Groundwater sustainability indicators for the Brahmaputra basin in the northeastern region of India

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Abstract The Brahmaputra River, flowing through the northeastern region of India, has a catchment area of 194 413 km^2 and an average annual flow of 537.2 km^3. The four states of the Brahmaputra basin, viz. Arunachal Pradesh, Assam, Meghalaya and Nagaland, have total replenishable groundwater resources of 1.438, 24.719, 0.539 and 0.724 km^3, respectively. In the Brahmaputra basin, the identified groundwater sustainability indicators show spatial and temporal variations and may be divided into five categories. These are: (a) socio-economic, involving a threat to groundwater due to societal needs such as the prevalence of shifting cultivation, the land tenure system, deforestation cropping patterns or land use and population growth; (b) meteorological, concerning the amount and duration of rainfall, *in situ* rainwater retention, rate of infiltration, amount of surface and sub-surface flow, aquifer recharge capacity and contamination of groundwater with fertilizers and agricultural chemicals as well as urban wastes; (c) environmental, relating to floods and droughts; (d) resilience or the ability of the system to maintain groundwater levels despite major disturbance and stability under stress conditions; and (e) policy domain and management, including developmental works, spatial and intergenerational equity and relationship between people and policy makers.

Key words Brahmaputra basin; groundwater; northeastern India; rainfall variability index; sustainability indicators

INTRODUCTION

Caution in the use of groundwater is essential for its long term sustainability (ICAR, 1998). The Brahmaputra basin in northeastern India receives about 390 km^3 of water as rainfall but its indiscriminate use and mismanagement has led to the whole hydrological system of the region being in a fragile state (Sharma, 2001). The basin is inhabited by various tribes, mostly confined to the hills, whose perceptions and approaches towards water use and management are specifically related to groundwater sustainability. The most important demand on sustainability indicators is their validity. The ideal indicator has to be ecologically realistic and managerially useful. Assessment and selection of valid groundwater sustainability indicators serve as a tool for rational decision-making and evaluation. The indicator should measure what it is supposed to detect. However, there is a requirement for sustainability indicators that cover a broad range of aspects, not all of which can equally be met. Management solutions should be able to restore more natural, dynamic behaviour of the water system, because this will minimize the volume of water discharged from the area and maximize water conservation. Indiscriminate use of rainwater, due to faulty agricultural practices, deforestation involved in shifting cultivation, socio-economic implications and lack of infrastructural facilities, results in very high soil erosion rates, the silting of river beds and floods in the plains of the region (Sharma, 1990). This affects groundwater recharge and it is difficult to quantify the unsaturated infiltration processes of rainwater in field soils accurately, although it is a major source of groundwater recharge in the northeastern region of India. Urbanization has a significant effect on many of the processes that control stream flow (McCuen, 1998). Due to the complex considerations in the sustainability of groundwater, it is also difficult to ascertain the exact behaviour of many sustainability indicators in the study area. However, an attempt has been made to identify and investigate groundwater sustainability indicators for the study area.

STUDY AREA

The study area comprises 201 189 km^2 in the northeastern region of India (Fig. 1). The region is endowed with rich water resources but these are in a fragile state because of indiscriminate use. The Brahmaputra River has a maximum discharge of 0.7 million cusecs and has more than 100 tributaries of which 15 on the northern side and 10 on the southern side are fairly large (Borthakur *et al*., 1989). The basin can be divided into

