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Groundwater Development and Use in Agriculture in India

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Abstract: *The main objectives of present paper are to overview the groundwater economy of India, to analyse the status of groundwater resources and its use in agriculture in India and to draw conclusions for policy implications. The paper has made extensive review of available literature on groundwater economy of India and has utilised the potentially rich sources of secondary data available through the publications of the international institutions, the Government of India and the research conducted by individual researchers. The groundwater economy of India has boomed in recent past and considered highly significant not only for the livelihoods and food security of the poor, but also as an engine of rural and regional economic growth. In terms of the economic value of groundwater production, India has active groundwater markets. The declining water resources in India pose a water management and governance challenge to policy makers. There have been issues of weak enforcement of the existing laws, ensuring adherence to quality standards, insufficient coordination, and overlapping roles of line ministries and departments, inadequate application of market-based instruments. No doubt, water policies of India clearly emphasize sustainable utilization of water resources, still India has to go a long way to take control of a rather dim scenario of water resource management.*

INTRODUCTION

The total volume of water on Earth is about 1400 million km^3, of which about 35 million km^3 (2.5%) is freshwater (Shiklomanov, 1993). The usable freshwater sources (lakes, rivers, and relatively shallow groundwater basins) is only about 200000 km^3 of water (less than 1% of all freshwater) and only 0.01% of all water on Earth. The replenishment of freshwater depends on evaporation from the surface of the oceans to the tune of about 505000 km^3, or a layer 1.4 metres thick annually. Another 72000 km^3 evaporates from the land (Gleick, 1993). The global total fresh groundwater is 8 million km^3 to 10 million km^3, which is more than two thousand times the current annual withdrawal of surface water and groundwater combined. Global annual precipitation is 577,000 km^3 per annum. About 79% of rain falls on the oceans, 2% on lakes, and 19% on land. The high proportion of rain, which falls on the land, is lost to evaporation or runoff. Only 2,200 km^3 or 2% percolate into the groundwater store. Groundwater still makes up 97% of global freshwater (excluding ice). Global groundwater use is about 1000 km^3 per annum, which is around 8.2% of renewable groundwater resources (Shah, 2000). The pressure on groundwater is rapidly growing due to availability of cheap drilling and pumping technologies and energy subsidies. The unplanned, unmanaged, and invisible exploitation of groundwater has been dubbed as the silent revolution (Llamas & Martínez-Santos, 2005; Llamas & Martínez-Cortina; 2009).

In the second half of the twentieth century, groundwater abstraction has increased very rapidly due to high population growth, technological and scientific progress, economic development and food demand (Shah *et al.*, 2007). There have been temporal and spatial variations in groundwater abstraction across the globe. In 2010, the world's aggregated groundwater abstraction is estimated at 1,000 km^3 per annum (IGRAC, 2010; Siebert *et al.*, 2010). The current global abstraction of groundwater is about 26% of total freshwater withdrawal, which is 8% of the mean globally aggregated rate of groundwater recharge. Globally, groundwater supplies more than 50% of all drinking water, 43% of irrigation water (Siebert *et al.*, 2010), 40% of total industrial water withdrawals, 50% of total municipal water withdrawals (Zekster & Everett, 2004), 22% of domestic water use (IGRAC, 2010), and meet water needs of more than 1.5 billion urban dwellers (Salman, 1999).

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Water availability is increasingly scarce and per capita water supplies are declining. About 1.8 billion people will face "absolute water scarcity" and 350 million people will face "severe water scarcity" by 2025, posing threats to food security (Seckler *et al.,* 1999). About one-third of the world's population suffers from moderate-to-high water stress and 40% of the world's population was suffering from serious water shortages by the mid-1990s (CSD, 1997a). There will be severe localized water scarcities in countries even with abundant water. Actual global withdrawals are declining rapidly. There has been decline in groundwater levels in mountain basins (Motagh *et al.*, 2008), the extensive aquifer systems of the Indus basin (Rodell *et al.*, 2009; Centre for Water Policy, 2005) and the North China Plain aquifer (Kendy *et al.*, 2004; Sakura *et al.*, 2003; Liu *et al.*, 2001). By 2020, two-thirds of the world's population will be living in water-stressed countries (CSD, 1997b) and water use is expected to increase by 40% and 17% more water will be required for food production to meet the needs of the growing population over the same period.

