Some aspects of South Asia's groundwater irrigation economy: analyses from a survey in India, Pakistan, Nepal Terai and Bangladesh

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Abstract Since 1960, South Asia has emerged as the largest user of groundwater in irrigation in the world. Yet, little is known about this burgeoning economy, now the mainstay of the region's agriculture, food security and livelihoods. Results from the first socio-economic survey of its kind, involving 2,629 well-owners from 278 villages from India, Pakistan, Nepal Terai and Bangladesh, show that groundwater is used in over 75% of the irrigated areas in the sample villages, far more than secondary estimates suggest. Thanks to the pervasive use of groundwater in irrigation, rain-fed farming regions are a rarity although rain-fed plots within villages abound. Groundwater irrigation is quintessentially supplemental and used mostly on water-economical inferior cereals and pulses, while a water-intensive wheat and rice system dominates canal areas. Subsidies on electricity and canal irrigation shape the sub-continental irrigation economy, but it is the diesel pump that drives it. Pervasive markets in tubewell irrigation services enhance irrigation access to the poor. Most farmers interviewed reported resource depletion and deterioration, but expressed more concern over the high cost and poor reliability of energy supply for groundwater irrigation, which has become the fulcrum of their survival strategy.

Résumé Depuis 1960, l'Asie du Sud a émergée en tant que plus grand utilisateur d'eaux souterraines pour l'irrigation dans le monde. Par ailleurs, on connaît peu de choses sur l'économie bourgeonnante, le maintien actuel de l'agriculture de la région, la sécurité alimentaire et les moyens d'existence. Les résultats de différentes études socio-économiques, sur 2,629 propriétaires de puits de 278 villages d'Inde, Pakistan, Népal et Bangladesh, montrent que l'eau souterraine est utilisée sur 75 % des aires irriguées dans les villages échantillonnés, loin de ce que les estimations suggérèrent. Du fait de l'utilisation envahissante de l'eau souterraine pour l'irrigation, les régions utilisant l'eau de pluie sont rares, bien que les villages alimentés par eau de pluie abondent.

L'irrigation avec l'eau souterraine est d'une manière quintessence complémentaire, utilisée le plus souvent pour les céréales inférieures et les légumes secs, alors que l'utilisation intensive de l'eau pour le blé et le riz domine les aires de canaux. Les subsides pour l'électricité et l'irrigation par canal, forme l'économie sub-continentale de l'irrigation, mais ce sont les pompes diesel qui la conduise. Les marchés envahissants des services de forages pour l'irrigation, améliorent l'accès de l'irrigation pour les pauvres. La plus part des fermiers interviewés ont reporté un épuisement et une détérioration de la ressource, mais sont surtout concernés par le coût et la faible rentabilité énergétique de l'eau souterraine pour l'irrigation, qui est devenue le point d'appui de leur stratégie de survie.

Resumen Desde 1960 el Sur de Asia ha emergido como el usuario más grande del mundo de agua subterránea para riego. Sin embargo, se conoce poco acerca de esta creciente economía, que constituye ahora el pilar de agricultura de la región, la seguridad alimentaria y la subsistencia. Los resultados del primer levantamiento socioeconómico de este tipo, que involucra 2,629 propietarios de pozos de 278 poblados de India, Pakistán, Nepal teria y Bangladesh, muestra que el agua subterránea es usada en más de 75% de las áreas irrigadas en los poblados muestreados, mucho más que lo sugerido por estimaciones secundarias.

Debido a el amplio uso de agua subterránea en riego, las regiones agrícolas abastecidas por agua de lluvia son raras aunque abundan poblados con parcelas alimentadas por lluvia. El riego por agua subterránea es quintaesencialmente suplemental, utilizado principalmente en cereales inferiores económicos en agua mientras que el trigo de uso intensivo de agua y el sistema de arroz predominan en áreas de canales. Los subsidios en electricidad y riego de canales moldean la economía de riego sub-continental, pero es la bomba de diesel la que la mueve. Los amplios mercados en

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servicios de riego de pozos entubados estimulan el acceso al riego para los pobres. La mayoría de agricultores entrevistados reportan un deterioro y escasez del recurso pero expresaron más preocupación por el alto costo y dependencia de los pobres en el abastecimiento de energía para regar con agua subterránea, lo cual se ha convertido en el punto de apoyo de su estrategia para sobrevivir.

Keywords Agriculture · South Asia · Groundwater development · Well-owner survey · Socio-economic aspects

Introduction and approach

Agricultural irrigation through the use of groundwater derived from private wells and tubewells, has emerged as a major phenomenon in South Asia over the past few decades (GOI 2001a,c; Debroy and Shah 2003; Shah et al. 2003; Qureshi et al. 2003; Mukherji and Shah 2004; Dhawan 1995; Saleth 1998; Moench 1992a, 1995, 2001; Custodio and Llamas 2003; and also unpublished literature from D. Pant and M. Belbase of the International Water Management Institute, Nepal, 2003; and Roy K.C. and Mainuddin M of the Bangladesh Agricultural Research Institute, and the International Water Management Institute, Thailand, 2003). However, research to understand the big picture of this booming economy, and farmers' perceptions about its challenges, has so far remained limited. The data sets generated by the governmental departments provide some insights into the nature, extent and behaviour of groundwater resources and aquifers but little about the wide-ranging socio-economic impacts of groundwater irrigation. In India, for instance, the publications of the Central Ground Water Board provide district-wise data on pre and post-monsoon water levels, and district-wise estimates of recharge are also available (GOI 1995). The Minor Irrigation Census provides good district-wise data every 5 years on the number and type of groundwater structures in states covered by it, but has a reporting time-lag of 5–7 years (GOI 2001b). Season and crop survey reports provide an idea of the irrigated area covered by different irrigation sources. However, the kind of data compiled, sources, methods used and the survey period/frequency vary across the countries; as a result, it is difficult to piece together a coherent picture on a sub-continental scale. Much discussion about groundwater economy and policy in the region–including some big picture analyses (such as Moench 1992b; Postel 1999; Burke and Moench 2000)–are based largely on episodic data. This paper summarizes some analyses based on the first-ever sub-continental survey of the groundwater economy conducted by the International Water Management Institute's IWMI-Tata Water Policy Research Program in 2002. The survey covered all of India, all of Pakistan except Balochistan, 20 districts of Nepal Terai and all of Bangladesh. Sri Lanka has witnessed an increase in groundwater irrigation in its northern and eastern parts (Kikuchi et al. 2003); however, it was excluded from this survey because groundwater irrigation does not seem to dominate Sri Lanka's irrigation economy like it does in the countries covered by the survey. The objectives of the survey were:

1. To understand the spatial and temporal patterns of groundwater irrigation relative to the hydrogeological conditions in different parts of the sub-continent
2. To develop an estimate of groundwater contribution in irrigated areas and compare it with other available estimates
3. To analyse energy pricing and supply policies as a key driver of the region's groundwater economy
4. To analyse the dominant role of the diesel pump in providing supplemental irrigation-on-demand
5. To analyse the size and significance of pump-irrigation markets in the region's groundwater economy
6. To ascertain farmer perceptions about key challenges facing the groundwater irrigation economy of South Asia.

Since the main objective of the survey was to make an overall socio-economic assessment of groundwater contribution to South Asian agriculture, the sampling plan was driven by the need for geographic representation. The region, shown in Fig. 1, was divided in to 278[1] grids, each of 1 degree longitude and latitude. A village was chosen from each grid ensuring that it was roughly equidistant from villages surveyed from neighbouring grids. Two research instruments were used in each sample village: including (1) a 'village schedule' to compile a picture of the village as a whole from government records as well as through focus group discussion with a group of village elders who served as 'lead informers'; and (2) a 'farmer schedule' canvassed with 8–15 well/tubewell owners per village. Table 1 outlines the profile of the sample villages. The 278 villages covered approximately 224,000 households and an estimated population of 1.31 million people. The geographic area covered was 424,000 ha, of which 327,000 (77%) was estimated to be under cultivation.

Data collection and some analyses were done by 12 partner institutions who worked with the research team of the IWMI-Tata Water Policy Program. The partners who contributed to this research are listed in Appendix 1.

The survey data were analysed in a number of ways. Several partners developed analyses for the regions covered by them using survey data as well as the qualitative information they gathered in the course of interviews with farm households. There were also separate reports for India (Mukherji and Shah 2004), Pakistan (Qureshi et al. 2003), Bangladesh (K.C. Roy and M. Mainuddin of the Bangladesh Agricultural Research Institute, and the International Water Management Institute, Thailand, 2003, unpublished data) and Nepal (D. Pant and M. Belbase of the International Water Management Institute, Nepal, 2003, unpublished data). Each of these combined survey data with secondary information to create a picture of groundwater socio-ecology (interaction between hydrogeological,

[1] 292 villages were covered by the original sample; however, complete data sets are available only for 278 villages.

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Table 1 Profile of the villages surveyed

Country	Number of villages	Number of tubewell owners surveyed	Total number of groundwater structures owned by sample farmers	Net cultivated area in sample villages (000 ha)
India	149	1508	1936	151
Pakistan	80	525	736	34
Bangladesh	27	245	298	9
Nepal	22	351	380	4.5
Total	278	2629	3350	198.5

Source: primary survey conducted by IWMI in 2002

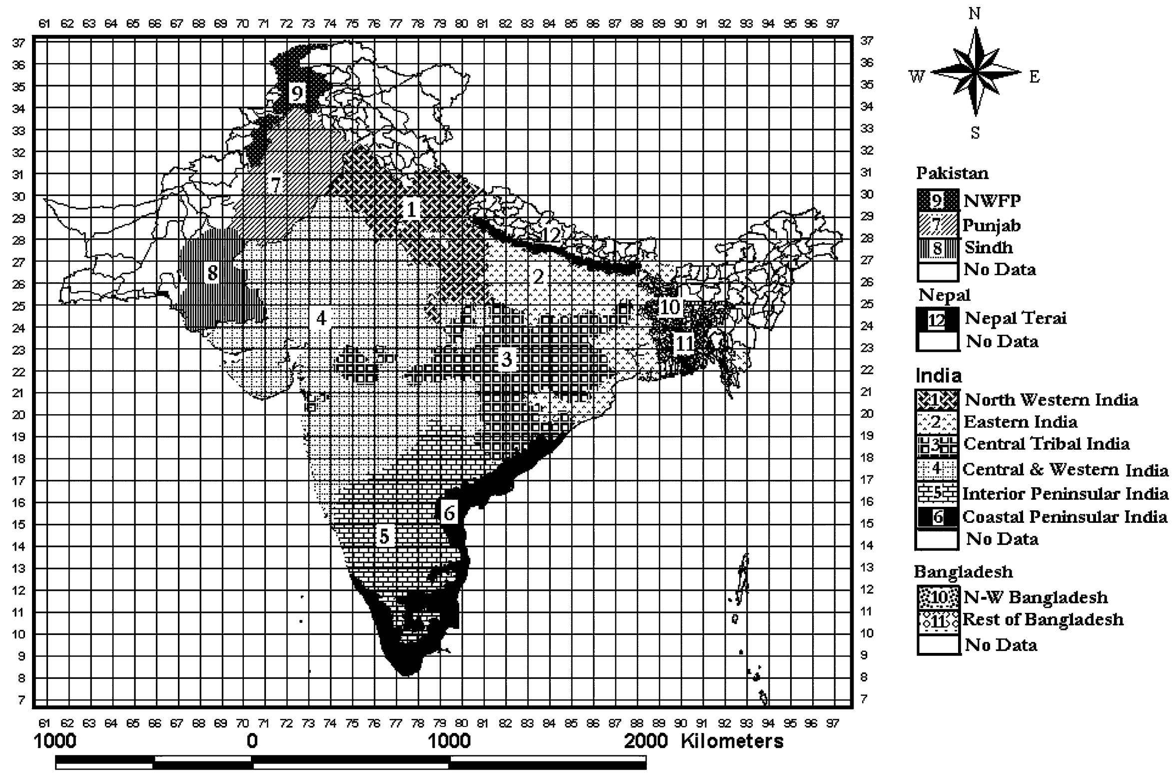

Fig. 1 Hydro-economic zones of the South Asian region and sample grids used in the IWMI-Tata survey, 2002

socio-economic and demographic variables) in the countries studied. All these papers were presented and discussed in the 2nd IWMI-Tata Annual Partners' Meeting during early 2003.

