MODULE 9

GROUNDWATER FOR FOOD SECURITY


HAOMAX
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DIESEL WATER PUMP

CONTENT

MODULE 9

Groundwater for Food Security

Imprint

A4A – aqua for all
AGW-Net – Africa Groundwater Network
ANBO – African Network of Basin Organisations
BGR – Federal institute for geosciences and natural resources
Cap-Net UNDP
BMZ – Federal Ministry for Economic Cooperation and Development
GWP – Global Water Partnership
IGRAC – International Groundwater Resources Assessment Centre
imawesa – Improved Management of Agricultural Water in Eastern and Southern Africa
IWMI - International Water Management Insitute

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GROUNDWATER FOR FOOD SECURITY

LEARNING OBJECTIVES

- To comprehend the scale and significance of groundwater in agriculture globally
- To know the regions with over- and under-utilisation of groundwater for irrigation
- To appreciate the economic and livelihoods implications of groundwater irrigation
- To understand the context and role of groundwater irrigation in Sub-Saharan Africa
- To understand the risks involved with groundwater irrigation
- To understand strategies to optimize and manage groundwater irrigation around the world
- To understand the nexus between water-, food-, and energy security.

9.1 Introduction and background

Groundwater is widely used in agriculture around the world. About 70 % of all groundwater used goes to agriculture, mostly irrigation (Fig. 9.1). At a global scale, between 20 and 40 % of irrigation water needs are satisfied by groundwater (Fig. 9.2 and Foster and Shah, 2012). Agriculture is the largest consumer of water compared to all other uses, such as domestic and industrial. Most water in irrigation is consumptively used by evaporation or transpiration as compared to non-consumptive use, such as domestic and industrial use that is returned as wastewater and can be reused.

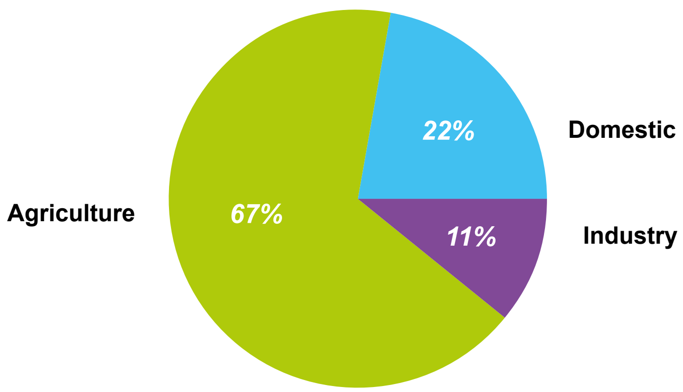

Figure 9.1. Global share of groundwater use for the three major sectors (van der Gun, 2012)

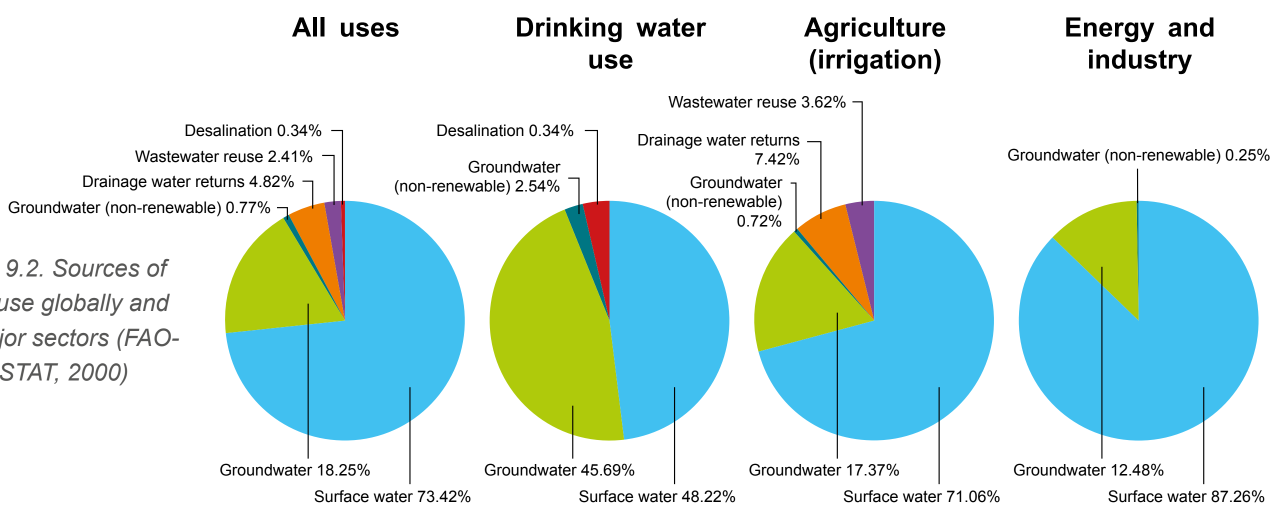

Figure 9.2. Sources of water use globally and for major sectors (FAO-AQUASTAT, 2000)

That groundwater use is significant in agriculture can be seen from Figs. 9.3 and 9.4 where the global distribution of groundwater use and groundwater-irrigated areas, respectively, are shown. There is a good correspondence between those areas with intensive irrigation and those with high groundwater use.

