Thematic Paper 8

Social adoption of groundwater pumping technology and the development of groundwater cultures;

Governance at the point of abstraction

Groundwater Governance
A Global Framework for Action

gef
www.theGEF.org

THE WORLD BANK

United Nations Educational, Scientific and Cultural Organization

International Hydrological Programme

FIAT PANIS

iah aih

Groundwater Governance - A Global Framework for Action

2011-2014) is a joint project supported by the Global Environment Facility (GEF) and implemented by the Food and Agriculture Organisation of the United Nations (FAO), jointly with UNESCO's International Hydrological Programme (UNESCO-IHP), the International Association of Hydrologists (IAH) and the World Bank.

The project is designed to raise awareness of the importance of groundwater resources for many regions of the world, and identify and promote best practices in groundwater governance as a way to achieve the sustainable management of groundwater resources.

The first phase of the project consists of a review of the global situation of groundwater governance and aims to develop of a Global Groundwater Diagnostic that integrates regional and country experiences with prospects for the future. This first phase builds on a series of case studies, thematic papers and five regional consultations.

Twelve thematic papers have thus been prepared to synthesize the current knowledge and experience concerning key economic, policy, institutional, environmental and technical aspects of groundwater management, and address emerging issues and innovative approaches. The 12 thematic papers are listed below and are available on the project website along with a Synthesis Report on Groundwater Governance that compiles the results of the case studies and the thematic papers.

The second phase of the project will develop the main project outcome, a Global Framework for Action consisting of a set of policy and institutional guidelines, recommendations and best practices designed to improve groundwater management at country/local level, and groundwater governance at local, national and transboundary levels.

Thematic Papers

No.1 - Trends in groundwater pollution; trends in loss of groundwater quality and related aquifers services
No.2 - Conjunctive use and management of groundwater and surface water
No.3 - Urban-rural tensions; opportunities for co-management
No.4 - Management of recharge / discharge processes and aquifer equilibrium states
No.5 - Groundwater policy and governance
No.6 - Legal framework for sustainable groundwater governance
No.7 - Trends in local groundwater management institutions / user partnerships
No.8 - Social adoption of groundwater pumping technology and the development of groundwater cultures: governance at the point of abstraction
No.9 - Macro-economic trends that influence demand for groundwater and related aquifer services
No. 10 - Governance of the subsurface and groundwater frontier
No.11 - Political economy of groundwater governance
No.12 - Groundwater and climate change adaptation

www.groundwatergovernance.org

Groundwater
Governance

A Global Framework for Action

GROUNDWATER GOVERNANCE:
A Global Framework for Country Action
GEF ID 3726

Thematic Paper 8: Social adoption of groundwater pumping technology and the development of groundwater cultures: governance at the point of abstraction.

MJ Jones (FAO Consultant)

Rome, January 2012

TABLE OF CONTENTS

LIST OF BOXES, FIGURES AND TABLES

Compilers Note:

The concentration of examples of groundwater irrigation from India and from the High Plains Aquifer in the United States of America (USA) reflects the extensive availability of appropriate technical papers. The considerable work undertaken and reported on from other major groundwater-based irrigation areas has been examined but coverage from these areas is more fragmented. However, the available papers in many cases report similar situations developing across all groundwater basins in Europe, Asia, the Middle East, Africa, Australia and the Americas.

The detailed role of pump-user management groups has not been specifically examined as these are seen as constantly evolving. The schemes are seen to expand, mature and decline as the social structure of the communities alter under the influence of external and internal political and economic developments.

1. Introduction

The last ten thousand years have seen water supply technology developed from the collection of surface water from rivers and ponds and groundwater from springs and wells in basic containers to complex pumped-piped distribution schemes. During the first nine thousand years, water resource developments and social regulation were aimed at satisfying domestic and irrigation supplies. The last few hundred years, however, have seen rapid advances in pumping technology that have outstripped the social adjustments to the rules governing the use of the resources.

Mankind was initially concerned about building effective groundwater-pumping machinery. However, once suitable technical and social solutions were developed, the impacts of large-scale groundwater abstraction were soon found to require new measures leading to legislation and conservation of the resource.

Over time a variety of pumps and motive mechanisms were developed as set out in “Mine Drainage, Pumps, Etc.” (Behr, 1896). This provides extensively illustrated descriptions of the latest technology at the end of the 19thcentury and has an appendix covering “Water-Raising Machinery for Irrigation or Land Drainage”. It also describes compressed air-powered and air-lift pumps. Two Food and Agriculture Organization of the United Nations (FAO) monographs – "Water Lifting Devices for Irrigation" by Molenaar (1956) and "Water Lifting Devices" by Fraenkel (1986) – provide further comprehensive summaries of traditional and motorized water-pumping technology at the time of publication. The 1956 monograph concentrates on describing and costing traditional and mechanized low-lift surface-water pumps for rice irrigation, while the 1986 monograph expands coverage to the design parameters, operational efficiency and economics of wind-powered and motorized pumping systems.