Overview of the irrigation economy of the sample villages

In analysing the survey data, the aim was to capture the socio-economic and hydrogeological diversity of the region. Therefore, the national political boundaries were retained, but within each country, states/provinces were grouped, or parts thereof, into hydrogeologically and socio-economically homogeneous zones. Eastern India, for instance came to include West Bengal, Bihar, coastal Orissa and eastern Uttar Pradesh, a region in the eastern Indo-Gangetic Basin (IGB) that shares the characteristics of alluvial aquifers, high rainfall and recharge, high concentration of rural poverty and stagnating agriculture. Nepal Terai also shares all these, but was treated as a separate zone because it belongs to a different national policy regime. Similarly, the central Indian tribal belt (zone 3 in Fig. 1) was carved out from several states and separated from the hard-rock inland peninsular India because the former is dominated by tribal communities that are different from the people inhabiting the latter region. In this manner, the sub-continent was divided into 12 so called 'hydro-economic (H-E) zones' based on their hydrogeological, socio-economic and political profile as set out in Table 2 and shown in Fig. 1.[2] Later in the analysis, these 12 zones were combined in a variety of ways to test a number of hypotheses regarding the functioning of the sub-continental groundwater economy.

In Table 2, an attempt has also been made to classify the 12 zones based on their overall groundwater resource

[2] There were some parts of some zones–Balochistan and Kashmir, Jammu and Kashmir, and hill areas of Nepal–which were not covered by the survey for a variety of reasons. These were excluded from the analysis.

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Table 2 Hydro-economic zones: regionalization and sample area characteristics

Region and Ref in Fig 1	Dominant features	No. of villages sampled	Coverage	Long-term average rainfall (mm)[a]	Nature of the aquifer	Canal irrigation as % of irrigated area	Index of groundwater resource potential[b]
1. North-western India	Canal irrigated intensive agriculture; conjunctive use	16	Punjab, Haryana and western Uttar Pradesh	733	Alluvial	>25	9
2. Eastern India	Abundant but under-utilized groundwater resource partly due to rural poverty	21	West Bengal, Bihar, coastal Orissa and eastern Uttar Pradesh	1473	Alluvial	10–15	11
3. Central India tribal belt	Poor, tribal communities, limited groundwater; under-utilized	22	Chhattisgarh, Jharkhand, 2, 4 and 5 villages from Gujarat, Madhya Pradesh and Orissa, respectively	1226	Semi-consolidated	<10	8
4. Central and Western India	Semi-arid conditions; intensive groundwater irrigation	55	Rajasthan, Maharashtra, non tribal districts of Madhya Pradesh and Gujarat	1084	Semi-consolidated	<10	8
5. Interior peninsular India	Hardrock aquifers, intensive groundwater irrigation	25	Interior districts of Karnataka, Tamil Nadu and Andhra Pradesh	1071	Consolidated	10–25	8
6. Coastal peninsular India	Alluvial aquifers, intensively exploited	10	Coastal districts of Andhra Pradesh, Tamil Nadu and Kerala	1652	Alluvial	10–25	12
7. Pakistan Punjab	Canal irrigated intensive agriculture; conjunctive use	36	Punjab province in Pakistan	725	Alluvial	>25	9
8. Pakistan Sindh	Canal irrigation; conjunctive use; arid climate	21	Sindh province in Pakistan	340	Alluvial	10–25	7
9. Pakistan NWFP	Hardrock aquifers; limited groundwater; under-utilized	23	NWFP in Pakistan	210	Semi-consolidated	10–25	5
10. North-west Bangladesh	Abundant groundwater, intensively used; groundwater vs. rural poverty	11	Former districts of Dinajpur, Rangpur, Bogra, Pabna and Rajshahi	1679	Alluvial	<10	11
11. Rest of Bangladesh	Abundant groundwater, intensively used; groundwater vs. rural poverty	16	The rest of Bangladesh	1689	Alluvial	<10	11
12. Nepal Terai	Abundant groundwater, under-utilized; groundwater vs. rural poverty	22	20 districts in Nepal Terai	1025	Alluvial	<10	9

[a]Rainfall data for H-E zones in India are taken from Agro-climatic Regional Planning Unit (1991). Rainfall data for North Bihar were applied to Nepal Terai; data for West Bengal were applied to Bangladesh; data for Kutch were applied to Sindh; and data for Indian Punjab were applied to Pakistan Punjab. Long-term average rainfall for different H-E zones were also cross-checked with IWMI's Climate Atlas

[b]This crude index of regional groundwater availability is computed by adding scores assigned to rainfall, aquifer type and canal irrigation availability as follows: Rainfall (mm): <250=1; 250−500=2; 500−750=3; 750−1000=4; 1000−1250=5; 1250−1500=6; >1500=7; Aquifer Type: *Consolidated* 1; *Semi-consolidated* 2; *Alluvial* 3; Canal irrigated areas as percent of net cropped area: less than 10%=1; 10–25%=2; more than 25%=3

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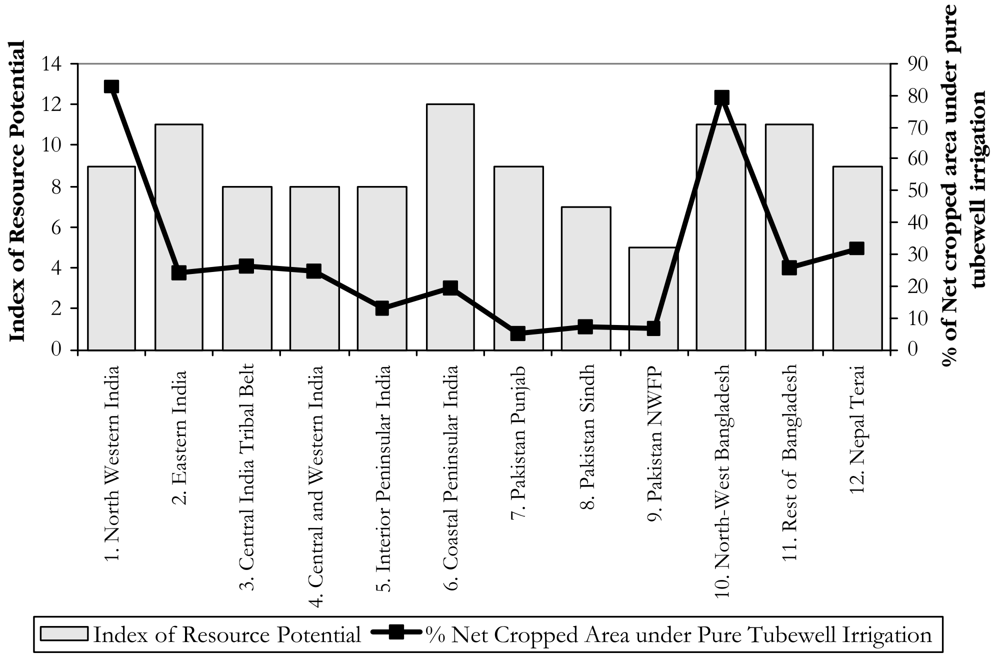

Fig. 2 Mismatch between groundwater availability (resource potential) and development

potential as determined by extent of precipitation, nature of the aquifer and the extent of cultivated area under canal irrigation. The procedure adopted is no doubt crude, since there are vast variations in all three conditions within each zone. However, it helps in the determination of whether the development of groundwater irrigation in each zone is broadly in tune with the resource potential. Figure 2 needs to be viewed with caution because the variables being compared bear different dimensions; but it does suggest that resource 'availability' and 'development' are not always in tune with each other. North-western India's dependence on pure tubewell irrigation does not match with its resource availability; and there is much scope for further development in eastern India, the 'rest of Bangladesh' and Nepal Terai. Somewhat surprisingly, pure tubewell irrigation in the Pakistan Punjab villages surveyed seems smaller compared to the potential; however, this may well be because Pakistan Punjab and even Sindh have more pure canal irrigation as well as conjunctive use compared to north-western India.

Development of groundwater irrigation has followed different trajectories in different hydro-economic (H-E) zones. In order to understand these, the IWMI-Tata survey of tubewell owners asked for the year in which they first completed and commissioned their wells/tubewells.[3] Figure 3 shows that although well irrigation has been practiced in the region for a millennia, South Asia's 'groundwater boom' is indeed barely 30 years old. It began in south and central India, where the largest stock of tubewell capital was accumulated before 1965 (see Fig. 3). Since then, almost everywhere in the region, the greatest increase in the number of groundwater structures has occurred only during the 1990s. Note also that growth in water extraction mechanisms (WEMs)[4] is by no means smooth. The number of new wells has tended to increase in spurts during drought years; this suggests that much groundwater development in the region reflects the farmers' efforts to cope with or survive droughts. While it is very likely that the increase in the number of tubewells has resulted in some increase in groundwater draft and area irrigated by groundwater, the relationship may not be proportional. In many regions, a growing number of tubewells are probably sharing the same or even smaller resource, with annual draft per tubewell falling as the number of tubewells rises. However, there are no data to verify this relationship.

The nature of South Asian irrigation

Although India has invested over US $27 billion (at March 2004 exchange rates) in establishing public irrigation projects in the major and medium sector since 1950, it is often said that the bulk, some 60%[5] (GOI 2001a), of the irrigated areas are served by wells and tubewells built by farmers with private investment. Does the IWMI-Tata survey throw any light on this important issue? Table 3 shows that, for the region as a whole, 44% of the 'net cropped area' in the sample villages is irrigated; however, 55% of the irrigated areas is served *exclusively* by groundwater; and 22% more is under conjunctive use of ground and surface water. The IWMI-Tata survey, then, suggests that groundwater contributes to over 75% of South Asia's irrigated areas, and pure canal irrigation constitutes 18%

[3] In hindsight this question may have been interpreted differently by different farmers and may have evoked different responses. The two most likely interpretations are: (1) When did you first acquire the well/tubewell in use now? (2) When did you first establish a mechanized well/tubewell. Under the circumstances, the best interpretation of Fig. 3 pertains to establishing the year during in which the respondent first acquired a mechanized well/tubewell.

[4] Open or tubewells mounted with either diesel or electric pumps.

[5] A variety of estimates are in circulation about the groundwater contribution to India's irrigated area. (NABARD 2005).

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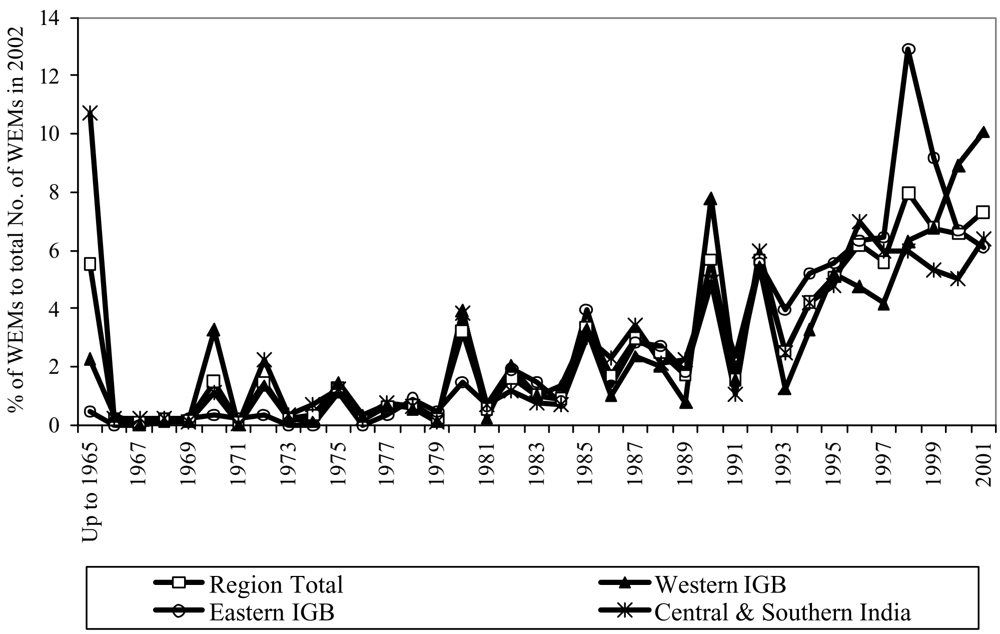