GLOBAL GROUNDWATER DEVELOPMENT SCENARIO

There has been a 'global boom' in groundwater irrigation in the last four decades. Groundwater is considered as more reliable source of water-supplies for agricultural irrigation. Globally, groundwater provides 50% of current potable water supplies and 20% of water use in irrigation (Morris *et al.*, 2003). Groundwater use often yields larger economic benefits per unit volume (UN/WWAP, 2003). Groundwater use is likely to increase rapidly in developing countries over the next 25 years due to population pressure, agricultural practices, increasing water demand, increased urban areas, industrial activity and energy demand (Gunatilaka, 2005). More than half of global groundwater abstraction is in India, the United States, and China (World Bank, 2010). Asia is the largest groundwater user in the world with India and China as the major players at an annual rate of abstraction between 1% and 2%. Millions of poor people in India and China depend on groundwater use for sustaining subsistence crop and livestock farming. More than 50% of the global annual groundwater use of 950-1000 km^3 is used for livelihood support (Shah, 2006). In India, more than 60% of irrigated areas are served by groundwater wells and a groundwater user produces a gross output of US $400/ha from irrigating crops (Llamas, 2003). Smallholders' livelihoods are significantly supported by groundwater irrigation, which has potently reduced rural poverty (Deb Roy & Shah, 2003).

There are six key attributes of groundwater (Shah *et al.*, 2007), such as nearly ubiquitous, abstracted quickly, cost effective, drought-resilience, provide water on demand, and face smaller transmission and storage losses than surface water systems. Irrigation uses 70% of the world's freshwater withdrawal, which increases up to 80-90% in semi-arid countries. Government water agencies have been mainly concerned with building and operating surface water supply systems (Llamas & Martinez Santos, 2005).

Groundwater is likely to play a critical role in addressing future water needs. Groundwater depletion is an increasing contributor to sea level rise (Konikow, 2011). The sustainability of the groundwater resource base is critical for meeting basic human needs. There are difficulties of estimating the contribution of groundwater to agriculture (Siebert *et al.*, 2010), municipal services (Foster *et al.*, 2012) and water supply and sanitation (UNICEF/WHO, 2011). Groundwater demand is expected to increase by more than 25% by 2025. There is uncertainty about continued access to shallow groundwater to meet world food production (Brown, 2008). Groundwater irrigates more than 50% of global cereal production (Burke *et al.*, 2012). Largest contribution to increased agricultural output is likely to come from irrigated agricultural intensification (FAO, 2011), with outcomes causing the aquifers becoming the perfect victim and likely to pose threats to regional food security. Globally, irrigation may increase at a relatively modest rate to reach 318 million ha in 2050 from 301 million ha in 2009, which will be an increase of 11%, or 0.24% per year. Due to severely limited surface water supplies, the pressure on aquifers is likely to be very large.

Groundwater is largely used for irrigation in two most populous countries, India and China, which is about half of the world's total annual use. However, there are regional variations in the groundwater use. For instance, southern China has abundant surface water, whereas the North China Plain and large parts of North India have heavy dependence on groundwater for irrigation. In India, groundwater is used to irrigate 60% of agricultural crops and groundwater abstraction has increased from 4 million to 17 million between 1951 and 1997. In 2010, India accounted for 230 km^3 per annum of groundwater abstraction, which is one-fourth of global groundwater use (World Bank, 2010). In India, agricultural output increased from $28.3 to $49.9

billion from 1970s to 1990s. In beginning of 1970s, groundwater contributed only 4.4% to agricultural output, which increased to 14.5% in mid-1990s.

Groundwater use has increased from 10-12 km^3 before 1950 to 240-260 km^3 in 2000 in the Indian sub-continent. Groundwater use increased rapidly in India and the North China in the 1970s and is still growing (Wang *et al.*, 2007). In 1970, groundwater wells irrigated nearly 10 million hectares in India, which increased to more than 35 million hectares of net irrigated area now. Groundwater-irrigated area has increased more than 500% since 1960 in India (Shah, 2009). Irrigated agriculture is the largest abstractor and consumer of groundwater. The largest groundwater-users are India (39 M ha) and China (19 M ha).

Hydro-geologically, the least favoured regions of India are using intensive groundwater irrigation. The density of tube wells is high throughout the Gangetic basin in India due to high groundwater availability and very high population density. The tube well density is also high in Tamil Nadu, Andhra Pradesh and Karnataka where water resources are limited but population density is high. However, tube well density is low in many parts of central India due to least developed groundwater resources and sparse population density (DebRoy & Shah, 2003). Similar pattern has been observed in China. Groundwater development is low in South China with abundant surface water and low population density but tube well density is high in the North China Plain due to low surface water resource and high population density. Intensive groundwater use without appropriate resource management regimes has resulted in resource degradation in India.

However, groundwater has not been properly managed (Mukherji & Shah, 2005). Groundwater management also confronts a brand new challenge of negative impacts of climate change (IPCC, 2007). The potential impacts of climate change on water resources have been widely recognized (IPCC, 2001) with main focus on quantifying the likely direct impacts of changing precipitation and temperature patterns (Arnell, 1998; Chen *et al.*, 2002; Cooper *et al.*, 1995; Croley & Luukkonen, 2003; Lo' aiciga *et al.*, 2000; Yusoff *et al.*, 2002). Therefore, groundwater management should be more strategic and proactive to cope with potential impacts of climate change, but received little attention (Kundzewicz *et al.*, 2007).