The four methods available to abstract water vertically against gravity from a dug-well or borehole are:

- direct lifting of a fixed volume with a container – rope and bucket(s) including the multi-container Persian Wheel;
- positive displacement of a volume by the movement of a plunger or intermeshing rotating walls[1];
- rotodynamic propelling by rotating blades or impellers (Figure 1) – shaft and electric submersible pumps, centrifugal suction (initial water flow at right angles to direction of rotation axis), turbines (water flow parallel or at and acute angle to rotation axis) and educator jet pumps;
- differential pressure by lowering the density of a water column – airlift.

Since 1900, progressive developments in pumping technology and motive power have underpinned an ever-expanding worldwide use of groundwater for rural, urban and industrial water supplies, as well as for livestock, agricultural and irrigation purposes. The main developments driving this expansion were the introduction of reliable diesel and electric-powered, shaft-driven, multi-stage centrifugal pumps. These have since enabled deeper aquifers to be systematically exploited.

Between the publication of the FAO monographs in 1956 and 1985, two highly significant developments in groundwater pumping became established. The first was the initiation by donor agencies and international lending institutions of large-scale hand-pump-based rural water supply programmes aimed at meeting the 1977 Mar del Plata (Argentina) Action Plan that led to the declaration of the 1981-1990 International Drinking-Water Supply and Sanitation Decade (IDWSSD).The second development was the evolution and rapid

---

[1] Dating to the 3rd century BC the force pump used a plunger to press water out of a cylinder. Plunger pumps require a non-return valve and can be mounted at the surface and rely on suction and air pressure to lift water to the surface and therefore have a maximum possible lift of less than 10 m. Plunger pumps set below the water surface in the well directly lift the column of water in the rising main, and the lift capability depends on the power available and the strength of the materials used to construct the pump. Both forms of plunger pump were in use by the 15th century AD. The rope or chain pump pulls a continuous string of plungers though guide and lifting pipes. Diaphragm pumps rely of displacement of a flexible membrane. Rotary progressive cavity pumps are in common use (Mono Pumps) but gear, screw, eccentric vane and squeeze pumps have more limited application.

expansion in the use of electric submersible pumps for groundwater-based urban water supplies and irrigation. Large-scale submersible pump groundwater irrigation took-off with the introduction of the centre pivot in Colorado in the 1950s (Kepfield, 1993).

In many countries, the adverse impact of this growth in use of submersible pumps on groundwater levels and/or quality triggered the need for legislation to regulate abstraction. The introduction of appropriate legislation, however, has been uneven given the population and economic demands placed on the groundwater resource base. In some cases, current legislation is conflicted by the impact of government subsidies and promotion to encourage further groundwater abstraction as typified by the biofuel market.

This thematic paper examines the historic and on-going development of water-lifting technologies and the governance problems and solutions that have arisen from controlled or uncontrolled groundwater abstraction. It also examines legislation on improved pump efficiency and the economics and life-cycle costing of borehole pumps.

Part 1: Baseline

2. Styles and Patterns of Groundwater Access and Use before Mechanized Drilling and Lifting

The development of steam power at the end of the 17th century marks an appropriate break in the development timeline for pumping technology. It also marks the point where direct-lift pumps were largely replaced by rotodynamic pumps that effectively propelled water upwards.

Pre-17th Century Developments

From the start, humans relied on open access to springs, river baseflow and shallow groundwater stored in sandy dry riverbeds as their main dry-season water sources. It is, therefore, reasonable to assume early humans established strategies to ensure safe access to these water supplies. There is evidence of their limited means for collecting and transporting water. Until recently, the Australian Aboriginal cultures with no ceramic technology used animal skins, delicately folded and stitched leaves, tree bark containers, wooded bowls and sea, egg and coconut shells as containers.

Society's systematic exploitation of groundwater for domestic and cattle watering coincided with the transition from forager to sedentary farmer. This followed the domestication of livestock and food plants between 9 000 and 11 000 years BP. Water availability was central in determining human settlement patterns. The group of 5-m-deep water wells of this age uncovered in Cyprus and elsewhere in the Eastern Mediterranean Region reflects a certain understanding of shallow groundwater occurrences. This was likely linked to experience gained when mining of flints and, later, metallic minerals for tool making. The establishment of settled farming inherently engendered the concepts of individual or communal ownership of land and water pointsthat required protection by physical force or a system of customary law.

Archaeological evidence shows the rapid diffusion of all forms of technological advances across North Africa, the Middle East, Arabia, Western Asia, the Indus Valley and beyond between 10 000 to 4 000 years BP. Parallel technological developments occurred independently across Eastern Asia and South America. By 4 000 BP, wood-lined hand-dug water wells were in routine uses for community water supplies.