Fig. 3 Pace of growth of water extraction mechanisms (WEMs) in survey villages: IWMI-Tata Survey of 2002

Table 3 Profile of irrigation by groundwater and surface water sources

Region (1)	Total cultivated land (ha) (2)	% rain-fed (3)	Area irrigated as % to cultivated land[a] (4)	% of cultivated area under respective sources of irrigation: Pure canal irrigation (5)	Pure groundwater irrigation (6)	Conjunctive use of ground and surface water (7)	Other sources (8)
North-western India	27,778	8.1	91.9	2.9	82.8	5.6	0
Eastern India	10,719	55.6	44.4	3.3	24.1	11.0	5.9
Central Indian tribal belt	11,762	58.3	42.3	0.7	26.4	13.3	1.3
Central and western India	57,913	71.4	28.6	0.6	24.8	2.0	1.2
Interior peninsular India	31,859	77.2	22.8	2.4	13.2	1.8	5.4
Coastal peninsular India	10,503	45.7	59.0	15.8	19.6	14.7	4.3
India	*15,0534*	*57.0*	*43.4*	*2.7*	*32.8*	*5.0*	*2.4*
Pakistan Punjab	63,149	56.9	50.5	16.0	5.0	21.9	0
Pakistan Sindh	4,056	52.5	43.1	19.9	7.3	20.3	0
Pakistan NWFP	7,885	49.5	50.4	28.5	6.8	4.7	0
Pakistan	*7,5091*	*55.9*	*44.2*	*17.5*	*5.3*	*20.0*	*1.4*
North-western Bangladesh	1,554	18.4	81.6	0	79.2	0	1.3
Rest of Bangladesh	4,350	43.9	56.1	0.2	25.8	6.2	23.8
Bangladesh	*5,904*	*37.2*	*62.8*	*0.2*	*39.9*	*4.6*	*17.9*
Nepal Terai	*4,542*	*42.1*	*62.1*	*28.3*	*31.8*	*0.3*	*0*
Region aggregate	**23,6070**	**55.8**	**44.5**	**7.8**	**24.2**	**9.7**	**2.0**
Source contribution to total irrigated area (%)				*17.8*	*54.8*	*22.0*	*4.5*

Source primary survey conducted by IWMI in 2002

[a]The questionnaire asked sample farmers to separately provide figures for their farm areas under rain-fed farming and under different sources of irrigation. Columns 3 and 4 are computed based on these; as a result, the sum of the % of rain-fed and irrigated area does not always add up to 100%

of the irrigated areas. Moreover, except in the southern Bangladesh villages where they still play a significant role, other sources of irrigation such as tanks and drains, have declined in their contribution in both relative and absolute terms even in southern India, where much is made of irrigation from earthen tanks.

Compared to the region as a whole, the picture for India is markedly different. Here, the irrigated area is 43% of the net cropped area, which is higher than the 40% estimate derived from Indian secondary data [6] (GOI 2001a). However, pure groundwater irrigation serves 76% of irrigated areas; and if conjunctive use areas are counted, which are 11.7%

[6] The National Sample Survey of 78,990 rural households around India, however, estimates the irrigated areas cultivated with the five major field crops (which account for 93% of the entire cultivated area) to be 66% (NSSO 1999a).

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Table 4 Comparing alternative estimates of sources of irrigation in India

Source of information	Year	Net cultivated area (million ha)	Rain-fed area (%)	Net cultivated area irrigated by surface flow (%)	Area irrigated by conjunctive use (%)	Area irrigated by groundwater (%)	Area irrigated by other sources (%)
IWMI-Tata survey	2002	0.2	57.0	2.7	5.0	32.6	2.4
Minor Irrigation Census (GOI 2001c)[a]	1993–1994	89.78	62.5	10.9[b]	–	19.8	6.8[c]
Ministry of Agriculture (GOI 2001a)	2000–2001	141.1	61.3	13.1	8.2	31.8[d]	2.1

[a]Gujarat, Jammu & Kashmir, Karnataka, Kerala, Maharashtra, Manipur, Nagaland, and Tamil Nadu are not included in the Minor Irrigation Census

[b]Major and medium irrigation project

[c]Surface flow

[d]Overlapping with surface-water irrigation (66.23−54.68=11.55 million ha)

of irrigated areas in the study, groundwater contribution extends to nearly 87% of sample irrigated areas in India. Pure canal irrigation serves just 6.2% of the irrigated areas in the Indian villages covered by the IWMI-Tata survey of 2002. Indeed, pure canal irrigation is insignificant in all H-E zones except coastal peninsular India, where it serves over 15% of the net cropped area. Other sources of irrigation (drains, tanks, etc.) are even more insignificant within the region as a whole and serve less than 5% of the irrigated areas. The Indian irrigation scene has become increasingly dominated by groundwater. Although this conclusion is derived from the survey data which is likely to be subject to sampling as well as measurement errors, even if it is broadly reflective of India's irrigation reality, there is cause for serious reflection.[7]

Table 4 compares areas in those sample Indian villages (IWMI-Tata survey 2002) irrigated by different sources with estimates by the Government of India (GOI 2001a) and those based on the Minor Irrigation Census (GOI 2001c). Since the latter excluded eight key states, its data do not compare well either with the IWMI-Tata survey results, or with GOI estimates for the country as a whole. The estimates from the IWMI-Tata survey results of the contribution of groundwater as well as 'other sources' to the net irrigated areas are remarkably close to GOI estimates. However, the IWMI-Tata estimates for rain-fed areas, as well as conjunctive water use areas, are less than GOI estimates. Especially intriguing is the sharp difference in the estimates at around $<3\%$ of the proportion of the irrigated area served by pure canal irrigation and the official estimates of this proportion at around 13%. This suggests that the performance of India's public irrigation systems may well be slipping. A slew of recent studies of major, medium and minor surface irrigation systems in Gujarat, Maharashtra, Tamil Nadu, Orissa, Karnataka and Haryana show that actual areas irrigated by most surface systems, large and small, are far smaller than planned and are declining over time (Meher 2003, and in unpublished literature presented at the National Workshop on 'Tail-enders and

[7] The Minor Irrigation Census (GOI 2001b), which covered all the Indian states except Gujarat, Maharashtra, Tamil Nadu and Karnataka, offers a rough reality check; however, this census reports data which is nearly 10-years old. According to this census, in 1993–1994, 38% of the net cultivated area was irrigated. The census computed that major and medium projects accounted for 39.4% of the irrigated areas while groundwater explained 50%; other surface sources accounted for 10.6%. The IWMI-Tata survey (in 2002) suggests that the structure of Indian irrigation is changing rapidly with canal dominated areas shrinking at a worrying pace. Recent large-scale surveys carried out in India by the National Sample Survey Organization lend indirect support to this contention that groundwater has become the mainstay of India's irrigation economy. The NSS 54th Round, which interviewed 78,990 rural households throughout India, estimated that while 61.2% of rural households are cultivators, 36% of all rural households interviewed (i.e., some 60% of cultivators) used irrigation (NSSO 1999a). NSSO (1999b) estimates that, of the irrigating households, some 40% depended on their own wells, another 27.2% relied on purchased pump irrigation, and 32.8% obtained irrigation from public/community surface and groundwater sources such as government canals, tanks, rivers, streams and public tubewells. This suggests that two-thirds of India's irrigation economy is dominated by private wells.

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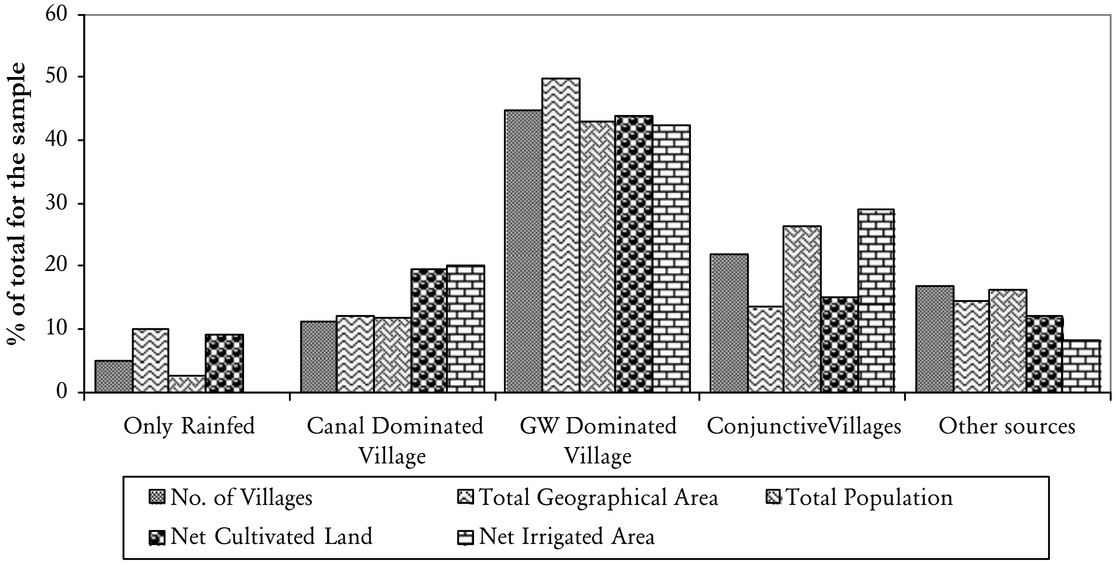

Fig. 4 Relative importance of wells, canals and other sources of irrigation in sample villages

other Deprived in Canal Irrigation Systems', Ahmedabad, 2003 including A. Shah; A. Rajagopal (Anna University, Chennai); S.K. Patil and R. Doraiswamy (Pragathi-Farmers Society for Rural Studies and Development); P. Vashishtha et al. (Agri. Eco. Research Centre, New Delhi); K.J. Joy and S. Paranjape of the Society for Promoting Participative Ecosystem Management, Pune, 2003). Moreover, there are isolated studies that point to conversion of canal irrigated areas into tubewell irrigated areas during the past 15 years. For instance, Singh (2003) notes that in the Indian Punjab, during 1983–1986 to 1997–2000, canal irrigated areas declined by 19.5% while tubewell irrigated areas increased by 29.5%; the number of tubewells increased from 0.4 to 0.76 million and the ratio of net area irrigated to net area sown increased significantly from 86.3 to 94.7%. Similarly for Rajasthan, Sharma and Varghese (1998) asserted that during 1981–1996, a period during which the Indira Gandhi Canal System and several other public irrigation projects were completed in Rajasthan, the net area irrigated by groundwater increased at the compound annual growth rate of 10.11% while that under canal irrigation grew only 3.14% per year. In the command area of the celebrated Bhakra Dam, described by Prime Minister Nehru as a 'temple of modern India', tubewell irrigation has rapidly replaced canal water. In the (Indian) Punjab, during 1990–2002, the gross cultivated area increased by 440,000 ha, while the canal irrigated area fell by 589,000 ha and the tubewell irrigated area increased by 837,000 ha (Gupta 2005).

In many parts of the world, such as most of Africa, scientists have talked about rain-fed and irrigated areas to characterise vast territories and formulate national or regional strategies for rain-fed farming. Around 1950, much of South Asia also likely fit this description of irrigated areas in British-built canal systems and rain-fed areas. However, the growing spread of groundwater irrigation during the past few decades has complicated the South Asian scenario to the point where it makes little sense to talk in terms of rain-fed regions, or areas, or even villages. Rockstrom et al. (2003) have suggested that "it is probably time to abandon the largely obsolete distinction between irrigated and rain-fed agriculture…"; the IWMI-Tata survey results of 2002 provide evidence to support this statement. Figure 4 classifies the 278 IWMI-Tata survey villages into five categories including (1) entirely rain-fed, (2) canal dominated, (3) groundwater dominated, (4) conjunctive use villages, and (5) villages dominated by other water sources such as tanks and drains. It shows that less than 5% of the villages in the IWMI sample can be said to be entirely rain-fed.[8] Similarly, there are very few villages in which canals are the *only* source of irrigation. When it comes to wells, however, the situation is the opposite; in 45% of the sample villages, groundwater is the only source of irrigation. This suggests that in nearly half of the sub-continent's villages, groundwater is the only supplement to rainfall; and in over 80% of the villages, groundwater irrigation supplements rainfall and other sources of irrigation.