Since 1990s, India's food production has hardly been affected by a single drought (Sharma & Mehta, 2002). The individual private farmers have unplanned and uncontrolled investment in tube wells in India, which is both demand and supply driven (Shah, 1993). Groundwater is widely used by farmers (Shah et al, 2007). The 'groundwater-irrigation boom' occurred from subsistence farming to large-scale crop production and commercial cash-crop cultivation (Garduno & Foster, 2010). It has helped alleviate agrarian poverty through increasing food security (Shah, 2009).

In India, groundwater development has served the purpose of a massive programme of strengthening rural livelihood (Shah, 1993). The booming groundwater use has significant role in livelihood and food security in India (Palmer-Jones, 1999). In the early 1990s, the contribution of groundwater irrigation to India's gross domestic product (GDP) was estimated at around 10% (Daines & Pawar, 1987). At present, the size of the India's groundwater irrigation would be around $50-55 billion.

Groundwater contribution to irrigated areas exceeds that of surface water and conjunctive use of surface water and groundwater at the farmer level is small. In North-western India, the bulk of the irrigation is delivered by wells and tube wells (DebRoy & Shah, 2003; Shah *et al.*, 2006). Groundwater irrigation in India is predominantly supplemental nature, which is significantly more productive compared with surface irrigation, because it offers irrigation 'on demand' which few surface systems can offer. Not only this, crop yield per cubic metre of water applied on ground water irrigated farms tends to be 1.2-3 times higher than that applied on surface water-irrigated farms (Dhawan, 1989). About 10% of the world's food production depends on groundwater use to the tune of 200 km^3 and of this 100 km^3 occurs in western India (Postel, 1999). Groundwater irrigation surpasses surface water in many regions. Agriculture uses 70% of total groundwater use followed by industry 20% and residential 10%.

GROUNDWATER DEVELOPMENT SCENARIO IN INDIA

India is the largest groundwater user (230 km^3 per year) through the construction of millions of private wells due to poor public water supply systems, new pump technologies and credit facilities, the flexibility and timeliness of groundwater as an attractive alternative to surface water, and government electricity subsidies. In 1960, about 1 million hectare of farmland was irrigated with groundwater in India, which increased very rapidly until recently compared to the United States, Mexico and China due to several reasons including unmetered and highly subsidized power supply to support groundwater irrigation. Groundwater irrigation has increased rapidly in India since the 1970s from 11.9 million ha to 33.1 million ha to 1990s by more than 178%, whereas canal irrigation increased only by 34%. In India, millions of private wells have been developed in the last six decades. Groundwater irrigates two-thirds of agriculture and accounts for 91% of total groundwater volume withdrawals (Aquastat, 2010). Groundwater provides 85% of rural drinking water and an increasing proportion of urban and industrial water supply.

In India, central and state governments have invested over US$20 billion in building new, and rehabilitating existing, surface irrigation systems in last more than three decades. However, the net area served by surface structures, small and large, has actually declined by over 3 million ha (Thakkar & Chandra, 2007). In contrast, net area served by groundwater has been steadily rising. About 78% of farmers are small and marginal farmers (operating less than 2 ha land) and operate 32% of the land, but own and operate 45% electric water-extraction devices (Government of India, Agriculture Census, 1995) and account for 40% of groundwater- irrigated area. Thus, small farmers are heavily dependent on groundwater irrigation (Tewari, 2003).

The contribution by groundwater irrigation is almost 35% more than surface-water irrigation (DebRoy & Shah, 2003). Groundwater irrigation encourages complimentary investments in fertilizers, pesticides and high-yielding seeds. Output per hectare from groundwater-irrigated areas is 1.2 to 3 times higher than surface-water irrigated areas (Dhawan, 1989). In recent past, dependence on groundwater use has increased tremendously (Sakthivadivel, 2007), which improved stability in cropping, but led to aquifer depletion (Rodell et al., 2009; Shah, 2009) due to more groundwater withdrawals than net recharge in north Indian states. To minimize decline of groundwater levels, Managed Aquifer Recharge (MAR) interventions are widely adopted across India, supported by local communities, state and central governments.

Groundwater greatly supports India's food and livelihood security (World Bank, 2010) and contributes about 9% to India's GDP (Mall et al., 2006). The groundwater demand is rising from the non-agricultural sectors (Shah, 2009). Groundwater irrigated areas has increased 5-fold in the last five decades (Garduno & Foster, 2010) and irrigates over 60% of the areas, which has been possible due to drilling technology, mechanical pumps and rubber pipes, and greater government support (Shah, 2009). The rapid expansion in groundwater use in India has been driven by tube well technology, government support and subsidies, and farmer preference for the inherent advantages of groundwater over other sources (World Bank, 2010). On aggregate, India is withdrawing more than the estimated safe yield. About 29% of groundwater blocks are in the semi-critical, critical, or overexploited categories. Average block sizes vary from 300 km^2 to more than 1,000 km^2 in the major states. Groundwater pollution is serious issue in India (Romani, 2006, 2010) due to contamination of aquifers with 47% and 83.2% sanitation coverage respectively for rural and urban areas. Besides, climate change uncertainties pose challenges for sustainable management of groundwater resources.