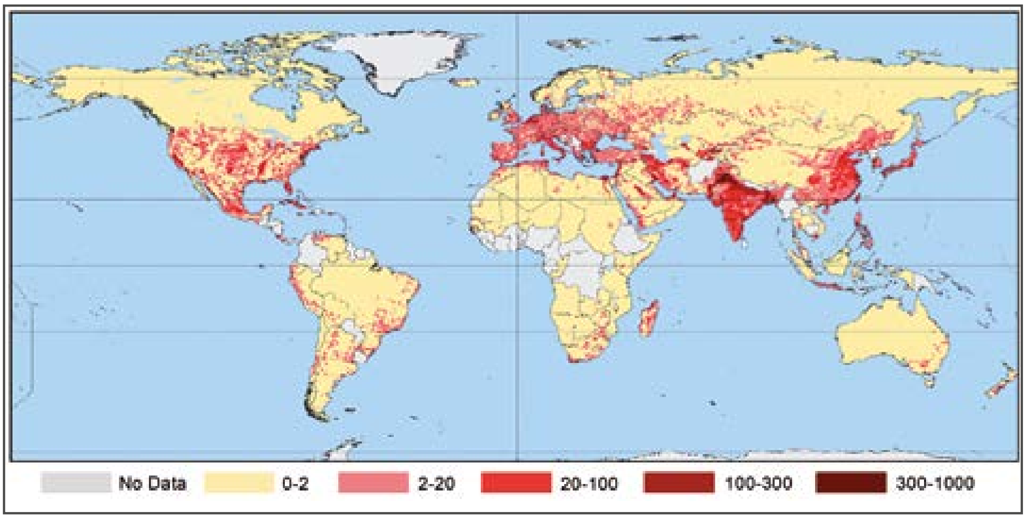

Figure 9.3. Global map of groundwater use
(Wada et al., 2010. Units in mm/yr in 0.5° 0.5° grid cells)*

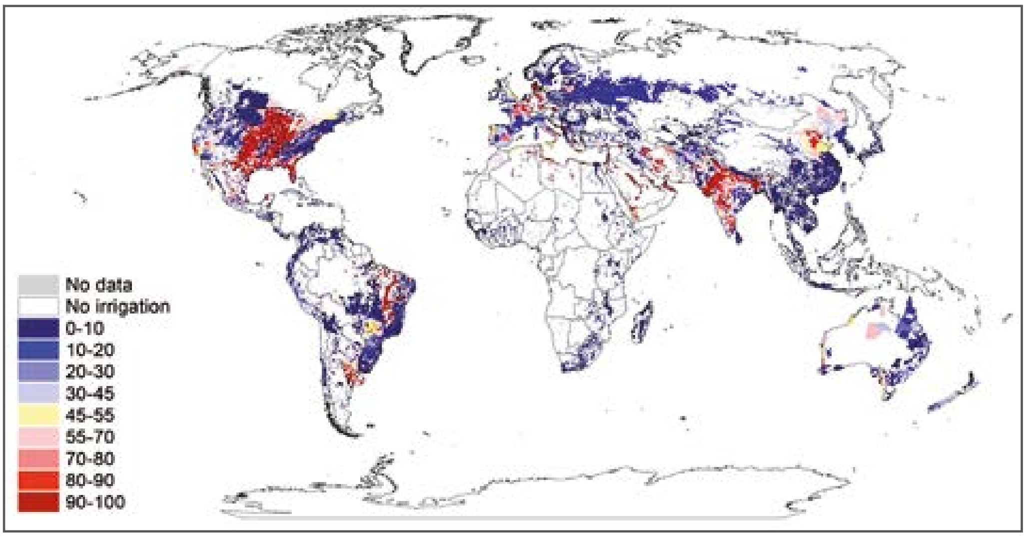

Figure 9.4. Global map of groundwater-irrigated areas
(Siebert et al. 2010. Percentage of irrigated area supplied by groundwater)

Most of this irrigation occurs in arid and semi-arid areas where the replenishment of groundwater is low (Fig. 9.5). This can easily be explained by the larger requirement to supplement crops with irrigation water in these areas. However, it also implies that there is a greater risk of over-exploiting the groundwater resources in these areas, because they are not replenished very rapidly or regularly.

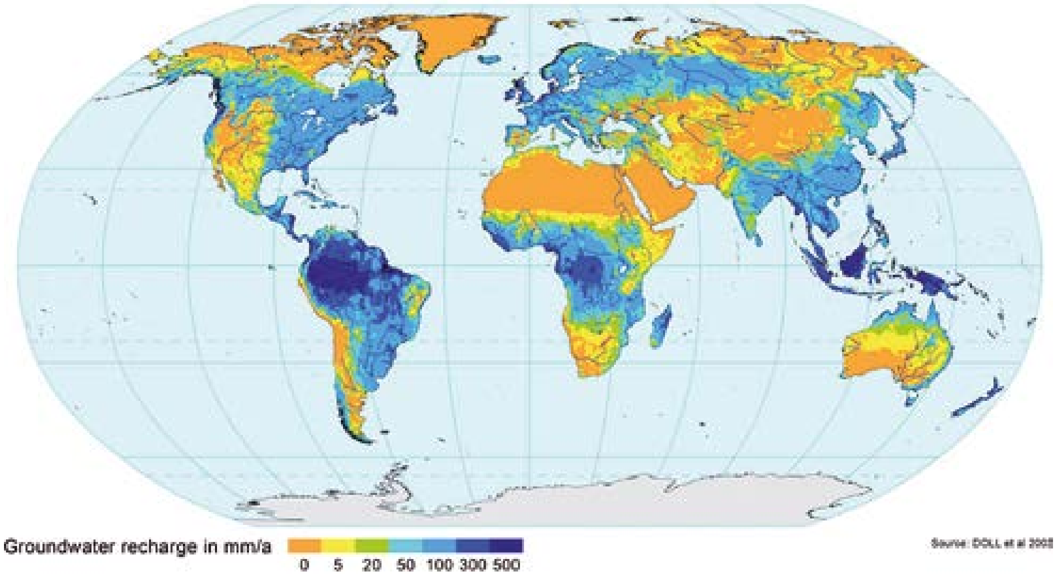

Figure 9.5. Average annual groundwater recharge, 1961 - 1990 (Döll and Fiedler, 2008)

Groundwater use within agriculture was initiated in Asia with the advent of the Green Revolution in the 1960s. Many countries, but particularly India, Pakistan, and China, supported more effective and productive agriculture through groundwater irrigation and use has significantly increased since then (Figure 9.6).