Table 5 shows that irrigation wells are important in all irrigated areas, including those dominated by canals. However, in groundwater dominated villages, 43% of the net

[8] This does not tally with a much larger sample survey carried out by India's National Sample Survey Organization (NSSO 2003) in which 4,646 villages were asked about the kind of irrigation facilities they had. Of these villages, 76.2% reported some kind of irrigation, implying that 23.8% of the villages had no irrigation source whatsoever. Of the villages that reported irrigation facilities, 64.3% reported wells and tubewells as their source of irrigation, 17.3% reported the availability of canals, and 16.7% reported irrigation from streams, tanks and other sources. While this survey suggests the existence of a larger number of rain-fed villages than the smaller IWMI-Tata survey does, it supports the IWMI observation that wells and tubewells are the dominant source of irrigation in Indian villages. Moreover, if one were to expand this sample to cover Bangladesh, Nepal Terai and Pakistan Punjab and Sindh, it is quite likely that the proportion of villages with canal irrigation would fall and those with tubewells as the only source would increase.

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Table 5 Relative shares of different irrigation sources in village groups with domination of canal, tubewell, conjunctive use and other irrigation sources

	Only rain-fed	Canal dominated villages	Groundwater dominated villages	Conjunctive use villages	Villages dominated by other sources	All villages[a]
Irrigation status as revealed by village leaders and officials (no. of villages)	14	31	124	61	47	277
Net cultivated land in sample villages (ha)	21,726	46,213	103,517	35,695	28,920	23,6071
% irrigated	0.2	45.9	43.1	85.1	30.5	44.5
% canal irrigated	0	32.7	0.0	9.2	0.4	7.8
% tubewell irrigated	0	10.6	42.9	13.0	11.1	24.2
% irrigated by canal and tubewells	0	2.6	0.0	58.5	2.9	9.7
% irrigated by tubewells and other sources	0	0	0	3.1	16.1	2.4

Source primary survey conducted by IWMI in 2002

[a]One village did not yield a village report

Table 6 Cropping patterns in villages dominated by different sources of irrigation

According to area under crops	Only rain-fed	Canal dominated villages	Groundwater dominated villages	Conjunctive use villages	Villages dominated by other sources	All villages
Most important crop group	Coarse cereals[a]	Wheat	Coarse cereals	Wheat	Paddy	Pulses, oilseeds, fibre
2nd most important crop group	Vegetables and fruit	Pulses, oilseeds, fibre	Pulses, oilseeds, fibre	Paddy	Pulses, oilseeds, fibre	Wheat
3rd most important crop group	Pulses, oilseeds and fibre	Paddy	Monsoon Paddy	Pulses, oilseeds, fiber	Vegetables and fruit	Paddy
4th most important crop group	Wheat	Coarse cereals	Sugarcane	Vegetables and fruit	Wheat	Coarse cereals

Source primary survey conducted by IWMI in 2002

[a]Include millets, sorghum, maize, etc

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cultivated area is irrigated by tubewells with little surface irrigation to support conjunctive use. In canal dominated villages, conjunctive use may occur at the village scale since the tubewell irrigated area, 10.6% of the cultivated area in these villages, likely recycles irrigation return flows from canal irrigation. In contrast, in conjunctive use villages, of the 85.1% irrigated area, 58.5% of land is irrigated by both canal and groundwater; here conjunctive use goes right down to the farm scale. In these villages, both groundwater and canal irrigation are likely to be more sustainable than elsewhere. Figure 4 shows that groundwater dominated villages account for 40–50% of the sample villages, geographic area, cultivated area, irrigated area and population in the villages surveyed.

Expectedly, the cropping patterns popular with farmers vary according to the irrigation profile of their village as shown in Table 6. In rain-fed villages, regardless of where they are, coarse cereals, pulses, oilseeds and cotton dominate cropping patterns but, interestingly, vegetable and fruit crops too are important. Canal dominated villages as well as conjunctive use villages, which dominate the Indo-Gangetic Basin, follow the rice-wheat cycle, but in groundwater dominated villages, coarse cereals, pulses, oilseeds and fibre crops are more important in terms of land allocation, although these also grow rice, sugarcane and wheat.

The energy-groundwater nexus

South Asia's groundwater economy is closely intertwined with its energy economy. Energy pricing and supply policies for agriculture have shaped the size and structure of groundwater irrigation economies that have emerged in different H-E zones. Debroy and Shah (2003) have drawn attention to the energy-divide as a major feature of India's groundwater economy. They have suggested that, owing to different electricity pricing and supply policies pursued by electricity utilities, India faces an energy divide. Eastern states in India have suffered progressive rural *de-electrification* [9] since mid 1980s (Sharma 1989; Shah 2001); as a consequence, groundwater irrigation has come to be increasingly dependent upon the more costly and dirtier diesel fuel. Shah (2001) also argued that because of its diesel-dependence, groundwater-rich eastern India and Nepal Terai under-irrigate and in general are unable to take full advantage of the one resource they have plenty of, viz. groundwater.[10] Extending the analysis to the subcontinental scale suggests that the diesel-electricity divide is more a north–south phenomenon than an east–west one, as Fig. 5 suggests. Groundwater irrigation throughout the Indo-Gangetic Basin and the North-West Frontier Province (NWFP) in Pakistan is dependent on oil/diesel engines; 75–95% of its installed pumping capacity uses diesel as the energy source, with north-western India– Punjab, Haryana and Western Uttar Pradesh–having a lower diesel horse power (HP) ratio than electricity at 54%. As we move southward, diesel is steadily replaced by electricity. This energy-divide has major implications for the economics of groundwater irrigation in South Asia.

It is useful to regroup the 12 hydro-economic (H-E) zones into 3 groups to highlight how electricity pricing and supply policies are central in shaping the sub-continent's groundwater economy. Group I represents H-E zones where the agricultural electricity supply is metered and enjoys little or no subsidy; group II represents regions where the electricity supply to agriculture is heavily subsidised in nominal terms but since electricity supply as well as infrastructure have deteriorated greatly, there is hardly any use for electricity in groundwater irrigation, and hence, little *effective* subsidy. Group III represents the vast part of western and southern India where electricity subsidy to groundwater irrigation is real and substantial. The preponderance of electric WEMs in group III shows the effects of perverse electricity subsidies on the political economy of groundwater irrigation in western and southern India. In contrast, in group I regions, where there is relatively little cost advantage in using electricity, diesel pumps dominate groundwater irrigation. Figure 6 shows the three energy policy groups of H-E zones. Table 7 sets out the electricity pricing and supply situation in different H-E zones and the logic for regrouping the 12 H-E zones into three groups.

The first hypothesis, already tested, is that electric WEMs dominate groundwater irrigation where *real* electricity subsidies are provided, which is in group III zones. Viewed together, Figs. 5 and 6 support this hypothesis. Electric WEMs dominate in central-western India and internal and coastal Peninsular India. In the central Indian tribal belt, they dominate less because the electricity supply environment in these regions is more difficult. North-western India shows a relatively high proportion of diesel pumps because many farmers keep stand-by diesel pumps to carry on pumping during power disruptions. Throughout Pakistan and Bangladesh, diesel pumps dominate because electric WEMs offer no particular economic advantage; they dominate in eastern India and Nepal Terai despite nominal electricity subsidies, because these regions have very poor power-supply conditions.

A related hypothesis concerns who gets power subsidies. Electricity subsidies are often justified on the grounds that they reach poor farmers. Indian states like Gujarat also designed progressive electricity tariff which required farmers with larger pumps to pay more per horsepower rating. S. Batra and A. Singh (students of the Institute of Rural Management, Anand 2003, unpublished), however, showed that in north-western India, diesel pump ownership is concentrated amongst small farmers, while electric pumps are concentrated amongst relatively larger farmers. Since diesel enjoys

[9] That is, the quantity, quality and infrastructure of the electrical supply to agriculture have all progressively deteriorated resulting in farmers replacing electric pumps with diesel pumps.

[10] The region also has much surface water. However, the lower Ganga Basin offers few sites for building large-scale storages. As a result, flood waters of Ganga and its tributaries cause much socio-economic and livelihood loss due to recurrent floods and acute surface-water logging. It has long been recognized that intensive groundwater development in the region may significantly ease flooding by curtailing the rejected recharge during and after a monsoon.

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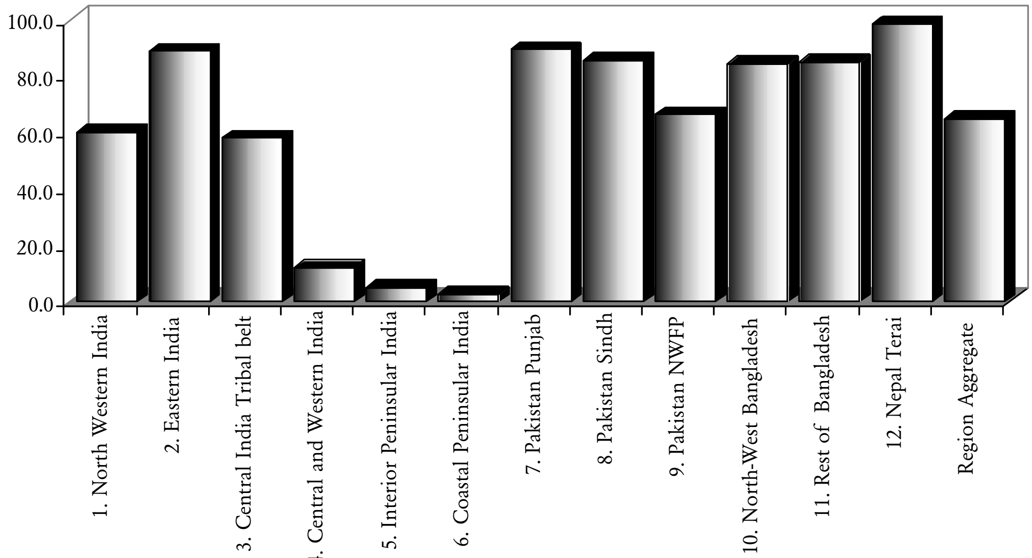

Fig. 5 Ratio of diesel pump horse power (HP) to total installed pump HP (%)

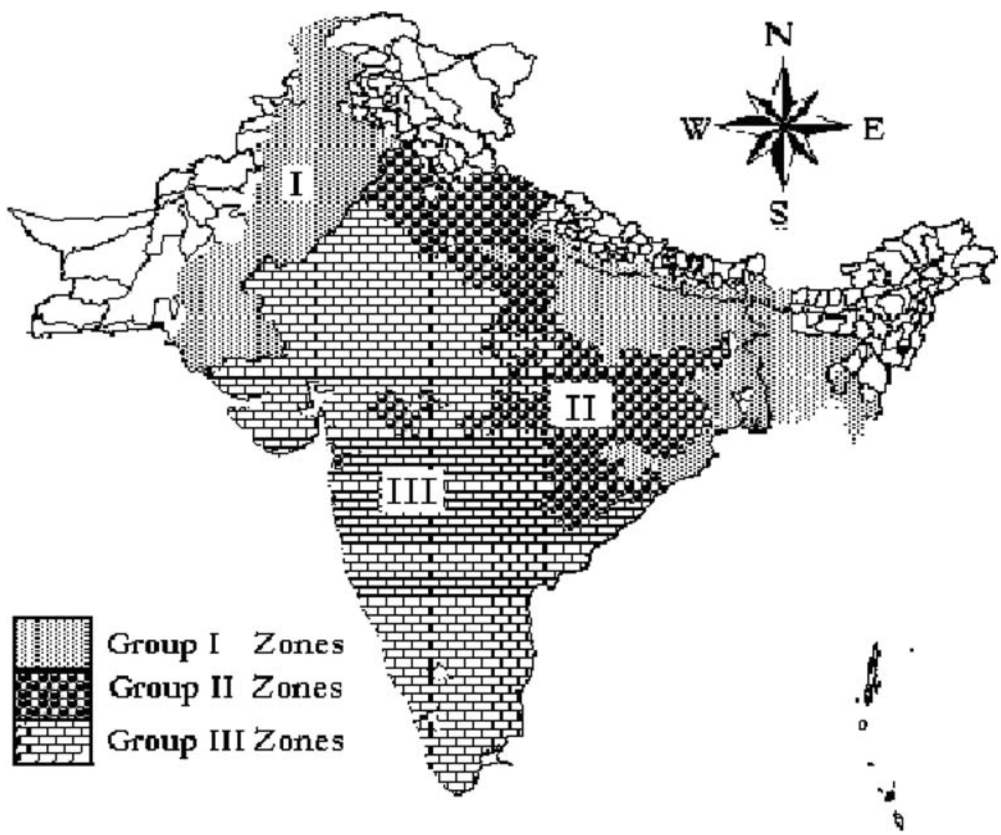

Fig. 6 Energy policy groups of hydro-economic zones

little or no subsidy, they argued, it is the large farmers who benefit more from subsidised electricity while poorer farmers are condemned to high-cost diesel energy. Howes and Murgai (2003) have similarly shown for Karnataka state of India that electricity subsidies justified in the name of the poor are cornered by the relatively more affluent farmers.