Under differing regional climatic regimes, three main forms of land use evolved:

- Dry land (rain-fed) arable farming developed in the topical and temperate humid zones.
- Surface water irrigation spread along the major river valleys around 8 000 years BP and more localized pockets of groundwater spring based irrigation developed in the more arid parts of Southern Arabia and along the Persian Gulf.
- In the sub-humid and semi-arid zones, nomadic pastoralists relied on seasonal vegetation cover and on surface and groundwater sources.

Ample surface and groundwater sources are found in rain-fed farming areas and potentially supported the high population densities as seen in the African Lakes Region.

In the tropical arid and semi-arid zones from North Africa to Central Asia, a weakening of the southwest monsoon around 5 700 BP caused a regional decline in precipitation. The climate shifted from sub-humid to semi-arid and arid, and the woodlands and savannah grasslands across a broad swath of the northern Sahara Desert retreated. The pastoralist and dry-land farming population moved east to the Nile Valley where they merged with a fast developing surface water irrigation farming culture that mirrored the cultures in the Tigris-Euphrates Valley and the Indus Basin (Bazza, 2007).

2.1 Lifting water through direct human and animal energy

Between 4 000 and 2 500 years BP, many of the traditional man-, animal- and water-powered low-lift devices to support the surface water irrigation were invented: the water was moved by lifting or paddling. The earliest and most widely used lifting device from 2 000 years BC was the shaduf, which was supplemented by Archimedes Screw around 100 BC. The use of a bucket and rope to lift water undoubtedly has the longest history, and its use in water wells was improved by the introduction of the windlass. These irrigation-based early societies implemented appropriate protocols and laws covering distribution of the surface water resources and maintenance of the supply systems. The bulk of the irrigation relied on the rise and fall of the river, with annual floods diverted into canal systems from where the water was allowed to flow by gravity or was lifted onto the surrounding fields.

The post 5 700 years BP decline in precipitation was accompanied by increasing unpredictability in the climate. Across southern Arabia and down the Pacific Coast of South America, the areas under irrigation declined steadily until the mean catchment precipitation fell below 70 mm at which stage irrigation was no longer viable. Populations were forced to withdraw to those areas where they could exploit spate floods and groundwater for irrigation. This is possibly best seen in the archaeological record of southern Arabia. Here Harrower (2006) provides a detailed account of archaeological research into the ancient spate irrigation systems dating from the mid to late 6 000 years BP in the Wadi Sana' that drains the Southern Jol in Wadi Hadhramaut-Massila Catchment, South Yemen. Extensive Neolithic tool-making sites and cattle remains dated to 7 000 years BP point to an ancestral pastoralist culture that was supplemented by spate flood diversion systems and spring fed irrigation until climatic conditions deteriorated about 4 000 years BP.

Similar developments can be traced along other Wadi Hadhramaut tributary valleys and to the East in Dhofar, Oman. Here, water wells at Shisur and Ma Shedid in Wadi Ghudun supported the agricultural developments centred on the ancient city of Ubar. There is a hiatus in the archaeological record in the Hadhramaut from 4 000 to 3 000 years BP. Following this there is evidence that shallow groundwater wells started to be used for extensive irrigation farming along the main Hadhramaut Valley. At present, there are still appreciable spring flows from the Umm er Rahumma Limestone supporting irrigated farming in tributary valleys, Wadi Ain, Wadi Idm (Ardar Raydah) and Wadi Sana'.

The implementation of irrigation systems must have rapidly progressed from an individual task to a collective undertaking that allowed the worldwide emergence of the early city-states. Prior to the spread of the Abrahamic religions, the religious and civil leadership powers of the surface water irrigation cultures were held by god-king-priest ruling elites who tightly controlled all aspects of the rights to land and water ownership. Many of the earliest written records of these irrigation-based societies concerned water rights and responsibilities for maintenance of the water capture and diversion structures. The situation regarding groundwater other than that developed by the qanat systems was largely outside the interest of the ruling elite. Thus, the early laws regarding groundwater centred on the private ownership of the land and the hand-dug wells. In many cases, the principles behind these laws have been largely carried over to the present day.

2.2 Mobilising gravity and drainage

The development of horizontal infiltration galleries to exploit groundwater from extensive mountain front outwash fans started around 1 000 BC in northwest Persia where they are known as qanat. They rely on gravity drainage (Mohammed Karaji, ca. 1100 AD) and likely were developed from observed groundwater flows that occurred when horizontal copper mine adits were driven into the watertable. Although length and depth of an average qanat are respectively around 5 km and less that 200 m, some may be considerably greater, reaching 70 km in length and 350 m in depth (Yazdi, 2006). During the Achaemenian period (550-330 BC) qanat construction was subsidized by tax relief: this benefit was reinstated during the post 621 AD Islamic Period when many of the qanat were controlled by the local government under formalized rules as set out in the "Alghani" – The Book of Qanat (Yazdi 2006). These included a minimum separation distance of 375 m between two qanats.