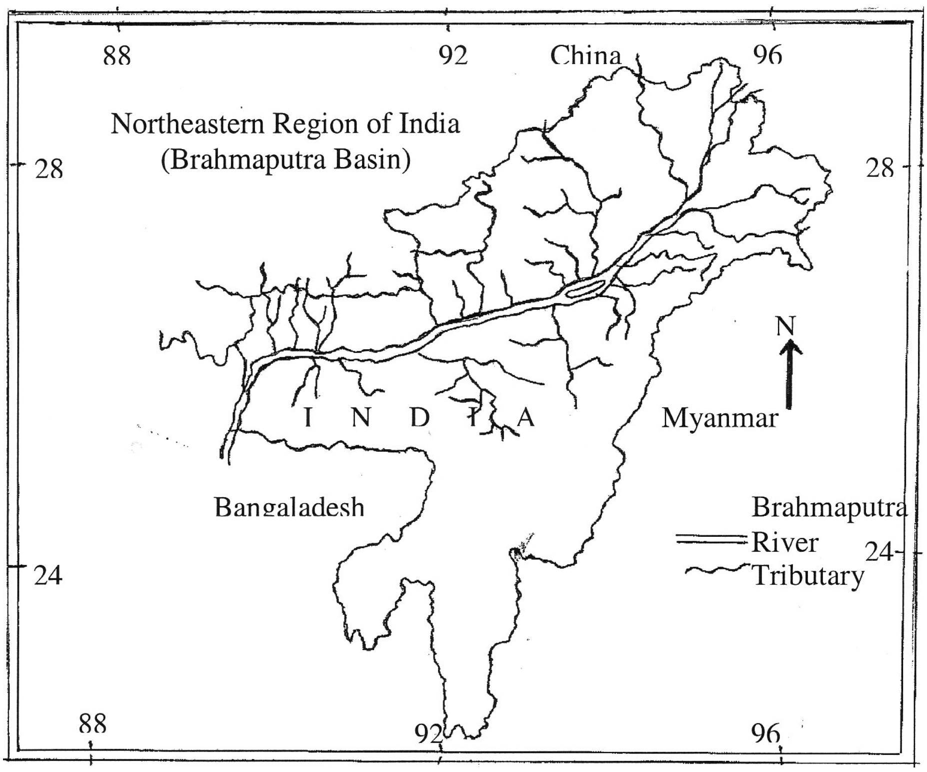

Fig. 1 Brahmaputra basin in the northeastern region of India.

three broad physiographic units comprising of the hills and mountains with high relief, the peninsular plateau, and the plains. The northern part of the Brahmaputra basin is a continuation of the Himalayan mountain system, while the southern part consists of hills and mountains underlain by Tertiary rocks. The Brahmaputra valley is an extension of Indo–Gangetic plains with a gradient of 15–20 cm km^{-1} and is prone to floods and waterlogging. The basin receives about 390 km^3 of rainwater annually, with an annual average precipitation of about 2500 mm. The altitudinal differences, coupled with a varied physiography, contribute to a great variation in climate and groundwater recharge (GWR).

The rainfall variability index was determined using the formula, RVI = $(P–Pm)/Q$, where RVI is the rainfall variability index, P is the precipitation at a station, Pm is the mean precipitation over the years and Q is the standard deviation for the years during which RVI is calculated.

SUSTAINABILITY INDICATORS

For interpreting sustainability in measurable terms, the spatial and temporal dimensions of the system to be analysed need to be defined and appropriate scales and time series have to be selected. The interface between runoff and groundwater is affected by gradient, geology of the area and physical and chemical properties of the soil. In addition, fluctuations in space and time, such as reversal of hydraulic gradient and processes interacting over different time scales, have to be considered. Recharge is the entry into the saturated zone of water made available at the water table surface, together with the associated flow away from the water table within the saturated zone (Freeze, 1969). In the Brahmaputra basin, groundwater sustainability depends on a range of factors which can be categorized into five classes.

METEOROLOGICAL FACTORS

Meteorological factors, such as amount and duration of rainfall, temperature, *in situ* retention of rainwater, rate of infiltration and amount of runoff as well as aquifer recharge capacity, are important indicators of groundwater sustainability. The Brahmaputra basin receives heavy rainfall at an annual average of about 2500 mm. Most of the rainfall is confined to the period from May to October (Table 1). In the basin, water levels of aquifers reach their peak from mid-August to mid-October. A time series of the rainfall variability index (RVI), showing the normalized annual departure, is presented in Fig. 2 and indicates groundwater status. The RVI varied from –1.64 to 1.93, but no particular trend in rainfall was observed with regard to deficit or surplus years. Taking RVI between –1.0 and 1.0 as normal years of rainfall, the deficit years were 1990 and 1996 and the surplus years were 1989, 1991, 2001 and 2002. Some rainwater is lost as surface runoff and some infiltrates into the soil zone. The soil continues to store more water until it reaches field capacity. At this point, the soil begins to drain and recharge can occur. Recharge may not occur at the same location where the rainfall is received. In the Brahmaputra basin rapid runoff occurs in hills and mountains due to steep gradients and water flows across the surface into dams