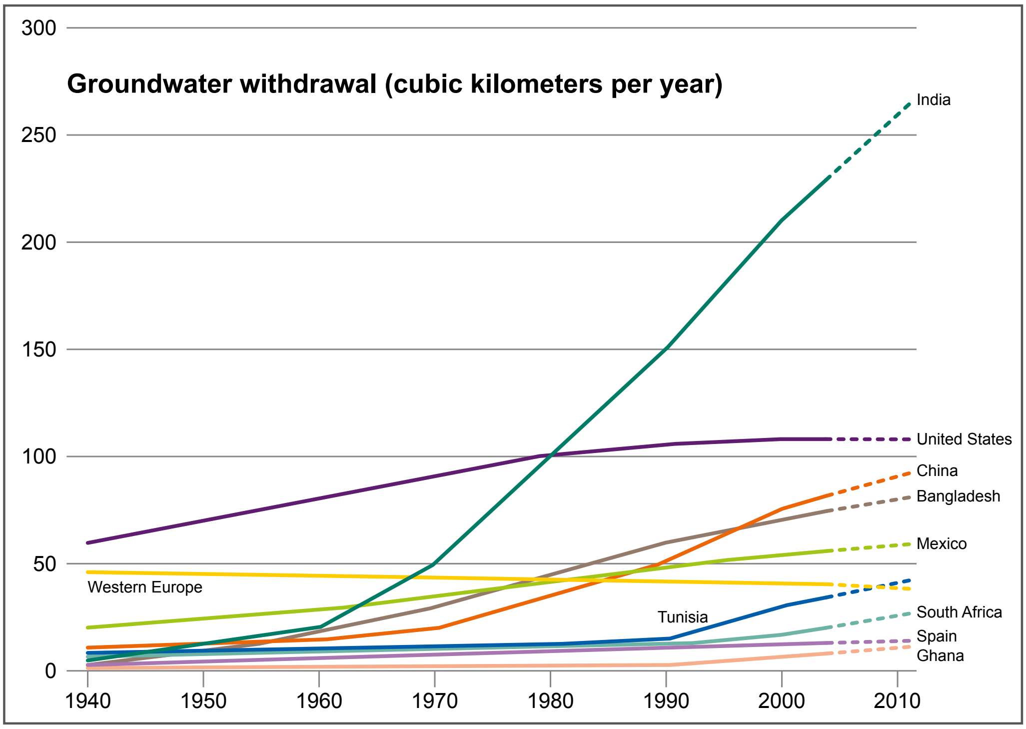

Figure 9.6. Groundwater withdrawal for selected countries (Shah, Burke, and Villholth, 2007)

This growth has been unprecedented in the human history and has implications for the available water resources and the environment in those areas where groundwater exploitation is particularly intense, as we shall see later.

9.2 Why is groundwater use in irrigation so popular?

Some of the inherent properties of groundwater are particularly favourable for irrigation (Box 9.1). These relate primarily to its ubiquitous and perennial presence compared to e.g. rivers. Such factors partly explain the preference of farmers to use groundwater rather than other water sources, most notably surface water.

In addition to these 'built-in' factors favouring groundwater, there have been a number of external factors that have helped promote groundwater use for irrigation. These include the development of drilling and pumping technologies needed to access and abstract the water. In early phases of development and in poor communities, groundwater use from shallow aquifers tends to dominate, but as the resource is exploited, the need to drill deeper arises with concurrent need for mechanical pumping, rather than human-powered lifting.

BOX 9.1. FAVOURABLE PROPERTIES OF GROUNDWATER FOR IRRIGATION

- ***Ubiquity:*** Groundwater is available almost everywhere and thus allows for decentralized and incremental development and management where needed
- ***Drought resistance:*** Groundwater is typically less vulnerable to drought than surface water sources since groundwater has a lagged response to changes in rainfall and faces fewer losses of water to evaporation. Hence, crop cultivation is also possible during dry spells and in drought periods, to a certain extent
- ***Reliability:*** Groundwater provides on-demand irrigation, which provides farmers freedom to apply water when their crops need it most. Improved reliability furthermore encourages farmers to invest in intensification through use of improved seeds, fertilizers, cultivation practices like water saving irrigation, and crop diversification. All these factors lead to increased land and water productivity
- ***Immediacy:*** Groundwater irrigation can be developed quickly by individual farmers or small groups, unlike large surface irrigation structures, which might require government participation or a large cooperative effort
- Low-cost: Capital costs of groundwater structures are much lower per area of irrigation than those of surface structures since reservoir construction is not required and water sources can usually be developed close to the demand. However operating costs tend to be higher for groundwater irrigation schemes
- ***Versatility:*** Groundwater may be strategically developed for multiple uses in rural remote areas, ensuring water for domestic as well as productive uses and hence addressing several development goals
- ***Flexibility:*** Groundwater may be developed in conjunction with other sources of irrigation to optimize overall water use and storage options

Cost-effective pumps are increasingly available, with makes from Asia being supplied and traded in many countries today. Drilling technologies, adapted to the various settings, are also generally available in most countries, though cost and efficiency varies quite a bit. Sales and services for these technologies are generally much better in Asia than in Africa, reflecting the longer history of groundwater development in that region.