Qanat technology was transferred from Persia to hydrogeologically favourable sites in the Near East, Central Asia, North Africa and Southern Arabia (Lightfoot, 2000).Here they are known under a variety of names, *falaj*

(Oman), *karez* (Afghanistan, China, Pakistan) and *foggara* (North Africa). These terms, however, frequently describe spring-capture structures and the downstream water channel with no underground infiltration gallery. The peak of qanat development occurred between the 16th and 18thcenturies when more than 380 000 were recorded in the Hamadan, Isfahan and Tehran regions (Yazdi, 2006). Yazdi also reports that 34 355 qanats were still in use during 2003-2004 with a combined yield of 8,2km^3/year.

2.3 Rules of the game under low intensity abstraction

The archaeological record shows the earliest pastoralist cultures freely exploited amply watered rangelands and adopted small-scale rain-fed cropping. The grazing areas of the more arid areas of the Near East are seasonal and localized. This forced the pastoralists to adopt a nomadic lifestyle. They, however, benefited from a favourable distribution of perennial rivers and springs for watering livestock that were supplemented with surface storage tanks and hand-dug wells. Most of the winter-grazing grounds were on the lower slopes of the mountains that flanked the lowland drainage basins close to the well-regulated centres of irrigation farming. These provided a ready market for the pastoralists' flocks of sheep and goats. Over time, pastoralists acquired formal rights to the winter grazing lands and access water. Both pre-Islamic and Islamic laws recognised and protected these rights.

The rangelands of the semi-arid Sahel and the Horn of Africa have more limited surface water sources. Here pastoralists rely on springs, water harvesting structures and hand-dug wells that have been in use throughout the archaeological record, essentially unchanged. Some were, and are, of substantial size and required regular communal maintenance inputs. Established by 7 500 years BP, the pastoralist and small-scale subsistence farming communities resisted or accommodated external influences that could have impacted on their stable social system of land use. This level of social stability is reflected in a long oral and written tradition as a series of city-states rose and declined from the 5th century BC onwards. Traditional rights to groundwater were centred on the collective clan tenure of lands and hand-dug wells. In many cases, the principles behind these rights have been largely carried over to the present day as typified in the Oromo-Borana customary lands in Ethiopia and North Kenya (Box 1). Across the Indian sub-continent, the step well that came into use around 200 AD is a more highly engineered version of the Borana "tula".

Box 1: Oromo Wells, Ethiopia

The Oromo have strong homogeneous culture and social order based on age groups (*Gada*). Covering large areas of Ethiopia and northern Kenya, the land they occupy lies in a range of agro-climatic zones. They have ancient collective democratic traditions that enabled them to practice sustainable landuse, underpinned by the concept of a proper and equitable distribution of arable and grazing lands.

The Borana are one of the major pastoralist groups of the Oromo. Their rangelands occupy the semi-arid parts of the Sidamo Region in southern Ethiopia and the more arid Marsabit Region of northern Kenya. The underlying beliefs of the Oromo are illustrated by this extract of a traditional poem about mother earth:

Upon you there is food.
Under you there is water,
We graze our herds on you.

To effectively manage the resources of their semi-arid and arid rangelands, the Borana employ rain-water harvesting, spring sources and hand-dug wells in a way mirroring mankind's first endeavours.

Figure B1-1 (left): Traditional Borana tula well, Sidamo Region, southern Ethiopia. Clusters of such wells are collectively clan-owned and maintained. The use is regulated by an appointed overseer (konfi) and in times of drought ,tula can be jointly used by an alliance of clans that share the upkeep of the well and surroundings. Access to watering days at the tula is allocated according to an established schedule. (Gufu Oba, 1996; Skinner, 2010).

Figure B1-2 (lower left): Traditional Oromo hand-dug well between Bora and Burka in northeast Ethiopia. Water is collected using leather buckets thrown hand-to-hand to the surface from some 15 m below ground.

Figure B1-3 (lower right): Borana tula well located in a community 30 km south-southwest of Wachile, Sidamo Ethiopia. Google Earth Image (4^{o} 16’ 54N” 38^{o} 58’ 30”S). Such wells have enabled the Borana to establish sustainable use of the available grazing across the rangelands.

2.4 Mobilising wind energy

The first use of wind power appeared around the 4th century AD in Europe and China and the use of horizontal sail windmills to pump water for irrigation was recorded in Afghanistan and Persia by 700 AD. In the 14th century AD, vertical sail windmills were in use for drainage in Holland but these had a very limited lift capacity (± 1m). The discovery of metal working prompted the use of bellows and fans to pump air for smelting and mine ventilation. These provided the blueprint for some of the first water pumps. Cylinder plunger pumps with packed seals were introduced in 1675.

By the end of the 17th century, many forms of low-lift devices were employed for pumping surface water for irrigation and domestic supply purposes. The options for meeting higher lifts required for abstracting groundwater from hand-dug wells or natural caverns were limited to using rotating devices fitted with a single or a multiple series of containers as typified by the Persian Wheel (Saqiya). At that time, it is reasonable to state that individual owners and communities were largely responsible for looking out for their own water supplies in terms of ownership.