How true is this at the sub-continental scale? Are owners of electric WEMs, who partake of the subsidy, better endowed than the diesel WEM owners, especially in regions where electricity supply to agriculture is subsidized? Table 8 analyses this issue for the IWMI-Tata sample and shows that, except in eastern India and Nepal Terai (group II), which are all but de-electrified and as a result have very few electric WEMs, owners of electric WEMs in general have larger and less fragmented land holdings compared to owners of diesel pumps. For group III zones, where electricity subsidy is real and sizeable, the average electric WEM owner has a 27% larger holding fragmented into 20% fewer parcels of land compared to an average diesel WEM owner, which does suggest that the diesel pump is the

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Table 7 Diesel price, electricity price and electricity supply environment in different hydro-economic zones

Energy policy groups of zones	Hydro-economic zone #	Region	System of electricity pricing	Electricity supply situation	Electricity tariff	Diesel price per litre
Group I	Zone 7	Pakistan Punjab	Metered	Good	PRs 3.5/kWh[a]	PRs 17–19
	Zone 8	Sindh	Metered	Good	PRs 3.5/kWh	PRs 16–18
	Zone 9	NWFP	NA	NA	NA	NA
	Zone 10	North-west Bangladesh	Metered	Good	Tks 2.73/kWh[b]	Tk 19
	Zone 11	Rest of Bangladesh	Metered	Good	Tks 2.73/kWh	Tk 19
Group II	Zone 12	Nepal Terai	Flat-rate	Poor	NRs 300/HP/month[c]	NRs 27–29
	Zones 1 and 2	Eastern India	Flat-rate	Poor	INRs 60/HP/ month UP	INRs 20
	Zone 2				INRs 6,000/year WB (5 HP)[d]	
	Zones 2 and 3				INRs 350/month Orissa (5 HP)	
	Zone 3				INRs 2,400/year Chattisgarh (5 HP)	
	Zone 3				INRs 50/HP/month Jharkhand	
Group III	Zone 1	North-western India	Flat-rate	Fairly good	0 in Punjab	INRs 18–19
					INR 60/HP/month Utter Pradesh (West)	
					INR 6,600/year Haryana (5 HP)	
	Zones 3 and 4	Rest of India	Flat-rate	Better than in eastern India and Nepal Terai until 2002	INRs 500/HP/year Gujarat	INRs 18–22
	Zones 3 and 4				INRs 300/month/tubewell MP	
	Zone 4				INRs 400/HP/year Maharashtra	
	Zone 4				INRs 95/HP/month Rajasthan	
	Zones 5 and 6				INRs 2,700/year Andhra Pradesh (95 HP)	
	Zones 5 and 6				INRs 3,000/year Karnataka	
	Zones 5 and 6				0 in Tamil Nadu	
	Zone 6				INRs 400/HP/year Kerala	

Source for columns 6 and 7 is the primary survey conducted by IWMI in 2002; in NWFP, no survey farmer owned electric WEMs. *HP* horse power; *WB* West Bengal; *MP* Madhya Pradesh; *UP* Uttar Pradesh

[a] US$: 59.3 Pakistani Rs in 2002

[b] US$: 57.9 Bangladeshi Takas (Tks) in 2002

[c] US$: 78 Nepalese Rs in 2002

[d] US$: 48.62 Indian Rs in 2002

Electricity tariff: *INRs* Indian rupees, *NRs* Nepalese rupees, *PRs* Pakistani rupees, *Tks* Bangladeshi Takas

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Table 8 The political economy of energy-irrigation nexus in South Asia

S. No	Name of the regions	Diesel pump			Electric pump		
		Sample size	Average holding (Ha)	No. of parcels of land	Sample size	Average holding (Ha)	No. of parcels of land
1	Group – I (Pakistan Punjab & Sindh + Bangladesh)	574	6.7	3.7	130	7.5	3.35
2	Group – II (Eastern India + Nepal Terai)	416	2.7	5.6	26	2.5	4.62
3	Group – III (all Regions of India except eastern India + Pakistan NWFP)	304	4.6	3.0	1,052	5.8	2.39
4	Region total	1,294	4.9	4.2	1,208	5.9	2.54

Source: primary survey conducted by IWMI in 2002

mainstay of the poorer farmers while electricity subsidies benefit affluent farmers more in relative terms.

A related issue is about how quick farmers are in responding to changes in electricity pricing and supply policies. Agricultural energy policies followed in different parts of the sub-continent have experienced all kinds of twists and turns since 1975. One after the other, most Indian state electricity boards abandoned metering farm power supply and switched to flat-rate power tariff linked to horse power of the motor pumps on electrified WEMs. This marked a watershed for the evolution of the region's groundwater economy, because with the adoption of flat tariff, governments gave up all pretence of full energy-cost recovery from pump irrigators; and power subsidy emerged as by far the most powerful weapon for populist policies (Shah 2001; Shah et al. 2004). Inspired by similar populist logic, the Nawaz Sharif government in Pakistan introduced flat electricity tariff in 1989; however, after a decade, the present government reintroduced metering of agricultural power supply in 2000 in Punjab and Sindh–the heartland of tubewell irrigation–and has begun charging for electricity at full cost-recovery rates. Bangladesh never tried flat tariff; but its groundwater economy in early years was dominated by small diesel pumps, since rural electrification progressed slower in Bangladesh (and Nepal Terai) than in the western parts of the sub-continent. Electricity pricing and supply policies then explain why electricity is the prime energy-source for groundwater abstraction in western, central and southern India, whereas elsewhere in the sub-continent, diesel is.

If the farmers' choice of diesel or electric pumps were strongly influenced by electricity pricing and supply policies in different regions, would it not show up in the age profile of diesel and electric WEMs? The survey data were analysed to compute diesel-powered tubewells as a proportion of the total number of tubewells established in each group of zones before 1970, during 1970–1980, during 1980–1990, during 1991–2000 and after 2000. The a priori expectations were that: (1) in group I zones which include Pakistan and Bangladesh, the diesel-to-total ratio would decline during the electricity subsidy period 1990–2000 in Pakistan (though not in Bangladesh); (2) in group II zones, the diesel-to-total ratio, which was already high during 1970s because of the low progress in rural electrification, would have increased sharply during the 1980s and 1990s due to the 'de-electrification' of the countryside; and (3) in group III zones, the ratio would continuously fall after 1980 as farmers strove to get electricity subsidies.

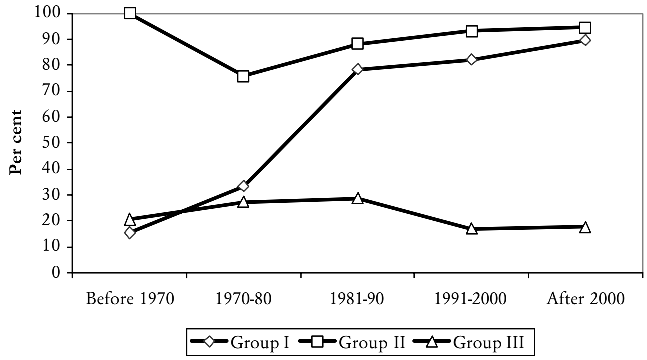

Fig. 7 Diesel WEMs as % of sample WEMs established during different periods

Figure 7 confirms expectation 3 clearly. In the group I and II zones, diesel-to-total ratio has risen steadily since 1970 due to the absence of significant electricity subsidies. The decline in the rate of growth of the ratio for group II zones during the early 1990s suggests a possible impact from the flat-rate and subsidised electricity tariff in Pakistan during that period. All in all, the way different governments have conducted their agricultural electricity pricing and supply policies have been central in shaping the choices of the farming community between diesel and electricity as the source of energy.

It was expected that energy pricing and supply policies would also have a significant impact on the 'operating factor' of WEMs—represented by the average annual hours of operation per WEM. The hypothesis was that the operating factor would be significantly higher for electric WEM owners compared to diesel WEM owners in group III zones that receive effective and substantial electricity subsidy, and that in the other two zones, the annual hours of operation per WEM might even be higher for diesel WEMs which need to work more to produce the same amount of water compared to electric pumps. Figure 8 supports the first part of this hypothesis but not the second one; it shows that electric WEMs everywhere have a significantly higher operating factor compared to diesel WEMs except in Nepal Terai and in Pakistan Punjab and Sindh. The low operating factor of electric WEMs in Nepal Terai is explained by the poor rural

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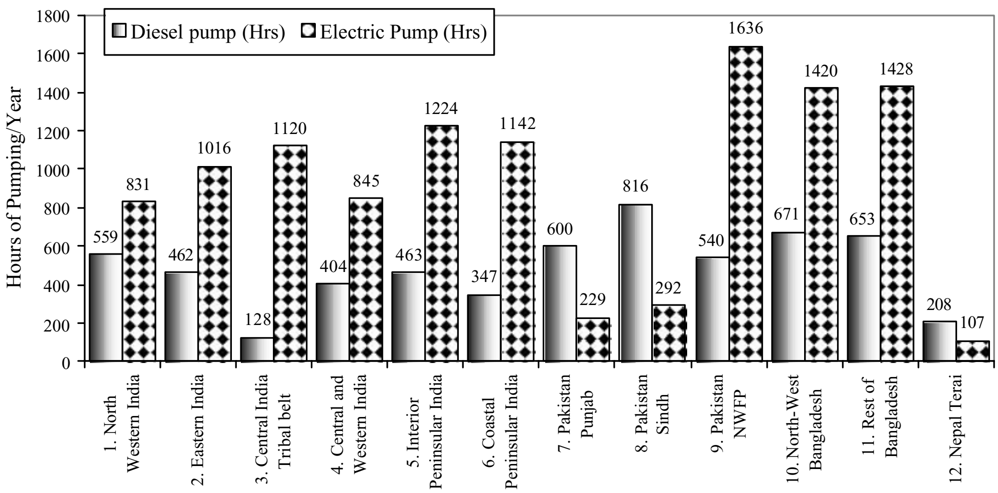

Fig. 8 Impact of flat-rate electricity tariff on pumping hours of irrigation wells

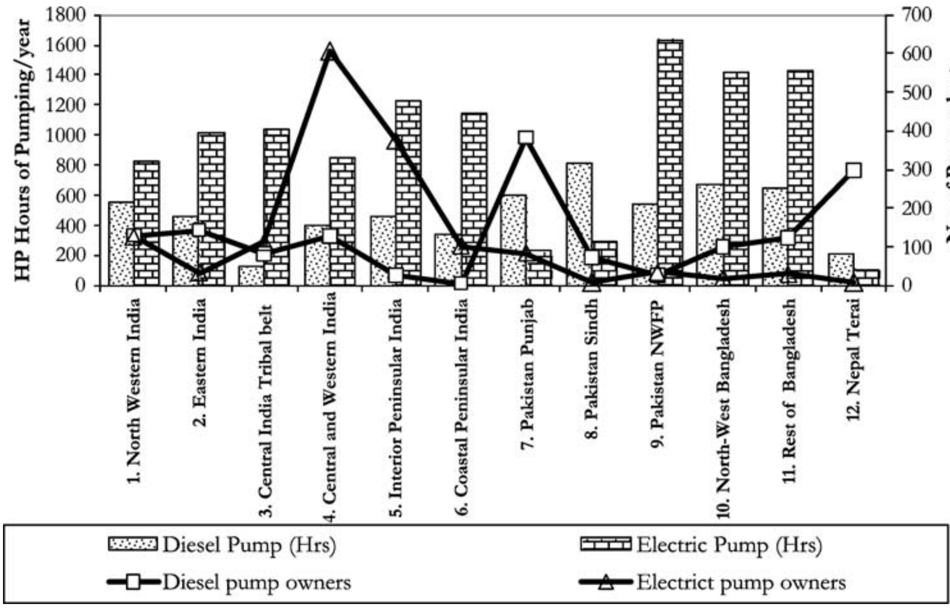

Fig. 9 Impact of flat-rate tariff on average annual HP hours of pumping

electricity supply; but in Pakistan Punjab and Sindh, the explanation is likely to be the high-metered electricity price. In the NWFP region, which enjoys an electricity subsidy and a flat tariff, the operating factor of electric WEMs is three times higher than that of diesel WEMs.