Another external factor that has facilitated groundwater development for irrigation is the expansion of rural electrification. This is exemplified in India, where groundwater irrigation proliferated in certain regions due to subsidized electricity supply to farmers. Electricity seems to be the favoured source of power due to lower prices and its 'cleanliness' compared to e.g. petrol or diesel. However, rural electrification still lags behind in parts of the world, like Sub-Saharan Africa (SSA), effectively hampering groundwater irrigation development.

Furthermore the increase in food demands (due to growing populations and affluence in lifestyles) has spurred the farmers to intensify their agriculture through irrigation and to cultivate higher-value crops. It has been found that due to the reliability of the resource and farmers' ability to control the application of groundwater, the yields and productivity of groundwater is higher than surface water (Deb Roy and Shah, 2003). With lower risk of crop failure when using groundwater, farmers also tend to invest more in other crop inputs, like fertilizers and pesticides, generally further increasing their productivity.

Food production with groundwater tends to increase production of vegetables and other higher-value crops relative to that of staple crops, especially in SSA. Hence, diets of poor farmers could improve in nutritional value when their food is sourced from groundwater, though no documented results for this are available. In Asia, groundwater is used also for staple crops like wheat, maize and rice.

Finally, increased knowledge of the groundwater systems by farmers, as well as their experience of positive outcomes, has further encouraged accelerated growth of groundwater fed irrigation observed in many parts of the world.

9.3 Livelihood impacts

For the reasons mentioned above, irrigation, and in particular groundwater irrigation, has been associated with poverty alleviation. A broad-scale positive correlation is found between groundwater irrigation development and reduced incidence of poverty in India (Fig. 9.7). This supports smaller-scale findings that farmers adopting groundwater irrigation are better-off than counterparts, who do not take up groundwater irrigation or take up other forms of irrigation (e.g. Shah et al., 2013). In Southeast Asia alone, it is estimated that more than 1 billion people are relying directly on groundwater for irrigation (Villholth and Sharma, 2006). However groundwater irrigation must prove profitable for the farmers investing in it, and in some cases (as in SSA) costs are often too high and hence prohibitive for the poorer farmers to invest. This implies that the benefits tend to accrue to less deprived farmers and development is slower (Villholth, 2013). Whether this aggravates disparity is not clear.

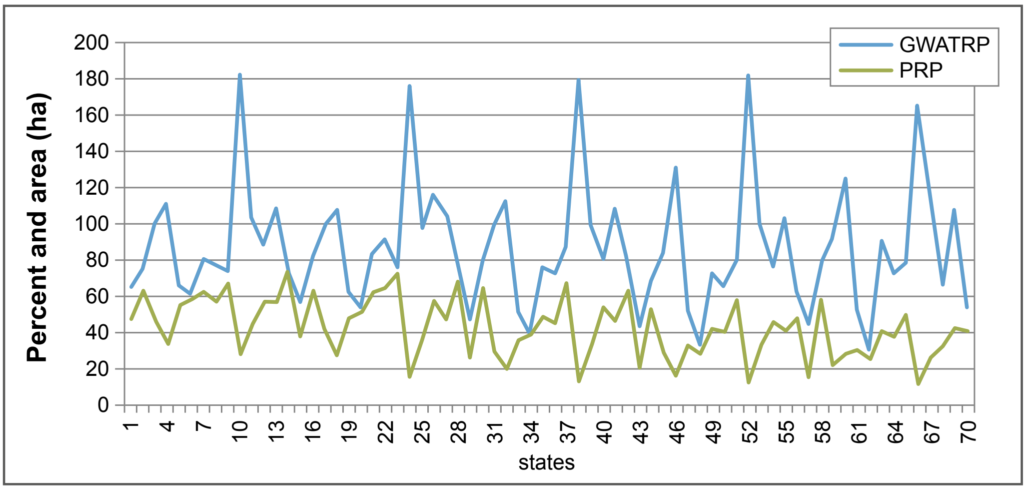

Figure 9.7. Relationship between groundwater irrigated area per thousand rural population (GWATRP) and percentage of rural poverty in Indian states (PRP) (Narayanamoorthy, 2007)

The case of Sub-Saharan Africa

Groundwater use in irrigation in SSA varies from small-scale smallholder schemes of less than one hectare to large-scale mechanized schemes larger than 100 hectares. A simple typology that encompasses the most prominent forms of groundwater irrigation in SSA is suggested in Table 9.1, which distinguishes between the depth of the groundwater utilized and the funding source.

Table 9.1. Typology of groundwater irrigation systems in SSA, including examples

		Depth of wells		
		Deep		Shallow
Funding source	Private	1. Commercial, larger-scale, mechanized, export-oriented		2. Informal, small-scale, farmer-driven
		Examples:	*Flower farms in Ethiopia, Center-pivot grain farms in Zambia*	*Vegetable growing schemes in Northeast Ghana*
	Public	3. Deep systems, subsidized		4. Shallow systems, subsidized
		Examples:	*Public schemes in Raya-Kobo in Ethiopia*	*Fadama systems in Nigeria*

Which category does most of the groundwater irrigation in your country fit into?