India's current water supply is approximately 740 billion m^3. By 2030, water demand in India will grow to almost 1.5 trillion m^3. Climate change impacts are expected to be most severe in India due to lower adaptation capacity (Gosain *et al.*, 2006). Climate change will affect river discharges directly (Scibek *et al.*, 2007; Jyrkama & Sykes, 2007). Most of India's river basins could face severe water deficit by 2030. There has been significant impact of climate change on groundwater recharge and its availability (Lo´aiciga *et al.*, 2000; Varanou *et al.*, 2002; Brouy'ere *et al.*, 2004; Allen *et al.*, 2004; Krysanova *et al.*, 2005; Scibek & Allen, 2006; Andersen *et al.*, 2006; Jyrkama & Sykes, 2007). Aquifer systems have greater buffering capacity against droughts and climate fluctuations (Dragoni & Sukhija, 2008; Shah, 2009). However, hard rock aquifers of India are highly vulnerable to climate change due to low groundwater storage and yields.

STATUS OF GROUNDWATER RESOURCES AND ITS USE IN AGRICULTURE IN INDIA

Water is essential for basic human need. It is a precious natural asset and pertinent for sustaining socio-economic development. With rapid population growth, industrialization and urbanization, including impacts of climatic change, there has been tremendous pressure on the world's water resources. Today, India is facing the emergent water crisis. The status of groundwater resources in India and the key issues therein are presented in table 1. In India, the water availability is increasingly declining. Besides, deteriorating water quality is also a major issue. India is already "water stressed" with per capita water availability below 1,700 m^3. With declining water

Table 1
Groundwater status in India

Water resource Potential	*Precipitation Patterns*	*Water storage Capacity*	*Competing Demands*	*Access to safe drinking water*	*Groundwater Usage*	*Per capita water availability*	*Groundwater Pollution*
Average annual 1,869 billion cubic metres (BCM)	Average annual Precipitation: 1,200 mm. Precipitation distribution: highly uneven, both temporally and spatially. Most precipitation: within 3 or 4 months in a year . Variation in precipitation: 100 mm in Western Rajasthan	Total storage reservoir Capacity: 212.8 BCM, 76.3 BCM under construction, and 107.4 BCM under consideration for construction.	Competing demands from domestic, industrial, and agricultural sectors, with likely continuation of this trend. Water requirements for various sectors of Indian industries almost doubled during last decade. Expected to increase	Improved access. No access to 26.8% of rural and 10% of urban population in 2001.	Stage of groundwater development: 58% in 2006 as against 30% in 1991. Inexorable rise in number of private tube Wells. Increase in budgetary subsidies to agriculture and decline in public investment in agriculture	Declined from 1,820 m3 in 2001 to 1,654 m3 in 2007. Water stressed country. Nine of 20 main rivers in a water deficient state. A low per capita storage of water, of only 213 m3.	High levels of chemical contamination at many places, with one in every eight habitations at risk. Several districts of different states contaminated by arsenic, fluoride, NO3, salinity, and so on. Fluoride being the most prominent

Source: CAEP-TERI (2011)

availability, India is likely to fall into the category of "water scarce" country with per capita water availability below 1,000 m^3. There have been increasingly rising water demands in India from industrial and domestic sectors along with the agricultural sector.

Groundwater has been used widely for irrigated agriculture in India. For example, about 60% of total irrigated area is served by groundwater. Groundwater has been developed rapidly in India since 1960s. Groundwater extraction mechanisms have increased from less than 1 million in 1960 to 26-28 million in 2002 (Shah, 2003). In India, about 1 million new tube wells are added per annum since 1988. However, in recent past groundwater dependence in agriculture has declined more rapidly in India. The data related to groundwater use in agriculture in India is presented in table 2.