2.5 Suction pumps – Low-lift agrarian societies

As engineering and metal working improved during the 18thcentury, effective lever-action cylinder hand-pumps came into wider use for lifting water from hand-dug wells for domestic purposes and they became central to meeting the demands of rapidly growing urbanized communities. However, with underground mining needing to move greater volumes of water, the18th and 19thcenturiesalso saw a shift from pure lifting of water to more efficient methods of pushing or impelling water against a head[2]. Based on advances in mathematical analysis, physics and metallurgy, practical designs for suction and positive-displacement reciprocating cylinder pumps started to be developed and patented. Among the theoretical advances were the definition of power in terms of rate of lift and weight by John Smeaton in 1752 and, based on Newton's laws, Leonhard Euler's mathematical analysis of centrifugal forces as applied to water pumping in 1754.

While the use of rotating fans for ventilating copper mines in Portugal possibly dates back to the 5thcentury AD, the concept for the centrifugal pump was set out by Italian engineer Francesco di Giorgio in 1475. The first centrifugal pumps with straight vanes appeared in the 17thcentury AD. Curved vanes developed by John Appold in 1851 were found three times more efficient than the straight vane centrifugal water pumps then in current use. Other developments around the same time were the introduction of the shrouded impeller, the whirlpool chamber and multistage pumps. The lifting heads achieved by centrifugal pumps, however, were constrained by the low shaft rotation speeds and the efficiency of the water seals[3]. The introduction of the vane diffuser in the last quarter of the 19thcentury saw a further increase in centrifugal pump efficiency.

2.6 Steam power – First motorised pumps and the beginnings of hydrogeological science

The parallel development of steam power saw, in 1712, the introduction of the Newcomen beam engine coupled to positive displacement pumps. Although initially used for mine dewatering, these pumps were soon in use for urban surface water supplies. The more fuel-efficient Watt steam engine was introduced between 1760 and 1775. This was followed by the high-pressure steam engine around 1800and the rapid introduction of a wide range of steam powered applications for industrial manufacture, railway locomotives, paddle wheel and screw driven ships. These demanded lighter, higher powered and faster engines. Stationary high-powered long-stroke engines had a wider application in water pumping as typified by the installation of the Kew pumping station on the River Thames upstream of London in 1837.

By the early 1800s, the main principles of geology were being established, and by the 1820s the basics of groundwater flow and occurrence had been defined in France, including an understanding of the artesian Paris Basin. Picked up by British geologists, this knowledge was applied to the artesian London Basin and opened up the possibility of future large-scale groundwater abstraction for urban water supplies.

As worldwide urban and industrial growth polluted the immediate surface water sources during the first half of the 19thcentury, newly established water supply companies turned to investigating and developing alternative groundwater resources. As part of a technical proposal to augment London's surface water supplies using groundwater from the Cretaceous Chalk aquifer, Mylne (1840) reports that the construction of artesian boreholes in the London Basin had become widespread. The wells were typically several metres in diameter and often had additional horizontal headings or adits. Supporters and objectors to this development demonstrated an understanding of the cone of depression around an abstraction well and the seasonal

---

[2] For the purposes of this paper the term "head" covers both the total physical distance water is lifted plus the hydraulic pipe losses.

[3] The pumping head capability of all rotodynamic pumps is a function of the impeller tip speed.

variations in groundwater levels in response to recharge (Stephenson, 1841; Clutterbuck, 1842, 1843 and 1850).

Many early urban supply schemes relied on overflowing artesian groundwater and there was no immediate need to turn to pumps. In London, 120-m-deep wells commissioned in 1844 powered the Trafalgar Square fountains until around 1890 when the declining artesian pressure had to be augmented by pumps. The decades following the 1850s saw rapid growth in urban populations and when, in 1854, John Snow demonstrated the Broad Street water well as the source of a major cholera outbreak in London, metropolitan authorities worldwide responded by commissioning and putting in place, large-scale water supply schemes based, in part, on groundwater. In North America, the majority of the urban groundwater supplies were taken from unconsolidated alluvial sands and gravels. In Europe, attention focused on pumping groundwater from consolidated sedimentary aquifers. This expansion created a demand for improvements in pump capabilities in terms of discharge and head.

With the introduction of steam-traction engines in the 1850s, farmers and miners had mobile power plants to drive a variety of water pumps for drainage and lifting purposes. The use of steam traction engines continued well into the 1930s. In addition, the powerful commercial DC and AC electric motors introduced in the mid 1880s were quickly adapted by pump manufactures as substitutes for existing steam engines and then for purpose-built belt-driven pumps. By the mid 1890s, reliable internal combustion engines were adopted to power both reciprocating cylinder and centrifugal pumps for water supply. In agricultural areas, motorized pumps began to augment the windmills that were in wide use for domestic and livestock water supplies and irrigation.