Table 1 Mean meteorological parameters for a station at an altitude of 980 m in the Brahmaputra basin.

Month	Rainfall (mm)	Temperature max.	min	Evaporation (mm)	Sunshine (h day^{-1})
January	17	16.3	6.7	81	7.0
February	21	19.4	10.4	109	8.0
March	57	24.5	13.9	181	7.4
April	197	27.6	18.2	182	9.5
May	251	26.8	19.9	106	5.4
June	442	27.2	20.4	114	3.8
July	415	26.0	19.8	79	2.9
August	363	26.1	19.2	94	3.2
September	314	26.2	19.2	83	3.4
October	243	25.2	16.2	77	5.2
November	116	22.0	10.1	72	8.6
December	10	19.0	6.2	77	8.0

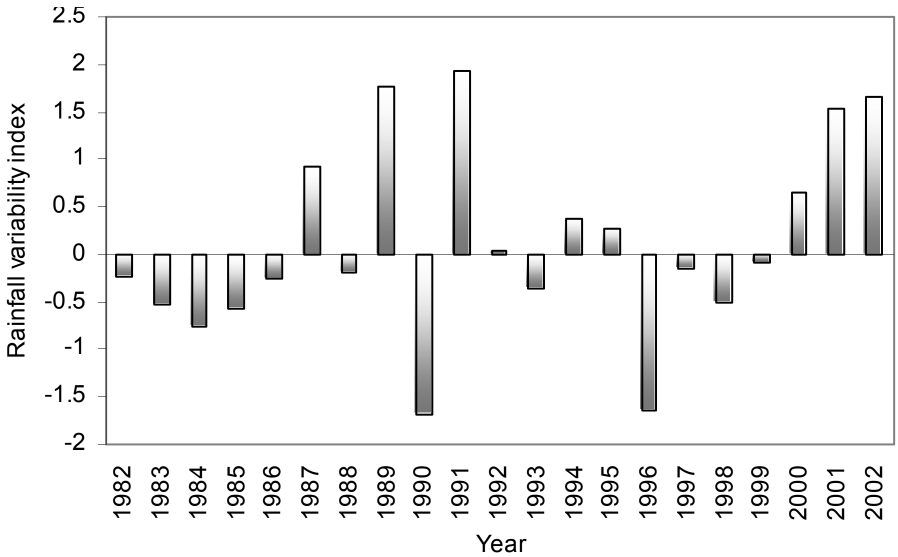

Fig. 2 Rainfall variability index at Barapani station in the northeastern region of India.

and streams. If the streams which collect the water run into aquifers, runoff recharge occurs. The type, amount and distribution of rainfall, infiltration characteristics, initial soil moisture content and topography influence the groundwater recharge.

The temperature variation in the Brahmaputra basin is an important factor in groundwater recharge and so is the sunshine receipt, which affects evaporation and transpiration losses (Table 1). The evaporation losses are higher from February to May when sunshine hours vary from 5.4 to 9.5 per day on average. *In situ* retention of rainwater depends on the nature of vegetation or the land use, soil characteristics and land management practices such as soil conservation measures.

Uncontrolled disposal of urban wastes into water bodies, open dumps and poorly designed landfills cause groundwater contamination and has become one of the most important toxicological and environmental issues in India (Singh, 2000). The use of fertilizers, pesticides and other agricultural chemicals, in an effort to increase crop productivity, has polluted the groundwater in the Brahmaputra basin. Precipitation causes large soil, nutrient and heavy metal ion losses through leaching, which results in contamination of groundwater in the basin (Sharma, 1990). Groundwater recharge depends on the infiltration rate, which is either downward or lateral, and the very slow renewal rate makes groundwater susceptible to depletion and pollution.