The distinction of depth is important, because investment costs to start groundwater irrigation increase significantly with depth. Deeper systems (Type 1 and 3) also tend to be more resilient against droughts as compared to shallow well systems. The distinction between funding source is also important as the control and management of the various systems differ widely. While the shallow informal smallholder systems (Type 2) are mostly unrecognised and unregulated by the public sector, the deeper systems (Type 3), due to significant public investments, are formally recognised by the public sector, typically requiring delegation of management to users' organisations. Finally, Type 4, exemplified by the fadama systems in Nigeria, encompasses shallow systems, but supported through public funds. As in Asia, groundwater irrigation has proven instrumental in poverty alleviation in SSA, when the poorest population groups simultaneously get access to groundwater through cheap wells and pumps as well as the necessary enabling factors associated with farming, e.g. access to energy, credit, agricultural inputs, and training (Villholth, 2013). Data from particular cases are given in Table 9.2.

Pictures illustrating the various systems are shown in Fig. 9.8.

Figure 9.8. Illustrations of the various groundwater irrigation types

The hydrogeology, in combination with the socio-economic and political factors, governs which types of groundwater irrigation are developed. Since the potential for groundwater irrigation development in SSA in general is large, various methods have been proposed to estimate the potential in terms of size of area and distributed locations. It is estimated that another 26 million households could benefit and about 13 million hectares of farmland could be sustainably irrigated with groundwater in thirteen selected countries of SSA (Pavelic et al., 2013). A simple compilation and analysis of groundwater irrigation-related indicators revealed a certain ranking in potential of fourteen different SSA countries (Box 9.2).

If not on the list, which group do you think your country falls into?

BOX 9.2. GROUP RANKING OF SELECTED COUNTRIES IN SSA WITH RESPECT

1. Low or localised potential:
   Kenya, Mali, Niger, South Africa, Tanzania
2. Still appreciable potential:
   Burkina Faso, Ethiopia, Ghana, Malawi, Mozambique, Nigeria, and Zambia
3. Great potential, but demand for irrigation limited at present:
   Rwanda, Uganda

Table 9.2. Data from irrigation cases, including groundwater irrigation, in SSA, with focus on smallholder systems

Country, region	Irrigation started	Plot size per HH[a] (ha)	GW depth, well type	Combined w. rainfed?	Lifting device, irrigation device	Crops, GWI season	GWI practitioners	Land tenure	GWI type (cf. Table 3)	GWI dev. stage[b]	Farming w. highest productivity[c]	External financial support	Reference
Ethiopia Raya-Kobo Valley	>1995	~ 0.25	Deep, wells (60-170 m)	Yes	Elec. pumps, furrow/ buckets/ sprinkler	Onion/ tomato/ pepper Dry season	Smallholder farmers	Lease/ share cropping/ own	3	2	Motor pump irrigation from GW	Partly gov't/ NGOs	Gebregziabher et al. (2013); Ayenew et al. (2013); Abate (2006)
Ghana Upper East Region	1890's	0.01-0.21	Shallow, dugouts/ HDWs[d]	Yes	Rope and buckets	Tomato/ onion/ pepper Dry season	Mostly women and youth	Lease	2	1	Bucket irrigators from GW	Limited	Obuobie et al. (2013); Namara et al. (2013); Dittoh et al. (2013)
Niger Niamay Capital District	>1990	0.13	Deep + shallow, various	Yes	Hand/foot pumps, buckets	Onion/ tomato/ cabbage Dry season	2/3 women	Individual/ collective	2	1	GW irrigation	Partly gov't/ NGOs	Torou et al., 2013
Nigeria Northern Nigeria	>1993	0.5 - 1.0	Shallow, boreholes	Yes	Motor pumps, flooding	Onion, cabbage, pepper, tomatoes All year	Smallholder farmers	Individual/ lease	4	2-3	GW irrigation	World Bank/ Gov't	Abric et al. (2011); Nkonya et al. (2010); Dabi (no year)

[a] HH: Household; [b] GWI development stage acc. to Deb Roy and Shah (2003). 1 signifies early stages of groundwater development while 4 indicates mature and over-development of groundwater; [c] Gross revenue per ha; [d] HDW: Hand-dug well

9.4 Too much and too little groundwater development for irrigation is a concern

Regions like SSA and Southeast Asia differ widely in the scale and significance of their groundwater irrigation (Fig. 9.4 and 9.6). In India, as an example, groundwater contributes to more than 60 % of the irrigated areas, whereas the same figure for SSA is between 10 and 20 % (Villholth, 2013). While irrigation in general is much lower in SSA than in Asia, demonstrating some overall impediments, these data show the quite different contexts and trajectories of groundwater development across the globe. It is generally surmised that Southeast Asia presents a case of overdevelopment of groundwater, while SSA is one of under-exploitation. In the first case, while groundwater has proven instrumental in alleviating poverty on a large scale in India, the conditions in some parts of the country are presently considered unsustainable, contributing to environmental degradation, diminishing profits from irrigation, and increasing conflicts between water users, etc. In SSA, it is considered that groundwater holds a large potential for further supporting small- and large-scale irrigation development, food production and poverty alleviation. In Table 9.3, the countries in the world with over-exploitation of groundwater are listed according to their depletion rates. It is seen that both developed as well as developing countries are struggling with depletion of groundwater resources.