India has around 20 million tube wells, which have created a 185-200 km^3 reservoir extracting 10,000 m^3 to irrigate 55-60% of crops. In India, the 'groundwater boom' has been attributed to government support to tube wells and electricity subsidies to farmers. Many state governments have begun restricting power supply to agriculture to cut their losses. In agriculture, energy-irrigation nexus can be a powerful tool for groundwater demand management (Shah *et al.*, 2003). There has been unique nexus between electricity and groundwater irrigation in India, which have benefited small farmers depending on rainfed agriculture with access to irrigation. With flat power tariff or free power, informal groundwater markets for irrigation service has benefited marginal farmers without own tube wells to buy groundwater at a reasonable price (Shah,

Table 2
Groundwater use in agriculture in India

Parameter	*India*
Percentage of population whose livelihood depend on agriculture	70
Percentage of population dependent on GW for irrigation	55-60
No. of people dependent on GW for irrigation, million	586-639
Start of GW irrigation boom	1970s
Annual Groundwater use (km^3)	185-200
No. of Groundwater structures (million)	20.0
Extraction/Structure (m^3/year)	9000-10000
Total annual GW recharge, BCM	432
Net annual GW availability, BCM	361
Total annual GW draft, BCM, recent data	150
Average output of groundwater structures m3/hour	25
Average hours of operation/well/year	315
Selling price of standard-sized pump irrigation (US$/hour)	1.0
Imputed value of groundwater used/year (Billion US$)	6.0

Source: Shah (2006)

1993; Mukherji, 2007; Shah, 2009). However, it has resulted in proliferation of blocks designated as semi-critical, critical and over-exploited.

In West Bengal, one-tenths of its shallow tube wells run on electricity (Mukherji *et al.*, 2012). The state has a total of 5.19 lakhs groundwater extracting mechanisms (GWEMs), of these 1.09 lakh run on electricity. The process of metering of electric tube wells was initiated in 2007 and by 2010, 70% of metering of electric tube wells were completed in the state. All state electricity boards (SEBs) have charged electricity tube well operations based on metered consumption up to early 1970s. Between 1970s-1980s, the SEBs found the transaction costs of metering to be prohibitively high and introduced flat tariffs for agriculture (Shah *et al.*, 2007). As a result, the transaction costs of bill collection was lowered, but affected adversely the electricity and groundwater sectors. Many state governments have used the electricity tariff as an electoral tool of appeasement and kept the flat tariffs very low (Dubash & Rajan, 2001). SEBs have used the unmetered electricity supply to hide their inefficiencies. In this way, the agricultural consumers become a liability for SEBs and affected quality of services. Not only this, the marginal cost of extracting groundwater was close to zero, which provided incentive for over-pumping. Recently, the area under paddy declined in some districts of West Bengal due to restrictive groundwater policies since mid-1990s (Mukherji *et al.*, 2012). Therefore, electricity supply management is essential to enforce its groundwater concessions.

CONCLUSIONS

There has been meteoritic spread of wells and tubewells in India. The groundwater economy of India has boomed in recent past and considered highly significant not only for the livelihoods and food security of the poor, but also as an engine of rural and regional economic growth. In terms of the economic value of groundwater production, India has active groundwater markets. The tubewell owners sell groundwater for irrigation to their neighbours at a price that exceeds their marginal cost of pumping. The groundwater economy has emerged due to a need felt by millions of farmers. The private capital investment in groundwater structures is two-thirds of public investment in surface irrigation. In the past 60 years, private groundwater investments in India has been about US$ 12 billion compared to public sector investment for irrigation at US$ 20 billion. However, financial and economic benefits from private investment in groundwater are considered many times greater.

The declining water resources in India pose a water management and governance challenge to policy makers. There have been issues of weak enforcement of the existing laws, ensuring adherence to quality standards, insufficient coordination, and overlapping roles of line ministries and departments, inadequate application of market-based instruments. For example, in India, there is an economic challenge to introduce a sustainable and equitable tariff structure for water. In most Indian cities, water is provided at a very low and subsidized cost, not reflecting the real cost resulting in wasteful use of the resource and acute shortfalls in revenue realization by urban water authorities, thereby, creating dependency on operating subsidies, capital grants and loans for developing new water infrastructure, which calls for tariff reforms to ensure water availability at its true value. No doubt, water policies of India clearly emphasize sustainable utilization of water resources, still India has to go a long way to take control of a rather dim scenario of water resource management.

REFERENCES

Allen, D. M., Mackie, D. C., & Wei, M. (2004), Groundwater and climate change: A sensitivity analysis for the Grand Forks aquifer, Southern British Columbia, Canada, Hydrogeol. J., 12, 270-290.

Andersen, H. E., Kronvang, B., Larsen, S. E., Hoffmann, C. C., Jensen, T. S., & Rasmussen, E. K. (2006), Climate-change impacts on hydrology and nutrients in a Danish lowland river basin, Sci. Total Environ., 365, 223-237.

Aquastat (2010), FAO's Information System on Water and Agriculture, *http://www.fao.org/nr/water/aquastat/countries_regions/india/index.stm.*

Arnell, N. (1998), Climate change and water resources in Britain, Climatic Change, 39(1): 83-110.

Brouy'ere, S., Carabin, G. & Dassargues, A. (2004), Climate change impacts on groundwater resources: Modeled deficits in a chalky aquifer, Geer basin, Belgium, Hydrogeol. J., 12: 123-134.