As the 19thcentury closed, engineers had produced very robust positive-displace pumps capable of lifting 10 000m^3/day to 150 metres and less reliable rotodynamic pumps capable of moving 2 000m^3/day but with a lift limited to a few metres by the shaft seals. Most expanding urban water companies constructed large diameter shafts and installed very large beam engines cylinder pumps to abstract groundwater. In many urban areas, the increase in public and private water supply abstraction had already resulted in significantly lower groundwater levels.

Away from Europe and the USA, many urban communities continued to rely on traditional groundwater sources. Qanats continued to supply many cities in Iran. The use of open hand-dug wells continued to supply many towns and villages with animal- and man-powered lifting devices. For example, groundwater was lifted from wells tapping the shallow aquifers of the Wadi Tuban at Sheikh Othman to an aqueduct feeding the port of Aden in southern Yemen as late as 1914 (Connelly, 2005).

3. Twentieth Century Developments

3.1 Shaft-driven pumps – From mines to agriculture

Between 1901 and 1920, in America, specialist pump-manufacturers' attempts to satisfy the new groundwater irrigation market in the Mid-West and Pacific Coast States with high-volume, low lift and line-shaft centrifugal suction pumps was slow to take off. In Nebraska[4] this was largely due to the speculative nature of the investment

in irrigation farming (Kepfield, 1993). The farmers found that under the prevailing economic conditions, there were too many risks involved in changing from their existing windmills and reciprocating pumps.

Prototype line-shaft turbine pumps were developed in 1897. These were quickly followed by the first commercial pumps in the early 1900s as several California manufactures saw the opportunity to satisfy the demand for high-yield pumps that would fit in small diameter water wells. Faced with declining groundwater levels and increased drawdowns as the use of these pumps grew, the manufacturers concentrated on improving the hydraulic efficiency and material quality of their pumps.

By 1920, the three main types of rotodynamic pumps – radial, mixed and axel flow – were in use (Figure 1). The essential components of the high-lift line-shaft pumps, the discharge head, the vertical drive shaft and support bearings and the centrifugal impellers and housing had been largely perfected. The introduction of the gear head pump drives enabled direct coupling of internal combustion engines and electric motors to high speed pumps.

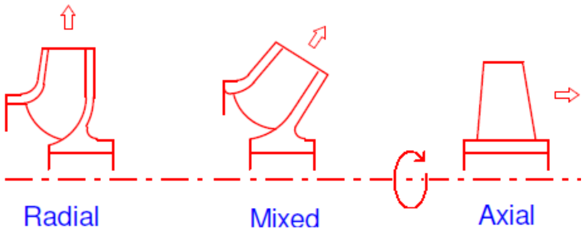


Figure 1: Basic classification of rotodynamic pumps (reproduced from BPMA, 2006).

3.2 The beginnings of groundwater irrigation – The High Plains Aquifer, USA

The take up by irrigation farmers in Nebraska in the 1920s remained low with irrigated lands beginning to extend up the interfluves from the shallow groundwater areas close to the main river valleys. Despite this reluctance to invest in new pumps due low grain prices, a minor drought in 1925-6 showed the advantages of groundwater based irrigation and by 1930 over one thousand pumps were used to irrigate some 12 000 ha In Nebraska (Box 2).

According to the 1930 census of Irrigation Districts in California some 100 000 ha of land was irrigated using 420 Mm^3 per year of groundwater pumped from wells (equivalent application 420 mm/year). This was about 15 percent of the total water diverted for irrigation and domestic supplies in the State. The USA Census data (Box 3) clearly reflects the major changes in the groundwater irrigation scene in the 19 main irrigation States as electric powered line-shaft turbine pumps became dominant. These changes were largely dictated by the 5-to-10-m decline per decade in groundwater levels across most irrigation areas.

From 1930, the introduction of higher performance line-shaft pumps, movable sprinkles and gated pipes, couple with cheaper high-speed petrol engines, lowered the costs and improved the reliability of irrigation. This led to an accelerating expansion in groundwater irrigation (Green, 1992). The impetus was further driven

---

[4] The State of Nebraska is cited as an example as it ranks first in the USA for groundwater-based irrigation.

by the 1930-36 “Dust Bowl” drought that affected most of the Great Plains area of North America lying to the West of the 100th meridian. The rapid expansion in rural electrification under the “New Deal” saw widespread phasing-in of electric motor-powered pumps and by 1944, over 5 150 groundwater irrigation areas covered some 100 000 ha in Nebraska (Conda, 1944).

Box2: Nebraska Growth of Groundwater Usage

The timetable of groundwater development for irrigation in Nebraska, USA, illustrates the interplay between government policies, economics, pumping technology, environmental impact and legislation. Surface water irrigation in the State started in the 1850s and by the 1960s, the surface-water-irrigated land covered about 400 km^2. Following droughts between 1883 and 1895, the State of Nebraska introduced laws governing the right to use surface water based on a *“first in time, first in right”* principle. The 450 000 km^2 High Plains Aquifer underlies parts of Nebraska, South Dakota, Wyoming, Colorado, Kansas, New Mexico, Oklahoma and Texas, in mid-western USA (Figure B2-1). Although large sections of the area are underlain by numerous oil fields, agriculture is the dominant economic activity. The High Plains Aquifer outcrop in Nebraska covers 130 000 km^2 and supports 3 000 to 3 300 km^2 of groundwater irrigation making it the largest State user in the USA.