However, comparing the operating hours of diesel and electric WEMs may be misleading as an indicator of energy use and groundwater extraction per WEM if there is significant difference in horsepower rating of pumps. Therefore, in Fig. 9, the operating factor was computed in terms of average horsepower-hours (HP-hours) per WEM by multiplying the operating hours of each WEM in the sample (see Fig. 8) by its HP rating and then averaging the HP-hours for the sample WEMs in each category. Figure 9 shows that nothing changes as a result of this refinement. Nepal Terai, Pakistan Punjab and Sindh continue to have lower operating factor for electric pumps than for diesel WEMs; elsewhere, electric WEMs work longer and harder compared to diesel WEMs. Figure 9 also overlays the number of owners of diesel and electric WEMs interviewed in each zone; these show that except in group III zones–central and western India, interior peninsular India and coastal peninsular India–electric WEMs are far fewer than diesel WEMs. Indeed, in group III zones, diesel WEMs are so few that estimates based on such a small sample are likely to be unreliable.

It was also expected that electric WEM owners in group III zones make more intensive use of energy and groundwater in irrigating crops compared to diesel WEM owners, since here the marginal cost of operating electric pumps is significantly lower compared to diesel pumps. Group II zones too would behave much like group III zones but would be constrained by a poor power supply environment. Figure 10 plots the average HP-hours of irrigation used per hectare of paddy by diesel and electric WEMs. Also overlaid are the number of sample respondents for which the averages are computed. The results are broadly in conformity with the IWMI-Tata hypothesis: in central and western India, interior peninsular India and coastal peninsular India, where farmers receive significant effective subsidy

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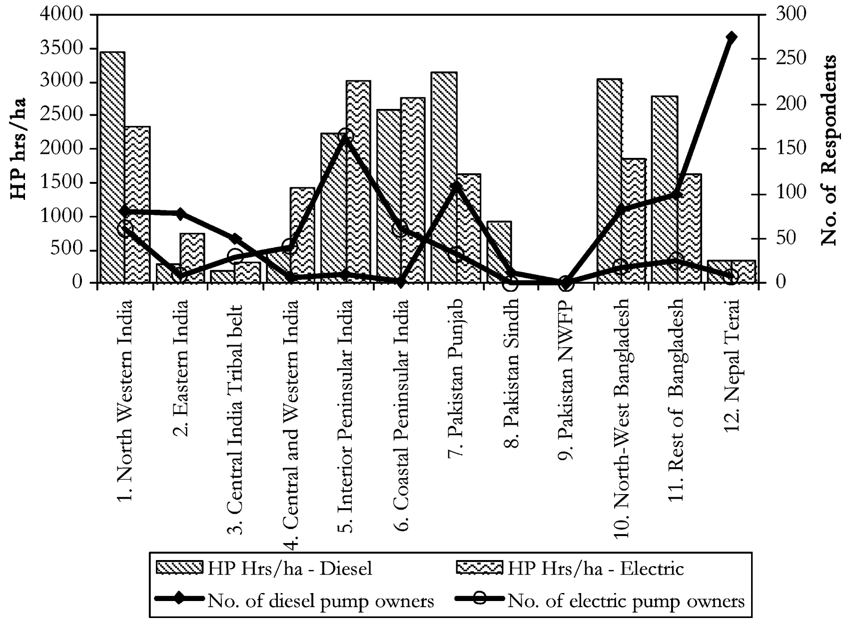

Fig. 10 HP hours of irrigation for paddy under diesel and electric pump irrigation

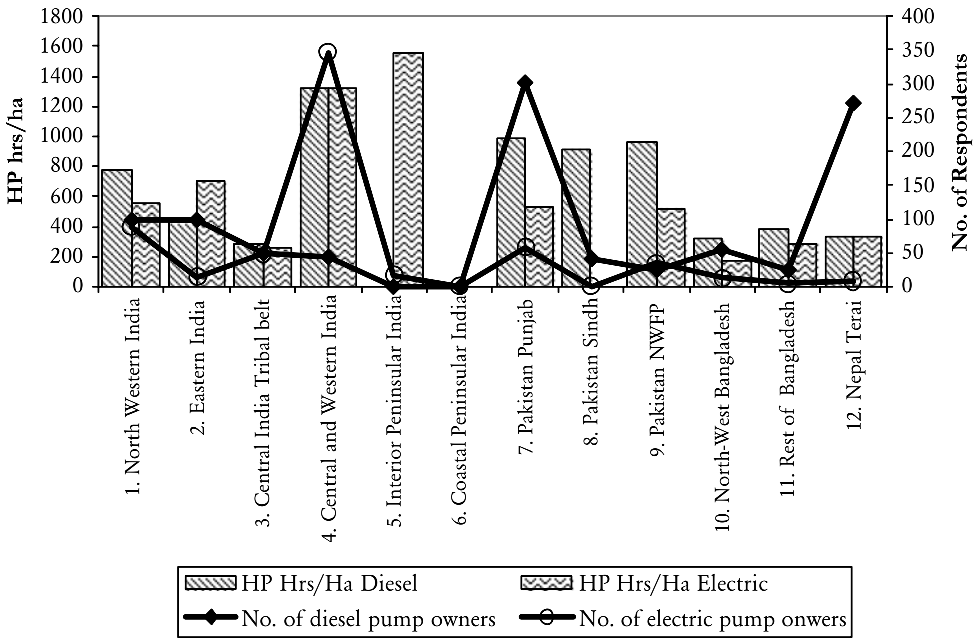

Fig. 11 HP hours of irrigation for wheat under diesel and electric pump irrigation

on electricity use, average HP-hours used by electric WEM owners is higher compared to diesel WEM owners. In Pakistan Punjab, Sindh, as well as the two regions of Bangladesh, which constitute the group I zones and where electricity supply to agriculture is metered and charged at near-commercial rates, diesel WEMs owners report higher average HP-hours. It is supposed that a part of the excess pumping hours of diesel WEMs here is to offset their lower efficiency compared to electric WEMs, therefore the real difference in HP-hours of electric and diesel WEMs in group III zones is larger than what the averages presented here imply. In group II zones, electric WEM owners also use higher HP-hours compared to diesel WEM owners, but the electric WEM owners of the paddy farmers interviewed in those regions is far too small to permit a firm conclusion. North-western India "bucks the trend" which otherwise holds everywhere; despite electricity subsidies, diesel WEM owners here use more HP-hours per hectare of paddy compared to electric WEM owners; and the number of observations for both the categories of pump owners is large enough that the result cannot be ignored. There is no clear explanation; however, a combination of factors—relatively high crop yield and correspondingly lower proportion of total value of output that pumping cost comprise, extensive conjunctive use of ground and surface water, poor electricity supply and others—might explain why average groundwater use by diesel WEMs is higher here than by electric WEM owners despite electricity subsidies.

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Table 9 Regression models with village-scale data: determinants of variations in net irrigated area across sample villages

1		Net irrigated area (ha)	Constant term	Electric WEMs (No.)	Diesel WEMs (No.)	Availability of canals (No.)	Proximity to river/stream (No.)	Tank/pond (No.)	Net cultivated area (ha)	R^2/Adj. R^2
2	Sample mean	390.5		36.5	23.9	0.46	0.46	2.19	812.2	
3	Min	0		0	0	0	0	0	13	
4	Max	11,345		920	1,010	2	3	151	29,554	
5	Model 1 Canal irrigation	Unstandardized co-efficients	−45.3	Excluded	Excluded	243.16	38.82	6.1	243.2	R^2=0.629
6		Standardized co-efficients				0.146	0.022	0.065	0.787	Adj. R^2=0.622
7		*T* ratio	−0.72			3.811	0.58	1.69	20.77	
8	Model 2 Canal & electric WEMs	Unstandardized co-efficients	−132.9	2.26	Excluded	244.5	64.9	6.2	0.352	R^2=0.676
9		Standardized Co-efficients		0.221		0.147	0.037	0.066	0.757	Adj. R^2=0.669
10		*T* ratio	−2.2	6.17		4.1	1.04	1.84	21.13	
11	Model 3 Canal, electric & diesel WEMs	Unstandardized co-efficients	−171.2	1.88	4.96	171.4	59.6	3.69	0.318	R^2=0.792
12		Standardized co-efficients		0.184	0.354	0.103	0.034	0.039	0.684	Adj. R^2=0.787
13		*T* ratio	−3.52	6.36	12.02	3.55	1.19	1.36	23.27	

Note. R^2 is the percent of the variations in the independent variable explained by independent variables. Adj. R^2=R^2 value adjusted for degrees of freedom. *T* ratio tests the statistical significance of each *b* coefficient. The coefficient is the partial derivative denoting the impact of unit change in independent variable on the dependent variable. *Adj* adjusted

The results for wheat irrigation show similar patterns in Fig. 11. In group I zones, diesel WEM owners invariably report higher HP hours per hectare compared to electric WEM owners. In group II and group III zones, electric WEM owners report higher HP-hours, and the differences become more pronounced when the pump efficiency differential between diesel and electric WEMs is factored in. North-western India "bucks the trend" as it does with paddy irrigation.

Diesel pump as the driver of South Asia's irrigation economy

Despite subsidized electricity and subsidised canal irrigation, it is the diesel pump which appears to have contributed most to South Asia's irrigation economy. The 293 villages in our sub-continental sample displayed large variations in their net irrigated area with the minimum being 0 ha, maximum being 11,345 ha; and the average for the sample villages being 390.5 ha. The hypotheses proposed by IWMI-Tata study are that: (1) these variations are explained by the extent of availability of canal, river, tank; electric WEMs and diesel WEMs in different villages; and (2) the impact of these different sources of irrigation on the net irrigated area per village varies. How can these hypotheses be tested?

In an attempt to break down the contribution of different sources to irrigation provision in the region, multiple regression models were run with the net irrigated area for the village as a dependent variable. The data used were from village schedules administered to lead informants from each of the 278 sample villages. Table 9 summarizes the results of three alternative regression models: the first model excludes electric and diesel WEMs; model 2 adds electric WEMs and model 3 adds electric WEMs as well as diesel WEMs. The inclusion of diesel WEMs has a dramatic impact on the explanatory power of the model as suggested by progressive increase in R^2 and particularly the adjusted R^2. The explanation may well be that neither electric WEMs nor public irrigation canals offer the farmers the control over water application that the diesel pump does.

Model 3, which explains 79.2% (as indicated by R^2 value of the equation) of the variations in the net irrigated area across 278 of the sample villages shows that, *ceteris paribus*, addition of a tank increases the net irrigated area of a representative village by 3.69 ha; proximity to a river or a stream adds 59.6 ha to the net irrigated area of the village; addition of a canal adds 171.4 ha; a diesel WEM adds 4.96 ha and an electric WEM adds 1.88 ha. In order to understand the aggregate impact of the different sources on the net irrigated area of the representative village, the coefficients are multiplied by the average number of units of different sources in the representative village as given in row 2 of Table 9. Doing this shows that diesel WEMs have by far the largest quantitative impact on the net irrigated area in the representative sample village. The same result is indicated by the standardised coefficient, a measure of the relative quantitative significance, for diesel WEMs

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Table 10 Groundwater use/ha in South Asia using tubewells

	HP[a] hours of pumping per ha	Total crop water requirements (m^3/ha) per crop season[a]	Groundwater draft (m^3)per hectare under		
			Worst scenario	Medium scenario	Optimistic scenario
			D=30 m; e=20	D=20 m; e=25	D=10 m; e=30
Wheat	656	4000	1180.8 (29.5)	1476.0 (36.9)	1771.2 (44.3)
Kharif rice	1,633	12,000	2939.4 (24.5)	3674.3 (30.6)	4409.1 (36.7)
Boro rice	3,266	18,000	5878.8 (32.7)	7348.5 (40.8)	8818.2 (48.9)
Oilseeds	816	5,500	1468.8 (26.7)	1836.0 (33.4)	2203.2(40.1)
Coarse cereals	811	5,000	1459.8 (29.2)	1824.8 (36.5)	2189.7 (43.8)

Source: primary survey conducted by IWMI in 2002; *D* suction depth in meters; *e* average pumping efficiency. Figures in parentheses show groundwater draft as percentage of crop water requirement

[a](Michael 2001)

in row 12. In model 3 (row 12), the standardised coefficient of diesel WEMs is nearly twice the value for electric WEMs and 3.5 times the value of canal irrigation. Plugging the sample mean values of the independent variables into Model 3 (row 11) gives an estimate of the mean net irrigated area of sample villages at 388.58 ha, which is close to the observed value of 390.5 ha.