Brown L. R. (2008), Plan B 3.0: Mobilizing to Save Civilization, W.W. Norton & Company, New York.

Burke, J., Siebert, S., Hoogeveen, J., Frenken, K., Steduto, P. & Faures, J.M. (2012), The demand for groundwater services in agriculture: Implications of a global inventory, FAO, Italy & Institute of Crop Science and Resource Conservation, University of Bonn, Germany.

CAEP-TERI (2011), *Environment and Development: China and India.* Joint study by the Chinese Academy for

Environmental Planning (CAEP) and The Energy and Resources Institute (TERI). New Delhi: TERI Press.

Centre for Water Policy (2005), *Some Critical Issues on Groundwater in India,* CWP, Delhi.

Chen, Ch., Pei, Sh. & Jiao, J. (2002), Land subsidence caused by groundwater exploitation in Suzhou City, China, Hydrogeol. J., 11: 275-287.

Cooper, D.M., W.B. Wilkinson, & N.W. Arnell (1995), The effects of climate changes on aquifer storage and river baseflow, Hydrol. Sci. J., 40(5): 615-631.

Croley, T.E. & C.L. Luukkonen (2003), Potential effects of climate change on ground water in Lansing, Michigan. J. Am. Water Resour. Assoc., 39(1): 149-163.

CSD (1997a), *Comprehensive Assessment of the Freshwater Resources of the World, Report of the Secretary-General,* United Nations Economic and Social Council *http://www.un.org/documents/ecosoc/cn17/1997/ecn171997-9.htm [Geo-2-117]*

CSD (1997b), *Overall Progress Achieved Since the United Nations Conference on Environment and Development. Report of the Secretary-General, Addendum - Protection of the Quality and Supply of Freshwater Resources: Application of Integrated Approaches to the Development, Management and Use of Water Resources*. United Nations Economic and Social Council http://www.un.org/documents/ecosoc/cn17/1997/ecn171997-2add17.htm [Geo-2-118]

Daines, S.R. & Pawar, J.R. (1987), Economic returns to irrigation in India, SRD Research Group Inc., USA, Agency for International Development Mission to India, New Delhi.

DebRoy A, & Shah T. (2003), Socio-ecology of groundwater irrigation in India, In: Llamas M. R, Custodio E (eds) Intensive use of groundwater: Challenges and opportunities, Balkema, The Netherlands, 307-336.

Dhawan B. D. (1989), Studies in irrigation and water management, Commonwealth Publishers, New Delhi.

Dragoni, W. & Sukhija, B. S. (2008), Climate change and groundwater: A short review, Geol. Soc. London Sp., 288, 1-12.

Dubash, N.K. & Rajan, S. C. (2001), Power politics: Process of power sector reform in India, *Economic and Political Weekly*, 36(35): 3367-3390.

Food and Agriculture Organization of the United Nations (FAO) (2011), The State of Food and Agriculture 2010–2011, Women in Agriculture: Closing the Gender Gap for Development. FAO, Rome.

Foster, S., Breach B. & Mulenga, M. (2012), Urban groundwater use and dependency: Baseline review of state of knowledge and possible approaches to inventory, FAO commissioned report December, 34pp.

Garduño H. & Foster S. (2010), Sustainable Groundwater Irrigation: Approaches to reconciling demand with resources, GW-MATE Strategic Overview Series, No. 4, World Bank, Washington DC.

Gleick, P. H. (1993), *Water in Crisis: A Guide to the World's Freshwater Resources,* New York, Oxford University Press.

Gosain, A. K., Rao, S. & Basuray, D. (2006), Climate change impact assessment on hydrology of Indian river basins, Curr. Sci., 90, 346-353.

Government of India (1995), Agriculture census, Ministry of Agriculture, GOI, New Delhi.

Gunatilaka, A. (2005), Groundwater woes of Asia, Asian Water, January/February.

IGRAC (International Groundwater Resources Assessment Centre) (2010), *Global Groundwater Information System (GGIS),* Delft, the Netherlands, IGRAC.

Intergovernmental Panel on Climate Change (IPCC) (2001), Climate Change 2001, Impacts, adaptation and vulnerability, Chapters 10, 11, 17 and 18, Contribution of Working Group II to the 3rd Assessment Report of the IPCC.

Intergovernmental Panel on Climate Change (IPCC) (2007), Climate Change 2007 - Impacts, Adaptation and Vulnerability Working Group II contribution to the Fourth Assessment Report of the IPCC.

Jyrkama, M. I. & Sykes, J. F. (2007), The impact of climate change on spatially varying groundwater recharge in the grand river watershed (Ontario), J. Hydrol., 338, 237–250.

Kendy, L., Zhang, Y., Liu, C., Wang, J. & Steenhuis, T. (2004), Groundwater recharge from irrigated cropland in the North China Plain: Case study of Luancheng County, Hebei Province, 1949–2000, *Hydrological Processes,* 18: 2289-2302.