Some of the reasons for the disparity in groundwater development between Asia and SSA are:

- Larger population density in Southeast Asia, necessitating intensified agriculture
- Cheaper and easier access to pumps and drilling technologies in Southeast Asia
- More profound embedding of the Green Revolution in Asia
- Lack of community tradition in irrigated cultivation, compared to rain-fed arable cropping and extensive livestock rearing in SSA
- Poor rural infrastructure, roads, storage facilities etc.
- Limited commercial ventures in SSA.
- Very low levels of rural electrification in SSA, coupled with the elevated cost and distribution difficulty associated with use of diesel fuel for pumping
- Inadequate access to financial credit for irrigation hardware acquisition and purchasing essential production inputs in SSA (such as quality seeds and agrochemicals)
- Better and more productive aquifers in Asia

Which of these reasons do you think are most critical?

Table 9.3. Reported groundwater abstraction rate (A) and model-estimated groundwater depletion rate (D) for selected countries in subhumid to arid regions, with ranges of uncertainty given in parenthesis, for the year 2000. Depletion is the rate of abstraction exceeding long term average recharge (Wada et al., 2012)

Country	Abstraction (A) (km^3 / yr^{-1}	Depletion (D) (km^3 / yr^{-1}	D/A (%)
India	190 (±37)	71 (±21)	37 (±19)
United States	115 (±14)	32 (±7)	28 (±9)
China	97 (±14)	22 (±5)	22 (±9)
Pakistan	55 (±17)	37 (±12)	69 (±48)
Iran	53 (±10)	27 (±8)	52 (±24)
Mexico	38 (±4)	11 (±3)	30 (±11)
Saudi Arabia	21 (±3)	15 (±4)	72 (±30)
Russia	12 (±2)	1.5 (±0.5)	14 (±7)
Italy	11 (±3)	2.3 (±0.6)	21 (±13)
Turkey	8 (±2)	2.4 (±0.8)	31 (±18)
Uzbekistan	6.5 (±1.8)	4.0 (±1.4)	63 (±43)
Egypt	5 (1.3)	3.0 (±1.2)	61 (±43)
Bulgaria	4.8 (±1.4)	2.0 (±0.8)	42 (±32)
Spain	4.6 (±1.1)	1.7 (±0.6)	37 (±23)
Argentina	4.5 (±0.9)	0.9 (±0.3)	20 (±11)
Libya	4.4 (±1.2)	3.1 (±0.9)	70 (±43)
Ukraine	4.2 (±0.9)	0.3 (±0.08)	7 (±3.5)
Romania	3.5 (±1)	1.3 (±0.6)	38 (±30)
Kazakhstan	3.4 (±1)	2.0 (±0.5)	59 (±35)
South Africa	3.0 (±0.7)	1.5 (±0.5)	50 (±30)
Algeria	2.5 (±0.7)	1.7 (±0.6)	69 (±48)
Greece	2.4 (±0.6)	0.34 (±0.1)	14 (±8)
Morocco	2.4 (±0.4)	1.6 (±0.5)	67 (±34)
Australia	2.1 (±0.4)	1.0 (±0.3)	48 (±24)
Tajikistan	1.9 (±0.5)	1.2 (±0.4)	61 (±40)
Yemen	1.9 (±0.5)	0.9 (±0.3)	49 (±31)
Turkmenistan	1.85 (±0.5)	1.25 (±0.5)	70 (±50)
Syria	1.59 (0.4)	1.23 (±0.3)	78 (±41)
UAE	1.55 (0.3)	1.18 (±0.4)	76 (±42)
Tunisia	1.55 (±0.5)	0.65 (±0.2)	42 (±30)
Peru	1.23 (±0.4)	0.32 (±0.08)	26 (±17)
Bolivia	0.68 (±0.2)	0.25 (±0.08)	37 (±25)
Israel	0.61 (±0.2)	0.38 (±0.1)	62 (±41)
Kyrgyzstan	0.61 (±0.2)	0.31 (±0.1)	51 (±37)
Jordan	0.52 (±0.2)	0.22 (±0.08)	42 (±38)
Mauritania	0.51 (±0.1)	0.36 (±0.1)	71 (±35)
Oman	0.50 (±0.2)	0.2 (±0.06)	39 (±33)
Kuwait	0.29 (±0.1)	0.25 (±0.09)	87 (±70)
Qatar	0.18 (±0.05)	0.15 (±0.06)	83 (±60)
Globe	**734 (±82)**	**256 (±0.38)**	**34 (±9)**

9.5 Solutions to under- and over-use of groundwater for irrigation

Modifying current approaches to use and management of groundwater for irrigation may not be straightforward, neither in the over- nor the under-exploitation cases. However, optimising use in both cases is imperative for long-term sustainable environmental and socio-economic outcomes. For SSA, the situation is more a case of under use of the groundwater resource for irrigation. The role of groundwater managers will then be more aligned to finding ways to stimulate development of this sector.

Some questions that may arise for water managers are:

- How do RBOs in Africa manage the development of groundwater fed irrigation in SSA?
- How can RBOs avoid the overexploitation of groundwater that has been witnessed in south-east Asia?
- What role can RBOs play in stimulating groundwater use for irrigation?
- What may be effective management systems for groundwater irrigation at different scales of development and use?
- What can be the role of TBOs in management of groundwater irrigation?
- Why should RBOs in Africa invest in groundwater management for irrigation when groundwater use is so limited and conflicts hardly exist and are very localized?

In Table 9.4, some overall options for improving use and management for groundwater irrigation are provided.

Which of these approaches are top-down or bottom-up? How to facilitate each?