Between 1901 and 1920, as mentioned earlier, American pump manufacturers’ attempts to satisfy the new speculative groundwater irrigation market in the Mid-West and Pacific Coast States with high-volume, low lift and line-shaft centrifugal pumps largely failed partly due mainly to unreliable belt drives and lack of suitable high-speed power units. In addition, irrigation farmers did not have access to the skills necessary for maintaining pumping equipment.

In Nebraska by 1928, the impact of groundwater irrigation on the water table along the Platte Valley was sufficient to dispel the idea that the resource was unlimited, and the State was called on to survey the resource. Published in 1943, the resulting report included mapping of the groundwater resources. On the other hand, rural electrification was a central programme to the 1935 American New Deal and the percentage of farms in Nebraska with electric power rose from 9,7 percent in 1919 to 95 percent by 1954.

Manufacturers were quick to produce electric-powered in-line shaft pumps. These were more efficient and easier to maintain than gasoline pumps and more consistent than windmills. This, coupled with pump-purchase credit plans prompted a rapid expansion in groundwater irrigation and by 1940 the State found it necessary to introduce new legal and technical management measures. Subsequently these were revised as natural conditions became better understood and demands on the resource changed. The first revision, passed in 1957, covered the registration of irrigation wells and placed a minimum 200 m well spacing. In 1969, legislation was consolidated under a bill establishing Land and Water Conservation Districts. The Groundwater Control Act passed in 1975 was supplement by the1996 Act (Legislative Bill 108) covering the integrated management of hydrologically connected groundwater and surface water.

The widespread introduction of the centre pivot irrigation spurred the main growth of groundwater irrigation from 1960 to 1980. This period gave rise to the philosophy of the USA water well drilling industry: "we drill water wells to sell pumps". After 1980, farm profits fell due to low agricultural commodity prices and rising pumping cost caused by declining groundwater levels. Since then most economic studies show groundwater irrigation to have negative returns without the receipt of external subsidies (Gilson*et al.*, 2001). In 1988, agricultural economists projected a slow withdrawal from irrigated farming to dry-land farming as the water table declined, and new investment in wells and irrigation equipment became uneconomic (H. P. Mapp, 1988).

The area under irrigation from 1980 to 1998 was stabilized by a variety federal subsidies and tax breaks, including resource depletion relief and guaranteed crop prices. Between 1998 and 2001, increased subsidies covered a dip in commodity prices and boosted the farming economy across the High Plains. In addition, targeted subsidies to encourage soya-based biodiesel production were introduced in 2002, followed in 2005 by more emphatic subsidies for the production of grain crops for ethanol biofuels. In 2007, the USA declared a nationwide target of 133 Mm^3 /a bio-ethanol production by 2017. To achieve this, further subsidies and easing of land use restrictions were introduced (Water Science and Technology Board of the National Research Council, 2007). The Environment News Service (ENS, 2007) estimates4 Mm^3 of process water is required to produce 1 Mm^3 of bio-ethanol on top of the irrigation water demand required to produce corn feedstock.

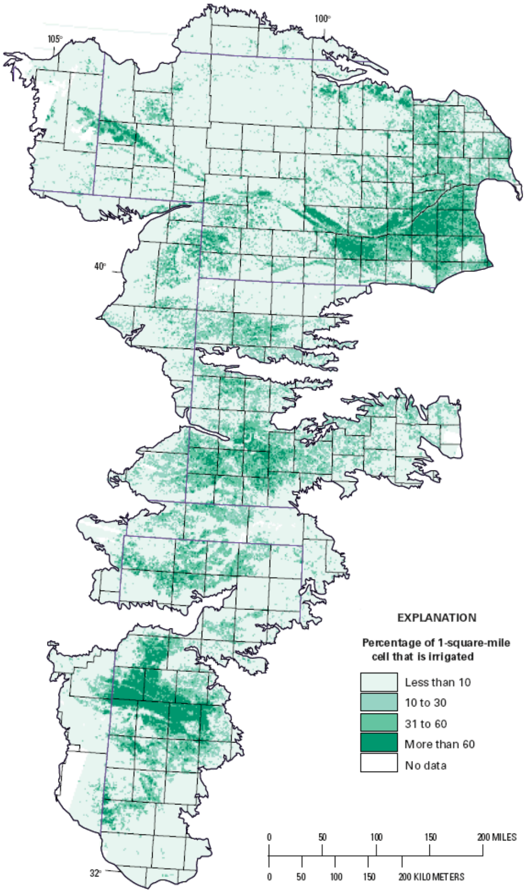


Figure B2-1: High Plains distribution of irrigated lands (adapted from Litke, 2001)