SOCIO-ECONOMIC AND LAND USE FACTORS

Management solutions should aim at restoration of the more natural, dynamic behaviour of the water system, because this will minimize the volume of water discharged from the area and maximize water conservation. Dynamic surface water control implies that greater water level fluctuations are allowed within the constraints of agricultural activity and safety (Vermeulen *et al*., 2001). The underlying socio-economic basis for water development in the northeastern region of India is characterized by the disparity between the needs of urban and rural areas, and by socio-cultural rituals with regard to land use and mismanagement of rainwater, which affect groundwater recharge. The prevalence of shifting cultivation, affecting an area of 14 660 km^2, involves large scale deforestation. In consequence, more than 60% of rainwater is translated into runoff, and groundwater recharge is poor. About 601 million tonnes of soil and a large amount of crop nutrients are displaced every year from the region. This results in silting of river beds and floods in the plains, thereby causing variation in GWR at different locations. Efforts to decrease the use of shifting cultivation have met with little success because the practice is not only a set of agricultural operations but is strongly involved with the beliefs, attitudes and tribal identities of the people. Many festivals and rituals are associated with the practice. The sense of non-belonging to the land is a major cause of its mismanagement and the indiscriminate use of water, which affects GWR. The hydrological and geomorphologic response also depends on plant cover and land use. Runoff coefficients and soil erosion rates were found to be higher from cultivated land, especially from areas of shifting cultivation. During the last 50 years, attention has been given to improving agriculture in the region in order to feeding fast growing population, and this has resulted in higher water demands. Changes in land use over time, coupled with their impacts on the water holding capacity of soils have affected GWR in the region.

Accelerating population increases and urban development (Table 2) with other human activity and land use changes have had a significant effect on the hydrological cycle in terms of both water quantity and quality in the region. Urbanization was relatively constant until 1950, but it increased thereafter from a quest to secure better amenities and jobs.

ENVIRONMENTAL FACTORS

In the northeastern region of India, floods occur in about 3760 km^2 of the area every year. The magnitude and duration of the flood period is a good indicator for GWR and its sustainability. Agriculture, including tropical deforestation for shifting cultivation contribute to the greenhouse effect by about 30%. Reducing these practices can reduce

Table 2 Average annual growth (%) of population in rural and urban areas in States of the northeastern region of India.

State	1961–1971		1971–1981		1981–1991	
	Rural	Urban	Rural	Urban	Rural	Urban
Arunachal Pradesh	2.91	---	2.71	8.74	2.44	9.82
Assam	2.82	5.01	1.98	3.24	2.03	3.33
Manipur	2.68	7.37	1.16	9.76	2.42	2.98
Meghalaya	2.82	2.25	2.36	4.95	2.78	3.13
Mizoram	1.57	9.74	2.33	11.71	0.03	9.59
Nagaland	2.84	9.87	3.42	8.50	4.25	5.49
Tripura	2.94	4.55	2.71	3.29	2.45	6.26

Source: Census of India, 1991

large emission of CO_2 and other trace gases. Methane emissions occur from flooded rice fields and the northeastern region of India has >70% of the cultivated area under rice. A reduction of 10 to 30% in methane emissions is possible from rice paddies by changing the irrigation regime to encourage intermittent flooding in order to allow oxygen to enter the soil. Emission of greenhouse gases is related to groundwater levels. By lowering the groundwater levels, nitrous oxide emissions may be permanently enhanced and methane oxidation rates stimulated. An increase of the atmospheric CO_2 concentration will stimulate the photosynthetic rate and, if this is translated to an increase in growth, it will also result in an increase in water use efficiency.