Table 9.4. Approaches to enhance sustainable use of groundwater for irrigation in Southeast Asia and Sub-Saharan Africa

Sub-Saharan Africa	South-East Asia
Develop national and regional policy for groundwater irrigation development	Diversify livelihoods away from groundwater irrigation
Develop maps and knowledge of the aquifers at various scales	Encourage groundwater development in less developed regions
Promote and support aquifer development by appropriate gw irrigation systems (table 9.1)	Ration electricity supply to irrigation while making it reliable
Expand reliable rural electrification	Increase irrigation efficiency
Improve rural roads	Encourage rainfed and drought-resistant crops
Provide incentive subsidies for eg. pumps, electricity, drilling etc.	Encourage local management of groundwater among the farmers
Improve market chains for equipment & crops	Encourage artificial groundwater recharge
Promote user based gw allocation and management systems.	Conjunctive use of groundwater and surface water
Improve land tenure security	
Incentivize rural food processing industries	
Expand curriculum of extension workers to include groundwater irrigation aspects	
Develop micro-credits targeted to smallholders to access groundwater irrigation	
Empower farmers to organise themselves to request policy changes	

Such social changes tend to take time to gain a strong foot-hold but where real economic and financial gains are to be made, communities around the world have shown rapid adaptability to take advantage of favorable conditions. RBOs can be the catalysts for such positive changes in SSA.

9.6 The new approach: The nexus between water-, energy-, and food security

As there is limited access to water, sanitation, food and energy (often due to poor management and governance structures), a rapidly growing population will put even more stress on the availability and the sustainability of the planet's resources. The systems that help produce and bring fresh food and energy as well as clean, abundant water to all of us, are intertwined. It takes water to create food and energy, it takes energy to move and treat water and to produce food, and sometimes we use food as a source of energy. These systems have become increasingly complex and dependent upon one another as the resources come under increasing pressure. As a result, a disturbance in one system can wreak havoc in the others, so it is important to achieve a sustainable balance between the three. Therefore, it is important to realise the interdependency in these sectors to avoid the growing trade-offs between these development-goals.

When groundwater resources are accessed to provide for irrigation demand, the nexus between water-, energy and food security is evident. There will be an energy demand to lift the water to the surface and to distribute it to the crop. Energy access and price are strong drivers for groundwater abstraction. Several countries around the world have subsidised diesel or electricity for the agricultural sector to secure farmer's incomes and national food sovereignty. Such subsidy incentives tend to lead to an expansion of the area on which water intensive crops are cultivated with water inefficient technologies that finally result in the depletion of groundwater. Especially in many arid countries where groundwater resources are non-renewable this is a particular problem. Such depletion also has vast implications for the energy sector which looses income and becomes bankrupt.

Agricultural output remains fundamental to national well-being and to economic output. However, integrating the interdependencies between energy-, food- and water security in national policies and programmes have the potential to improve the economy, conserve natural resources, and increase food security.

In many places in Africa, electricity is not developed in rural areas and causes a constraint for the development of groundwater, beyond simple manual lifting for small-scale irrigation. Conversely, electricity development often is associated with greater dependence on groundwater for irrigation

No system is perfectly elastic and there will be many complex trade-offs, spatially and materially, in the nexus between water-, food-, and energy security. Export of food is a virtual export of energy and water; and vice versa for food imports. In summary, when advocating for the development of groundwater-based irrigation, basin organizations and other decision makers should address the interdependencies between water-, food-, and energy security. Increasing groundwater irrigation through subsidies to energy for farmers may be tricky, as it may strain the energy systems, may benefit certain population groups, and encourage unsustainable groundwater use. Decision makers need to ensure that the development of groundwater for irrigation is a sustainable endeavour and a positive development for all components of the society, and not just for one class against the interests of another.

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9.8 Exercise

Tragedy of the Groundwater Commons

Rules of the Game

Version: 19 Sep. 2013

Frank van Weert (IGRAC) and Karen G. Villholth (IWMI)

General rules

There are nine farming households and one fishing household (there are nine teams in total playing the game).

The farming households each have a farmland of 100 hectares and each have their own groundwater well (needed for groundwater irrigation). Only one type of crop is grown.

Only the fishing household is allowed and able to fish in the community lake and the lake water level is dependent on the groundwater level. The layout of the wells and the lake are shown in Figure 1. When groundwater is pumped, some wells may interfere with each other. This means that one well will be drawn down not only by that well but also by the surrounding wells (Figure 2).

The game consists of a series of simulation runs, each representing one growing season.

Each farming household can produce one harvest per simulation run and the fishermen household can produce one fish catch per simulation run.

After each simulation run, the groundwater and lake level go back to 'normal' (no physical memory effect in the hydrogeological system).

Performing livelihood activities have associated costs and benefits (see below) and these costs and benefits accumulate over multiple simulation runs. The team that accumulates most net benefits over the series of simulation runs has won. However, note that maximizing production (cropping area) may not optimize net incomes! Various mechanisms may limit the net outcome:

1. The drawdown of the groundwater level, which implies a larger cost of abstracting groundwater
2. The drying of the lake, which implies an environmental (health) cost
3. Climate shocks that limit the crop yields
4. Penalty costs for drafting groundwater above an upper cap that has been decided by a majority of well owners
4. All households start with an equal capital of 0€.
6. If a household reaches a debt of 250€ the household is out of business for the rest of the game.
7. Players are able to set the rules if a majority agrees: however transaction costs are involved.

