state use groundwater for their water needs. Hence apart from agricultural areas, there is a need to monitor and estimate the groundwater use and status for such cities and towns, wherein such estimates have to be performed at a very fine spatial scale. Currently there is no monitoring approach at the required scale. Under the project for integrated urban water management being carried out by Arghyam (an NGO), the first author is performing studies of groundwater assessment and management for Mulbagal town in Karnataka. One aspect of this study is to assess the status of groundwater at a fine scale relevant to the town for a better management of the resource.

- **Combining scientific understanding with local knowledge**: There is a vast though possibly un-systematized body of local knowledge that needs to be integrated into the science of groundwater management to make it practical and scalable to the size of the problem. Shaw and Sutcliffe (2003) in their documentation of ancient small dams in the Betwa basin of central India link the size of these structures to the runoff from their catchment. This link leads one to believe that the builders of these structures followed some variant of the rainfall-runoff curve during their design of these structures and that they used sound observations of local hydrology. Recently, Krishnan et al. (2008) found that one efficient way to tap such local groundwater knowledge is through well drillers. In the Vaishali district of Bihar state in eastern India, a new methodological approach was used to identify and sensitize well drillers towards creating a local groundwater database. A localized lithology of a single village was created using both the experiential knowledge and current practice of these drillers. Especially in the case of hard rock areas, tapping such information from well drillers and harnessing it can potentially open up a new direction for localized groundwater management. Krishnan et al. (2008) believe that the large scale picture of surface lineaments available through geophysical and remote sensing studies, imparts a global picture to this localized knowledge and a potential fusing of these two can be highly potent. Similarly the state-organized data collection of electrical energy consumed at each well when combined with number of hours of supply and yield of wells can be a wealth of information on the spatial and temporal dynamics of the plot level groundwater pumping in a village or a watershed as illustrated in Figure 5b of this study. Such information linking agricultural productivity, land use and land cover patterns can also provide estimates of economic variables at smaller spatial scales and can lead to better estimates of vulnerability and externalities of other forcing apart from groundwater. An example of obtaining annual groundwater storage change in each village from conventional modeling combined with gathering auxiliary data is demonstrated above.

- **Management strategies**: Watershed development projects (e.g. ‘Sujala’ watershed project in Karnataka State), have been taken up across the country as a water recharge technology with an objective to improve the productive potential of selected watersheds and their associated natural resource base (Milne, 2007). Rainwater harvesting technologies are being promoted to mitigate the groundwater quality threats for safe drinking water needs. Recent approaches (APFAMGS, 2006) are also looking into the demand-side management through participatory hydrological monitoring, a strategy adopted to transform individual groundwater
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Users into water resource literates. Based on this knowledge, the farmers have started appreciating the causes leading to groundwater changes, rainfall-recharge relationship, pumping capacity of bore wells and water requirements for various crops. Such strategies can foster community-based agreements to regulate measures of groundwater use and facilitate farmers’ ability to adjust to changing groundwater conditions.

- **Water Policy impact assessment with multi-agent systems**: Multi-agent systems are being developed for stimulating the participative approaches to the management of common resources, and for building a new culture of environmental responsibility shared by the stakeholders, decision- and rule-makers (Barreteau *et al*., 2001; Becu *et al*., 2008). A deep reform of water resource management in south India is likely to have to reconsider among others the link between land ownership and water resource ownership, the pricing of the resource, the pricing of power consumption, and charges for the use of and access to the public infrastructure for irrigation (and other supplies, energy, roads, etc.), as well as the market-driven options in agricultural development, and co-dependency of the city and rural areas. Many different policy orientations supported by the proper legal tools (the design of which is itself presenting a large variety of possibilities) can be conceived, with huge potential impacts on the resource, ecosystem and environmental sustainability, and also on the social organization and economy. The targeted impacts motivate the development and enforcement of legal frameworks (laws and institutions). Some unexpected impacts are also most likely to occur, the new rules triggering social adaptations and socio-environmental feedbacks. Plausible scenarios of what might happen when a new water policy will be adopted can also be built using hybrid multi-agent systems (modeling the roles and decision-making processes under legal and other normative constraints), and equation-driven systems (modeling hydrological and ecological dynamics) in interoperability with GIS. We are now beginning to assemble the various building blocks allowing us to simulate via computer simulation the potential direct and indirect impacts of the enforcement of new public policy in the interrelated domains of water resource and environmental management (Boulet *et al*., 2009), in the specific context of the Cauvery River basin, as conceived from the point of view of a panel of scientific disciplines. Such simulation tools will also play a key role in the comparative studies of the differential impacts: (a) of different policy and legal frameworks on the same “social-ecological system” (Ostrom *et al*., 2007), and (b) of the same policy and accompanying legal framework over different socio-ecosystems, in very uncertain environmental, climatic, social and economic contexts (Anderies *et al*., 2007).

**CONCLUSIONS**

We have seen in this study that a statistical treatment of long time series of the water table level strongly suggests a marked depletion of the groundwater resource, in particular in the irrigated watersheds in two districts of Karnataka state, which are in the Kabini River basin. It is likely that such depletion cannot be explained by a reduction of the yearly rainfall input or inter-annual monsoon variability. Today the overuse and overexploitation of the groundwater resource is probably the main cause of this
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trend, a practice that has overall allowed India to significantly increase the ratio of the national food production to population size since Independence. But this policy might not be sustainable, even over a relatively short time scale of a few years or decades. At the same time the needs of agriculture and industry, and for water supply to the cities, are rapidly increasing. The economic development of up-stream States and watersheds is affecting down-stream States and watersheds, with both the overuse of groundwater and surface water affecting each other and leaving rivers with intermittent courses, and dams or tanks dry or with a negative recharge balance over a period of years.

At a State level the development of technological platforms (including GIS, models, multi-agent systems, etc.) allowing for an \textit{a priori} impact analysis and assessment of the planned water public policy or water-related legal systems (including the norms, institutions and organizational networks) must be developed by scientists in close cooperation with policy- and rule-makers, in order to explore various social-ecological trajectories toward sustainable development, with the choice of a specific scenario being of course left to the will of civil society and of its representatives at the various governance levels.

One practical conclusion of this work is that for purposes of assessing the intensity and sustainability of groundwater use, data should not be averaged at the taluk scale, but at a smaller scale that accounts for the distribution of groundwater users within each taluk. The science-based decision support tools that can provide information at village/small watershed scale also need to be developed, which can alleviate the current constraints impeding the planning and decision-making due to lack of data at a smaller scale. An approach is presented by combining conventional modeling with such auxiliary data sets at village scale to estimate annual groundwater storage change in each village of a watershed of about 80 km$^2$.

Further it is demonstrated that through the spatial and temporal modes of empirical orthogonal function analysis of the rainfall and groundwater levels, it is feasible to identify the regions affected by groundwater pumping or anthropogenic activities. Identifying such regions from a large regional data set is helpful for targeting management plans.

Finally there is a need for long-term observatories studying the integrated water cycle and the impacts on water resources through the survey of land use and cover changes over the years, and at the different spatial scales covering the local to basin-wide dynamics. Such observatories will also survey the evolution of the technology used and agricultural practices and strategies, along with approaches to improve the estimate of the impact of the different crop types on the water cycle.

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