Konikow, L. (2011), Contribution of global groundwater depletion since 1900 to sea-level rise, *Geophysical Research Letters*, 38: 1-5.

Krysanova, V., Hattermann, F., & Habeck, A. (2005), Expected changes in water resources availability and water quality with respect to climate change in the Elbe River basin (Germany), *Nord. Hydrol.*, 36, 321-333.

Kundzewicz, Z. W., L. J. Mata, N. W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen, & I.A. Shiklomanov (2007), Freshwater resources and their management. In: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (ed. by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson), 173-210. Cambridge University Press, Cambridge, UK.

Liu, C. M., Yu, J.J. & Kendy, E. (2001), Groundwater exploitation and its impact on the environment in the North China Plain, *Water International*, 26(2): 265-272.

Llamas, R. (2003), "Epilogue", Water International, 28(3): 405-409.

Llamas, M.R. & Martínez-Santos, P. (2005), Intensive Groundwater Use: Silent Revolution and Potential Source of Social Conflicts, *Journal of Water Resources Planning and Management*, American Society of Civil Engineers, pp. 337–341.

Llamas, M. R., & L. Martínez-Cortina (2009), Specific aspects of groundwater use in water Ethics: Marcelino botin water forum 2007, (ed.) M.R. Llamas, L. Martínez-Cortina and A. Mukherji. London, UK: CRC Press.

Lo´aiciga, H. A., Maidment, D. R. & Valdes, J. B. (2000), Climate-change impacts in a regional karst aquifer, Texas, USA, J. Hydrol., 227, 173-194.

Mall, R. K., Gupta, A., Singh, R., Singh, R. & Rathore, L. S. (2006), Water resources and climate change: An Indian perspective, Curr. Sci., 90, 1610-1626.

Motagh, M., Walter, T., Sahrifi, M., Fielding, E., Schenk, A., Anderssohn, J. & Zschau, J. (2008), Land subsidence in Iran caused by widespread water reservoir overexploitation, *Geophysical Research Letters,* 35(16).

Morris, B. L., Lawrence, A. R. L., Chilton, P. J. C., Adams, B., Calow R. C. & Klinck, B. A. (2003), Groundwater and its Susceptibility to Degradation: A Global Assessment of the Problem and Options for Management, Early Warning and Assessment Report Series, RS. 03 3, United Nations Environment Programme, Nairobi, Kenya.

Mukherji, A. & T. Shah (2005), Groundwater socio-ecology and governance: A review of institutions and policies in selected countries, *Hydrogeology Journal,* 13(1): 328-345.

Mukherji, A. (2007), The energy-irrigation nexus and its impact on groundwater markets in eastern Indo-Gangetic basin: Evidence from West Bengal, India, *Energy Policy*, 35: 6413-6430.

Mukherji, A., Shah, T. & Banerjee, P.S. (2012), Kick-starting a second green revolution in Bengal, India: *Economic and Political Weekly*, 47(18): 27-30.

Palmer-Jones, R.W. (1999), Slowdown in agricultural growth in Bangladesh: Neither a good description nor a description good to give, pp. 92–136, In Sonar Bangla? *Agricultural Growth and Agrarian Change in West Bengal and Bangladesh* (Rogaly, B., Harris-White, B., and Bose. S. Eds). Sage Publications, New Delhi.

Postel, S. (1999), *The Pillar of Sand*. W.W. Norton, New York.

Rodell, M., Velicogna, I. & Famiglietti, J. S. (2009), Satellite-based estimates of groundwater depletion in India, Nature, 460, 999-1002, August 20.

Romani, S. (2006), Ground Water Management: Emerging Challenges, In S. Romani *et al.*, eds. *Ground Water Governance,* New Delhi: Capital Publishing Co.

Romani, S. (2010), *Characterization of Groundwater Pollution Issues in India,* WB consultancy for ESW-groundwater governance Study, Washington, DC: World Bank.

Sakthivadivel R. (2007), The Groundwater Recharge Movement in India, In Giordano, M. and Villholth, K.G. (Eds) *The Agricultural Groundwater Revolution: Opportunities and threats to development,* Wallingford: CAB International, pp. 195-210.

Sakura, Y., Tang, C., Yoshioka, R. & Ishibashi, H. (2003), Intensive use of groundwater in some areas of China and Japan, In Intensive Use of Groundwater: Challenges and Opportunities. Llamas, R. & Custodio, E. (eds). A.A.Balkema, The Netherlands, pp. 337-353.

Salman, A.A.S. (Ed) (1999), Groundwater Legal and Policy Perspectives, World Bank Technical Paper 456. Washington, DC: World Bank.

Scibek, J. & Allen, D. M. (2006), Modeled impacts of predicted climate change on recharge and groundwater levels, Water Resour. Res, 42.