Claims that groundwater accounts for 60% of India's gross irrigated area are often contested on the grounds that even if 200 km^3 is taken as the annual groundwater draft for irrigation, it can barely meet the crop water requirement of 25–30 million ha of land at 6,500–8,000 m^3 of water that a hectare of field crop would transpire, especially because India has large areas under rice which uses 10–12,000 m^3 of water/ha consumptively. This is a valid point. One response is that the South Asian farmers, especially when irrigating with groundwater, undertake only supplemental irrigation to their crops at a critical period of moisture stress. In doing so, they obtain lower yields than fully irrigated crops but are able to significantly better rain-fed yields.

Using the pumping efficiency equation (Michael 2001) to compute tubewell discharge,[11] three alternate estimates of groundwater use/ha are presented in Table 10 and address five crops grown by farmers covered by the IWMI-Tata survey. These are compared with water requirements based on evapo-transpiration (E-T) of these crops (Michael 2001). This comparison suggests that the South Asian groundwater irrigator seems to supply only 30–50% of the crop water requirement using tubewells. This supports the earlier suggestion that much tubewell irrigation in South Asia is supplemental. It is also likely optimal. Studies show that while crop yields may peak by irrigating at full E-T supply, returns to water peak at 70%, or even less, of water supply at full E-T level (Perry and Narayanamurthy 1998).

The results of the survey point to the distinct nature of groundwater irrigation economy in South Asia and its impact on enhancing the productivity of what is largely rainfed farming. Rockstrom et al. (2003, page 146) assert that:

> Dry spells constitute a core driving force behind farmers' risk aversion strategies. Risk aversion also contributes to the urgent soil-fertility deficits resulting from insignificant investment in fertilizers. For many smallholder farmers in the semi-arid tropics, it is simply not worth investing in fertilizers (and other external inputs) so long as the risk of crop failure remains a reality every fifth year and the risk of yield reductions every second year. These high risks are associated with periodic water scarcity during the growing season. . .

The wildfire spread of groundwater irrigation especially with diesel pumps throughout South Asia is quintessentially a mechanism to cope with these risks.

Pump irrigation markets

Studies during the 1990s suggested pump irrigation markets are booming in western and peninsular India (Shah 1993; Kolavalli and Chicoine 1989) and Bangladesh (Palmer-Jones 1993). However, not much about them was heard in eastern India. Some speculations were offered too about how to characterise pump irrigation markets according to the degree of their development, and what factors might determine it. Shah (1993) had suggested that one way to gauge the degree of development of pump irrigation markets was by their *depth* (significance of pump irrigation transactions for sellers as well as buyers) and *breadth* (high proportion of WEM owners and non-owners participating in exchange transactions). In Table 11, the percent of sample villages reporting water markets and the percent of the owners interviewed reporting water sale suggest how broad-based pump irrigation sale-purchase transactions are in the region, suggesting also the degree of breadth of the market. Likewise, the percent of total pumpage sold and

[11] Discharge (m^3/ha) $= \frac{\text{HP}\times\text{hours/ha}\times 75\times\text{pump efficiency (\%)}}{1{,}000\times\text{head (m)}}$. where 1,000 is the specific weight of the water. The average energy efficiency of Indian irrigation pump sets is widely recognized to be abysmally low. Patel and Pandey (1996)who rectified 3,600 irrigation pumps in Gujarat noted that "the levels of consumption of electricity or diesel in the farmers' pump sets are 150–200% of the desired/achievable limits (p. 13)" and can be improved by simple rectification with minimal investments. Also see (Sant and Dixit 1996; Operations Research Group 1991, and TERI, 1996).

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Table 11 The size of the pump irrigation market economy

	% of sample villages reporting water markets	% of well-owners selling water in villages reporting water markets	Average hours sold per water seller	Hours sold as % of hours of pumping	Average size of buyers' area served (ha)
North-western India	75.0	28.4	117.2	3.4	2.0
Eastern India	81.0	57.0	136.8	13.6	0.7
Central Indian tribal belt	9.1	1.9	90.0	0.2	0.3
Central and western India	23.7	10.7	595.0	6.7	1.4
Interior peninsular India	27.3	6.7	306.8	1.3	0.5
Coastal peninsular India	30.0	8.5	81.4	0.6	0.3
Pakistan Punjab	75.0	49.6	325.2	18.4	2.8
Pakistan Sindh	42.9	28.6	105.6	3.0	1.7
Pakistan NWFP	18.2	20.3	91.7	3.2	0.8
North-western Bangladesh	100.0	85.9	640.3	67.7	0.2
Rest of Bangladesh	100.0	87.0	650.9	69.0	0.3
Nepal Terai	90.9	67.3	95.9	29.3	0.6
Region Aggregate	52.2	35.0	318.6	12.7	0.8

Source: primary survey conducted by IWMI in 2002

the average buyers' area irrigated per tubewell indirectly suggests the depth of the pump irrigation market.

It was also suggested that pump irrigation markets would show a high degree of development in regions where pump density is neither too high nor too low and groundwater recharge available is abundant. Since the late 1980s, when some of this debate took place, the complexity of the region's groundwater socio-ecology has changed in a profound manner. Also, some of the impacts seen today (Table 11) do seem to be explained by the hypotheses covered by the late 1980s debate. Low breadth and depth of pump irrigation markets in central-western India, interior peninsular India and coastal peninsular India, where columns 2, 3, and 5 in Table 11 have lower values compared to other regions, suggest that pump irrigation markets have probably shrunk here compared to the mid-1980s; firstly because many more farmers have their own WEMs and secondly because the recharge available per WEM has declined, forcing WEM owners to conserve their limited water for self-use.

In contrast, both breadth and depth indicators are amongst the highest in eastern India, Bangladesh, Nepal Terai, Pakistan Punjab and north-western India. Here, water markets are still active because the recharge available per WEM is still high due to high natural recharge in the eastern IGB and conjunctive use in the western IGB. In the eastern Gangetic Basin, water markets are in their prime with columns 2, 3, 4 and 5 in Table 11 taking about the highest values found anywhere in the sub-continent. However, the impact of rising pump density is evident in Pakistan Punjab and north-western India in the small proportion of WEM owners selling water, and in the very small percent of their total groundwater output. Relatively high depth and breadth values for Pakistan Punjab and Sindh also perhaps explain the larger inequality of land holdings there; this means the presence of a large class of pump-less small landholders or share croppers whom the small minority of tubewell owning gentry serves through these markets.

Finally, the central Indian tribal belt and Pakistan's north-west Frontier Province, both show low breadth as well as depth. Neither of these are as well endowed with groundwater as the eastern region is; however, both of these use only a small fraction of their resource. It is surmised that pump irrigation markets here are at an early stage of evolution; and they will acquire greater breadth and depth as these regions develop further in overall socio-economic terms.

Table 12 shows that despite the shrinking of pump irrigation markets in western and peninsular India, they are still a significant irrigation institution. For the sub-continent as a whole, the IWMI-Tata survey suggests that 35% of WEM owners sell water, sellers irrigating an average of 0.76 ha of water buyers' land. Projecting for the estimated total number of 18.4 million WEMs in the region, it is estimated that about 6.5 million WEM's irrigate around 4.94 million ha of land through pump irrigation sale, which is equal to the ultimate control area of the famous Sardar Sarovar Project[12]

[12] The Sardar Sarovar Project on the Narmada River in western India was one of the largest river-valley projects planned by India after it became independent. The project acquired worldwide notoriety because of opposition to it from environmental groups.

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Table 12 Drivers of water sellers' behaviour in South Asia

Category	Sample size (*n*)	Average annual hours of operation	Average annual hours of sale of water	Average size of land holding (ha)	Average number of parcels
WEM owners who sell water	868	702.92	330.37	4.27	4.37
WEM owners who do not sell water	1745	750.82	–	5.796	2.94

Source: primary survey conducted by IWMI in 2002

three times over. Saleth (1998) placed the figure of area irrigated through groundwater markets in India higher at 6 million ha. The 1998 National Sample Survey covering 78,990 rural households, however, estimates India's gross cultivated area irrigated with hired services (read 'pump irrigation markets') at 46% of the gross irrigated area, the estimate being lower for canal dominated areas (40%) than for non-canal areas (49%) (NSSO 1999a).[13]

The South Asian discussion on groundwater markets has also had a micro-analytic dimension focusing on the motives that drive water selling. Lay observers and journalists have generally been suspicious of pump irrigation sellers, who are commonly dubbed as 'water lords' or 'village water mafia'. However, social researchers too have documented and highlighted specific situations where such sellers emerged as monopolists (Janakarajan 1992; Wood 1999; Bhatia 1992). All in all, some of the water market literature has painted the pump irrigation seller as an opportunistic local "bigwig" who uses his pump ownership for extracting monopoly profits. If this were to be generally true, one would expect an average water seller to be a large farmer who would force up the water price by restricting the supply of water to his neighbours.

An alternate hypothesis was that an average South Asian pump irrigation seller is more likely a small farmer with fragmented land holding and the chief motive in selling pump irrigation would be the need for making the investment in WEMs viable by improving the capacity utilization. At the scale of South Asia, the IWMI-Tata survey lends support to this alternative hypothesis as Table 12 shows. Around a third of the 2,613 sample well owners were water sellers, and the average water seller had 23% smaller land holdings which were fragmented into 1.5 times more parcels compared to non-sellers. Without selling water, the well-owner's WEM would have operated at just around half the level of capacity utilisation achieved by non-sellers. It still does not follow that water sellers will not extract monopoly profits whenever they get an opportunity; however, it is useful to note that the driver of the pump irrigation markets is the need for more efficient and fuller utilisation of pump capital stock.[14]

Critical problems as perceived by farmers

While there is growing recognition that groundwater development has provided strong stimulus to agrarian growth in South Asia and helped strengthen rural livelihoods and food security, there is also growing concern in recent years about the dangers of over-exploitation of groundwater resources. Long-term decline in groundwater levels, deterioration of groundwater quality, problems of salinity, especially in the western Indo-Gangetic Plains, drying up of wet lands and low-flows in streams and rivers during summer months—are all highlighted as environmental ill-effects of unplanned intensification of groundwater use in agriculture (Shah 1993; Seckler et al. 1999; Seckler 1999; Postel 1999; Burke and Moench 2000).

What is the farmers' perspective on these issues? How critical do they feel is the issue of a long-term decline in water levels, something that would directly affect the sustainability of the groundwater economy? This information was expected to have been gathered when tubewell owners were asked to list critical problems facing groundwater irrigation and rank them in order of their criticality. Table 13 analyses these responses for 2,355 well owners who provided useful responses to the question. The table presents analyses of the problem ranked as 'most critical', 'second most critical' and 'third most critical'. It shows that declining water levels, high rate of well-failure, salinity and reduced well-yields are important problems perceived by some of the farmers interviewed. However, for by far the largest proportion of groundwater irrigators in the subcontinent, 'high energy costs' and 'unreliable electricity supply' are the most critical problem areas. The next in criticality is 'declining water levels'. High rate of well failure, salinity, reduced well yield are critical but for a much smaller proportion of interviewees.

Table 14 shows analyses of the same set of responses at disaggregated levels of the 12 H-E zones and provides a more textured picture. Firstly it shows that the high energy cost of pumping is identified as 'the most critical problem' by many more farmers in eastern India, Bangladesh and Nepal Terai (group II zones), where groundwater irrigation is almost entirely based on diesel pumps and secondly that the farmers in group III zones—central and western India, internal and coastal peninsular India—are not bothered

[13] This survey, as mentioned earlier, covered area cultivated with the five major field crops, which together accounted for 93% of the entire cultivated area.