RESILIENCE

Resilience means ability of the system to maintain groundwater reserves in spite of major disturbances. It is measurable in terms of productivity or groundwater recharge. The system should be stable under stress conditions and equitable in time and space as well as being autonomous in nature. No particular study is available regarding the resilience of groundwater in the northeastern region. However, experience shows that the groundwater system in the region is very stable. Moreover, heavy rainfall for about seven months in a year ensures adequate GWR.

POLICY DOMAIN

Due to an increase in population at an annual compound growth rate of 2.43% in the northeastern region of India, as well as the lifestyles practiced, there is diminishing per capita availability of water with time. There is a need for a policy from government to regulate the water system which covers planning, construction and operation of hydraulic infrastructure to ensure water supplies to various users. Inter-related users can be subjected to a prioritization scheme in the form of differential pricing and allocation for different users as well as conflict resolution (Andah, 1996). Such regulation is normally better if the physical water basin is taken as the basic unit of water management. Comprehensive and dynamic water policy has remained a debatable issue and two national water polices have been introduced by the Government of India (Government of India, 1987, 2002). An outline of the major features of water issues related to groundwater sustainability is given in Table 3. Improper policy and management can induce extreme events, degradation and pollution of groundwater and change in hydrological cycle. A cordial relationship between the people and policy makers is necessary to honour the legal provisions embodied in government policies on water resources management. The institutional framework for the management of water resources would include the organization that establishes the rules on the use of water resources, the legislative bodies and the agencies with regulatory or political functions and responsibilities. Though the rules say that groundwater exploitation should not exceed recharge, over-exploitation is going on unabated. A better relationship between functionaries and users would avoid conflict situations and ensure better coordination.

Table 3 Major features of water policies of 1987 and 2002 in India related to groundwater.

1987	2002
A periodic assessment of the groundwater on a scientific basis is stressed, taking into account the quality of water available and economic viability. Exploitation of groundwater should not exceed the recharge possibilities. Integrated and coordinated development of surface water and groundwater should be envisaged. Over-exploitation should be avoided.	In addition, the State and Central Governments should effectively prevent over-exploitation of groundwater. Groundwater recharge projects should be developed and implemented for improving the quality and availability of groundwater resources.
Water resources planning must be based on hydrological units, drainage basins or sub-basins. Recycling and re-use of water should be an integral part of water resource development.	In addition, non-conventional methods of water resources use, such as inter-basin transfers, artificial recharge of groundwater and desalinization as well as traditional practices of rainwater harvesting, need to be used.
Both surface water and groundwater should be regularly monitored for quality. A phased programme should be undertaken for improvement in water quality.	In addition, resources should be conserved and availability be augmented by maximizing retention, eliminating pollution and minimizing losses.
Water conservation consciousness should be promoted through education, regulation, incentives and disincentives.	In addition, the effluents should be treated to acceptable levels and standard before discharge to natural streams. Minimum flow should be maintained in perennial streams for ecological and social considerations.
A master plan for flood control and management for each flood prone basin to be prepared.	In addition, strict regulation of settlements and economic activity in the flood plain. The flood forecasting activities to be modernized.
Water rates should be such as to convey the scarcity value of the resource to the users and to increase the motivation for economy in water use. Water rates for surface and groundwater should be rationalized.	The water charges should cover at least the operation and maintenance charge of providing the service initially, and a part of the capital costs subsequently.

CONCLUSIONS

With increases in demographic pressure and urbanization in the northeastern region of India, the demand for food and water will increase greatly. Shifting cultivation, which is an uneconomic practice degrading resources, cannot fulfil these demands. There is a need for the introduction of viable and eco-friendly land-use systems, which are productive and can induce maximum *in situ* retention of rainwater to ensure groundwater recharge. The state governments in the region should provide more amenities and job orientation activities in the rural areas to eliminate the exodus of people to the cities. Soil conservation measures, such as bench terraces, trenches etc., have to be adopted on steep slopes in order to reduce runoff and loss of soil and crop nutrients and, in turn, prevent silting of river and streams beds and minimize the incidence of floods. There is a strong need to enforce the rules framed with regard to water resources management properly but with due care.

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