Scibek, J., Allen, D. M., Cannon, A. J. & Whitfield, P. H. (2007), Groundwater-surface water interaction under scenarios of climate change using a high-resolution transient groundwater model, J. Hydrol., 333, 165-181.

Seckler, D., Amarashinge, U., Molden, D., de Silva, R. & Barker, R. (1999), World water demand and supply, 1990 to 2025, *Scenarios and Issues*, Research Report 19, International Water Management Institute, Colombo, Sri Lanka.

Shah, T. (1993), *Groundwater Markets and Irrigation Development: Political Economy and Practical Policy,* Oxford University Press, Bombay.

Shah, T. (2000), Mobilizing social energy against environmental challenge: Understanding the groundwater recharge movement in western India, *Natural Resource Forum*, 24(3): 197-209.

Shah, T. (2003), Governing the groundwater economy: Comparative analysis of national institutions and policies in South Asia, China and Mexico, *Water* Perspectives, 1(1): 2-27.

Shah, T. (2006), Institutional groundwater management in the United States: Lessons for South Asia and north China. *Kansas Journal of Law & Public Policy,* 15(3): 567-571.

Shah, T. (2009), Climate change and groundwater: India's opportunities for mitigation and Adaptation, Environmental Research Letters, 4: 1-13.

Shah, T., DebRoy, A., Qureshi, A.S. & Wang, J. (2003), Sustaining Asia's groundwater boom: An overview of issues and evidence. *Natural Resources Forum,* 27: 130-140.

Shah, T., Scott, C., Kishore, A. & Sharma, A. (2007), Energy-irrigation nexus in South Asia: Improving groundwater conservation and power sector viability, In: Giordano, M., Villholth, K.G. (Eds.), *The Agricultural Groundwater Revolution: Opportunities and Threats to Development,* CABI Publishers, UK, pp. 211–243.

Shah, T., Singh, O.P. & Mukherji, A. (2006), Groundwater irrigation and South Asian agriculture: Empirical analysis from a large-scale survey of India, Pakistan, Nepal and Bangladesh, *Hydrogeology Journal,* 14(3): 286-309.

Sharma, S.K. & Mehta, M. (2002), Groundwater development scenario: Management issues and options in India. Paper presented at the IWMI–ICAR–Colombo Plan sponsored Policy Dialogue on 'Forward-Thinking Policies for Groundwater Management: Energy, Water Resources, and Economic Approaches' at India International Center, New Delhi, India, 2–6 September.

Shiklomanov, I.A. (1993), World freshwater resources, In P. H. Gleick (ed.), *Water in Crisis: A Guide to the World's Freshwater Resources,* New York, Oxford University Press

Siebert, S., J. Burke, J. M. Faures, K. Frenken, J. Hoogeveen, P. Döll & F. T. Portmann (2010), Groundwater use for irrigation: A global inventory, *Hydrology and Earth Systems Science,* 14: 1863-1880.

Tewari, D.D. (2003), Groundwater socio-ecology of the Limpopo province, South Africa: A preliminary study, Report submitted to IWMI-Tata Programme, Anand, Gujarat.

Thakkar, H. & Chandra, Bipin (2007), Rs 100 000 crores spent, but no additional benefits, no addition to canal irrigated areas for 12 years, *Dams, Rivers and People,* 5(8-9):1-6.

UNICEF/WHO (2011) Drinking Water Equity, Safety and Sustainability: Thematic report on drinking water 2011, WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation (JMP), New York. 64pp.

United Nations/World Water Assessment Programme (UN/WWAP) (2003), UN World Water Development Report: Water for People, Water for Life, UNESCO (United Nations Educational, Scientific and Cultural Organisation) and Berghahn Books, Paris, New York and Oxford.

Varanou, E., Gkouvatsou, E., Baltas, E. & Mimikou, M. (2002), Quantity and quality integrated catchment modelling under climate change with use of soil and water assessment tool model, J. Hydrol. Eng., 7: 228-244.

Wang, J., Huang, J., Rozelle, S., Huang, Q. & Blanke, A. (2007), Agriculture and groundwater development in northern China: Trends, institutional responses, and policy options, *Water Policy*, 9(1): 61-74.

World Bank (2010), *Deep Wells and Prudence: Towards Pragmatic Action for Addressing Groundwater Overexploitation in India*. New Delhi: the World Bank.

Yusoff, I., K.M. Hiscock & D. Conway (2002), Simulation of the impacts of climate change on groundwater resources in eastern England, In: Hiscock K.M., M.O. Rivett and R.M. Davidson (eds) Sustainable Groundwater Development, Geological Society, London, Special Publications, 193: 325-344.

Zektser I.S. & L.G. Everett (2004), Groundwater Resources of the World and their Use, Paris: UNESCO.