[14] A new paper by Sharma and Sharma (2004) on the functioning of groundwater markets in the arid and semi-arid zones of Rajasthan, however, suggest a different pattern than what the IWMI aggregate picture suggests. In this water scarce region, groundwater markets should have a relatively low breadth and depth. However, this paper shows that 103 of the 137 households interviewed in the semi-arid Alwar and Jaipur districts participated as water buyers and/or sellers; and 115 out of 143 interviewed in arid Jodhpur and Nagaur districts participated as buyers and/or sellers. These statistics suggest participation rates comparable to Bangladesh's. The Sharma and Sharma study also shows that in Rajasthan, where aquifers are deep and tubewells quite large, the modal seller is typically the large farmer, whereas over 90% of the buyers are small farmers with less than 2 ha of arable land.

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by energy costs, and understandably so; their major problem is ‘unreliable electricity supply’. Thirdly, this is a relatively less important issue for farmers in Pakistan as compared to energy cost, because they pay commercial rates for diesel as well as electricity; fourthly, farmers in north-western India find energy cost as well as unreliable electricity supply as critical, and farmers in NWFP in Pakistan find neither of them critical since, compared to Punjab and Sindh, NWFP farmers get cheaper electricity. Lastly, salinity is expectedly a key issue in Pakistan Punjab and Sindh (Khan et al. 2003; Qureshi and Masih, 2002; Sondhi et al. 2001; Tyagi 2001); but surprisingly, it does not figure in the responses of farmers from north-western India where falling water tables are listed as critical. This is also true for all three southern H-E zones of India, except for the Pakistanian Punjab farmers, but rate only after energy cost and unreliable electricity supply.

Table 13 The most critical problem facing groundwater irrigation according to the farmers

2,355 well owners sampled from South Asia	High energy costs	Unreliable electricity supply	Falling water tables	High rate of well-failure	Salinity in groundwater	Wells can be pumped for a short period
% of tubewell owners who rated this as the *most* critical problem facing groundwater irrigation	27.37	21.05	19.65	7.02	8.77	3.16
% of tubewell owners who rated this as the *second* most critical problem facing groundwater irrigation	18.25	9.82	18.60	8.77	6.32	11.58
% of tubewell owners who rated this as the *third* most critical problem facing groundwater irrigation	10.88	6.67	14.04	8.42	3.51	12.98

Total No. of villages corresponds to 278; Source: primary survey conducted by IWMI in 2002

Summary and conclusions

Groundwater use in irrigation has emerged as a major phenomenon in South Asian agriculture, especially after 1970; and the macro-dimensions of this important phenomenon have remained relatively understudied. Rare macro-level policy analyses that become available occasionally depend on secondary data which are often contested, and offer little understanding of the socio-ecological perspectives necessary to evolve a well-rounded picture of this huge and growing economy. In a limited attempt to evolve such a picture, IWMI collaborated with 14 partners to undertake a sample survey of 2,629 owners of WEMs from 278 villages in India, Pakistan (excluding Baluchistan), Nepal Terai and Bangladesh, using a spatially representative sampling method. Some early results of this survey were presented in Mukherji and Shah (2004). This paper provides some additional analyses, including tests of some interesting hypotheses that have been doing the rounds in South Asian discussions on groundwater irrigation. Some key findings and conclusions of the analyses are:

1. Although, from the viewpoint of long-term sustainability, groundwater development should be consistent with the availability of the resource in different regions, the analysis suggest uneven patterns of development in this respect. However, at the level of aggregation chosen, north-western India emerges as a serious case of overdevelopment of the resource; north-west Bangladesh has a large resource base that is intensively used; elsewhere in eastern South Asia, there seems to be room for carefully planned development.
2. At the sub-continental scale, the IWMI-Tata survey found that 55% of irrigated areas in the sample villages are under ‘pure groundwater irrigation’; this figure increases to 75% if conjunctive use areas are added. Pure canal irrigation serves only 14.5% of irrigated areas in sample villages, and ‘other sources’ account for less than 5%. In India, groundwater contribution is higher at

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Table 14 The farmer's main issues and the percentage of farmers in each region who labelled them as the 'most critical' problem and the 'second most critical problem' they face in tubewell irrigation

Region	High energy costs	Unreliable electricity supply	Falling water tables	High rate of well-failure	Salinity in groundwater	Wells can be pumped for a short period	Other
North-western India	25/25	38/31	25/25	6/6	0/0	0/0	0/0
Eastern India	45/27	41/5	5/18	9/9	0/0	9/9	9/0
Central Indian tribal belt	5/23	27/0	22/18	14/5	0/0	5/41	18/0
Central and western India	2/31	42/9	29/18	3/13	11/0	2/16	2/0
Interior peninsular India	4/8	40/24	28/36	8/8	8/0	0/16	12/0
Coastal peninsular India	0/0	50/10	10/30	0/0	0	10/20	10/0
Pakistan Punjab	33/25	0/8	31/17	8/17	19/8	3/11	3/8
Pakistan Sindh	43/10	0/0	14/10	0/0	29/23	0/0	5/0
Pakistan NWFA	9/14	5/0	14/18	5/5	5/0	5/0	0/0
North-western Bangladesh	68/5	0/10	0/8	0/0	2/0	0/0	0/0
Rest of Bangladesh	69/6	0/12	0/9	0/0	0/0	0/0	0/0
Nepal Terai	59/0	9/4.5	0/9	18/14	0/0	0/9	0/23

Source. Primary survey conducted by IWMI in 2002

76% of irrigated areas in the sample villages; with conjunctive use, this ratio rises to 87% of irrigated areas. All these estimates suggest groundwater irrigation to have acquired greater quantitative significance than what is generally believed to be the case in the region.

3. In the South Asian context, terms like 'rain-fed' and 'irrigated' areas are meaningful only on the scale of parcels of farm holdings. Just around 5% of the villages surveyed counted themselves as totally rain-fed; in 'tubewell dominated villages', accounting for 42% of the total net cultivated area from all the surveyed villages, groundwater irrigation accounted for over 95% of irrigated area. However, even in canal dominated villages and conjunctive use villages, 'pure tubewell irrigation' accounted for 25 and 15% of the total irrigated area, respectively.
4. The preferred crops in groundwater dominated villages are coarse cereals, pulses, oilseeds, fibres and monsoon season (kharif or monsoon) paddy—all of which thrive under supplemental irrigation; wheat-rice rotation dominates conjunctive use and canal dominated villages.
5. Groundwater development is believed to be in some ways self-regulating; as groundwater use intensifies in a region, declining water tables raise the cost of pumping, placing a brake on further development. However, there is little sign that such self-regulating mechanisms have begun to work in the sub-continent, if continued growth of WEMs is any guide; if anything, the analysis suggests that the real intensification has only begun during the past decade. Around 50% of the WEMs covered by the survey were established after 1993, and there seems to be no indication of decline in the rate of the growth of WEMs, although the rate of the growth in total groundwater withdrawal may well be lower than the rate of the growth in the number of WEMs.
6. Energy pricing and supply policies have played a central role in shaping South Asia's groundwater economy. At the sub-continental scale, a north–south energy divide was found with diesel pumps dominating the groundwater economy in the north, and electric WEMs dominating it in the south.
7. The analysis lends macro-level support to the hypothesis from micro-level research that the diesel pump is the mainstay of the poor and that the electricity subsidies provided in India are cornered primarily by the better off, since the average owner of the electric WEM has a larger, less fragmented land holding; and this gap becomes particularly sharp in all of India except the eastern region which has suffered progressive rural de-electrification.
8. There is also some support to the hypothesis that energy pricing and supply policies have a significant impact on the farmers' choice of electricity or diesel as the source of motive power, and also on their use of pumps. In Pakistan Punjab and Sindh as well as in Bangladesh, where electricity is metered and commercially priced, diesel and electric pumps are evenly balanced. In eastern India and Nepal Terai, where 'effective electricity subsidies' are zero or negative, diesel pumps have increased rapidly as a proportion of the total WEMs in use. In the rest of

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India, electric WEMs have been growing steadily since the 1970s in response to significant 'effective electricity subsidies' available to farmers. Electric WEMs everywhere are operated for longer hours per year as well as per hectare compared to diesel WEMs.

9. Do electricity subsidies also result in a higher use of energy and water per hectare? The survey offers indications that they do. For kharif paddy and winter wheat, the average hours of pumping per hectare are far higher for electric WEM owners in western and southern India compared to diesel WEM owners there, or all groundwater irrigators elsewhere.
10. On the sub-continental scale, however, no single factor has played as dominant a role in creating new irrigation as the diesel pump. In a regression model that relates the net irrigated area to the number of diesel and electric WEMs, and the presence of canal, river, tanks/ponds in 278 villages, it was found that the impact of diesel WEMs is twice that of electric WEMs and 3.5 times higher than canals in explaining variations in the net irrigated area across sample villages.
11. Claims that groundwater accounts for 60% of India's irrigated area are often contested on the ground that even if we take 200 km^3 as the annual groundwater draft for irrigation, it can barely meet the crop water requirement of 25–30 million ha of land at 6,500–8,000 m^3 of E-T per hectare of field crop, especially because India has large areas cultivated with rice which uses 10–12,000 m^3 of water/ha consumptively. The survey results show that tubewell irrigation in most parts of South Asia is supplemental irrigation; that the average groundwater use is at best 30–50% of the total E-T requirements of these crops. The farmers use tubewells to 'leverage' rainwater precipitation and soil moisture and seem to be effective in optimizing returns to irrigation.
12. The IWMI-Tata survey also throws light on the functioning of pump irrigation markets in South Asia. It shows that these have shrunk in terms of *breadth* as well as *depth* in much of western and southern India because of both the growing pump density and the declining groundwater availability per WEM; in contrast, pump irrigation markets are booming in eastern India, Nepal Terai and Bangladesh as well as in Pakistan Punjab. The analysis also estimates that some 5 million ha of land in South Asia are irrigated by purchased pump irrigation. These results, however, are at variance with some other large-scale surveys published recently (Mukherji 2005).
13. The veracity of the popular hypothesis that South Asia's water seller is a water lord who is 'pumping groundwater for power and profit' was tested. Whereas in specific situations this may well be correct, the sub-continental analysis shows that a typical water seller is a small landholder with fragmented land holdings who uses water selling to make the WEM viable.
14. While benefits of groundwater irrigation are widely recognized, there is growing concern about groundwater depletion and quality deterioration due to unregulated withdrawal. Finally, the survey tried to ascertain if farmers find water table decline, salinity, declining well yields as key problems facing them. The survey results suggested that by far the most important problems farmers perceive have to do with high energy costs of pumping and unreliable electricity supply. Falling water tables, salinity and others do figure, but are less critical than the energy cost and supply issues.

Particularly after 1970, South Asian agriculture has experienced a major boom in tubewell irrigation. Although this has gradually begun to register in water policy discussions, its wider implications are yet to be fully understood and appreciated. This paper has reported on some results of a large-scale survey of the groundwater socio-ecology of South Asia designed to understand these implications. It underscores the fact that in South Asia, groundwater irrigation is still in the growth phase; and that it is important to understand fully the dynamic of this economy before managers and policy makers can begin to think about effectively managing it.

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Appendix 1: List of IWMI partners in the study 'Groundwater socio-ecology of South Asia"

Country/region	Research partner
Pakistan	International Water Management Institute (IWMI), Lahore
Bangladesh	Bangladesh Agricultural Research Institute, Dhaka
Nepal Terai	Technical Development Associates Kathmandu
West Bengal, Assam, Bihar	IWMI-Tata Water Policy Program
Punjab and Haryana	Market Research Field Services, New Delhi
Uttar Pradesh and Uttaranchal	DRISTI Strategic Research Services, Mumbai
Andhra Pradesh and Karnataka	Institute of Resource Development and Social Management (IRDAS)
Orissa	Shristi, Bhubaneswar
Maharashtra and Goa	Consult India, Nagpur
Madhya Pradesh	Centre for Advanced Research and Development (CARD)
Chhatisgarh	People's Research Centre, Bhopal
Rajasthan	PROGRESS, Rajasthan
Tamilnadu and Kerala	Dhan Foundation, Madurai
Gujarat	R Rajan, Independent Researcher

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