Benefits (per simulation run, per household)

- 2 €/ha in case of farming
- 150 € for fish catch

Costs (per simulation run, per household)

Type	Amount	Explanation
Living cost	25 €	Note: Not playing (no livelihood activity) will cost you money anyhow!
Cost of fishing:	100 €	
Abstraction cost	Variable	is a function of volume of pumped groundwater, groundwater level and unit price per unit volume (0.002 €/m3)
Cap rule transaction cost	100 € divided by the number of players that join the rule for that simulation run	Advice: Convince others to join: it will make your transaction costs smaller; but be aware of free-riders!
Environmental (health) cost	35 €	When the lake runs dry fishing household is temporarily out of business, all households pay costs for getting sick because of protein deficit!
Social cost or benefit	20% of averaged cumulative net benefit from all the households	Paid by or accrued to all households in the subsequent run
Water saving equipment cost	150 €	Like drip irrigation kits. Implies 20% water saving and smaller farming costs. Investment is only done once during a game
Penalty cost for no compliance with cap rule		Is set by those who pay cap rule transaction costs and given to non-compliers

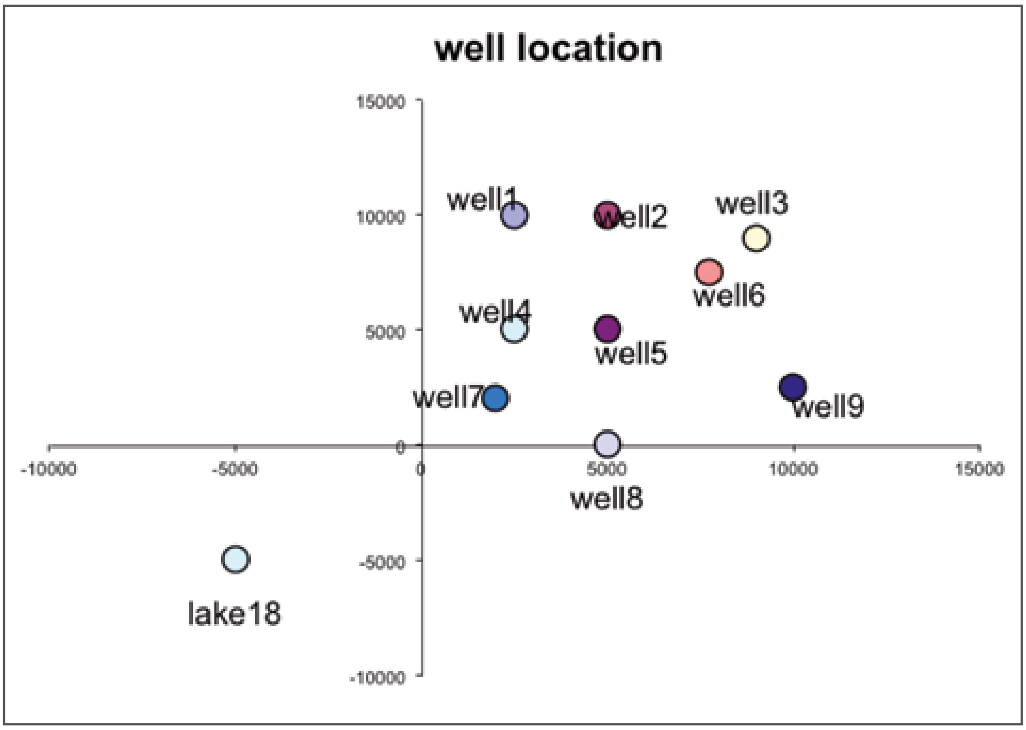

Figure 1. Location of wells and the lake

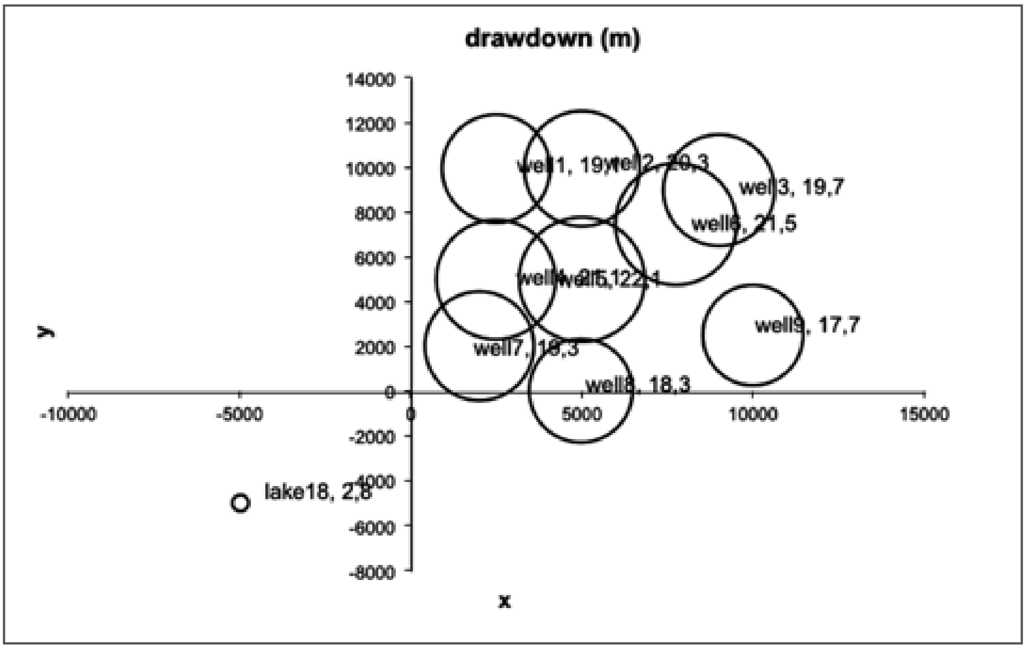

Figure 2. Illustration of interference between pumping wells

german cooperation

DEUTSCHE ZUSAMMENARBEIT

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