Box 3: Extracts from the United States Department of Commerce, Bureau of the Census, 14th, 15th and 16th Census (1920, 1930, 1940) of the United States: Irrigation of Agricultural Lands

Covering the 19 irrigation States(Arizona, Arkansas, California, Colorado, Idaho, Kansas, Louisiana, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington and Wyoming), the census data shows the steady growth in the number of wells and groundwater usage. It shows the transition from centrifugal to turbine pumps and the rise in the use of electrical motors. Also notable are the decline in steam power and the declining trend in overflowing artesian wells (the post 1900 impact of the artesian Dakota Sandstone Basin peaked in 1910-1914 and is seen to be declining by 1930 and is unremarked upon in the 1940 census).

	Flowing Wells	m^3/sec	Pumped Wells	m^3/sec	Pumps	m^3/sec	Motors
Pre 1860	9	0,02	75	3,84	101	5,68	89
1860-69	21	0,02	54	1,55	78	4,69	72
1870-79	107	0,41	82	4,31	115	51,61	105

1880-89	513	2,47	260	11,21	373	81,52	338
1890-99	319	1,35	610	27,19	714	0,17	623
1900-04	426	4,08	794	28,57	990	186,56	916
1905-09	396	7,07	1704	83,34	2 075	339,70	1 911
1910-14	677	7,36	5371	198,52	5 940	375,19	5 602
1915-19	517	2,62	6623	269,78	8 468	599,59	6 961
1920-24	572	3,62	7902	288,15	7 216	419,05	8 258
1925-29	532	4,48	10829	396,16	11 551	508,92	11 551

Table B2-1: Data from 1930 Census

	1920	1930	1940
Number of Pumped Wells	32,094	56,729	88,279
∑ Potential yield m^3/s	1160.6	2048.3	2735.3
Electric motor	289,018	876,186	1,118,024
Internal combustion engine	259,615	265,756	588,123
Water	8,093	12,058	-
Steam	10,768	872	-
Other*	125,429	50,343	56,540

Table B2-2: Data from the 1940 Census

	1920	**1930**	**1940**
Centrifugal	581 274	726 301	597 057
Turbine	24 390	302 294	901 157
Rotary	36 716	118 856	
Reciprocating	32 344	5 338	
Air Lift	10 072	1 627	
Plunger		17 503	17 558
Screw		8 732	
Water Wheel		285	
Bucket		117	
Scoop Wheel		45	
Other/Mixed*	143 307	50 343	56 540

Table B3-3: Data from the 1920, 1930 and 1940 Census

* Other and Other/Mixed largely implies a combination of pump types and/or power plants were in use.

3.3 Growth of groundwater-based urban water supplies

The demands of the urban water supply and mine dewatering markets at the beginning of the 20thcentury were largely satisfied by the existing high-head, high-volume, beam-reciprocating cylinder pumps. Although inefficient, these users valued the reliability and robustness of these machines and extended their use into the 1950s. With the recognition of biological pollution of groundwater, the first step in protecting urban groundwater supplies In the United Kingdom (UK) was the Margate Act of 1902 that empowered water boards to establish 1 500 yard (ca. 1360m) protection zones around their abstraction wells (Thresh and Beale, 1925).

Severe droughts in southern England between 1932 and 1934 prompted legislative moves in the UK and the establishment of a Water Unit within the British Geological Survey in 1937. By this time, with over 750 wells abstracting some 10 000 m^3/day within the London area, groundwater levels had declined from 15 to 45 m under the North London pumping stations of the Metropolitan Water Supply (Walters, 1936). The perceived mounting water resources deficit was addressed in the UK Water Act of 1945. This initiated a broad assessment of the Nation's water resources. In addition, the water companies began wholesale replacement of steam-powered groundwater-pumping machinery with electrically-powered close-coupled line-shaft pumps.

From the 1850s to the mid 20th century, expansion of the railways in South America, Africa, Australia and Asia was heavily dependent on groundwater wells for boiler water. These encouraged a rapid spread of drilled wells and pumps. For example, the boreholes drilled in Zambia between 1902 and 1908 for the railway connecting Livingstone to the Copperbelt discovered the prolific Lusaka dolomite aquifer, and the earliest private borehole recorded in Lusaka, Zambia, dates from 1909. Equally significant is the fact that the sites for the new capital cities in Zambia and Tanzania (Dodoma) were largely selected on the basis of recently discovered groundwater resources.

3.4 Electro-submersible pumps – Self-supply and the race to deplete

Manufacture of waterproof electric motor pumps began around 1904 and until the 1940s, the term submersible motor and pump was largely applied to sump and bilge pumps that worked under water. In the mid-1940s, the use of the term changed to describe the close-coupled electric submersible borehole pump configuration. With the introduction of powerful, high-speed, submergible electric motors and effective high-pressure shaft seals, specialized pump manufacturers developed high-lift centrifugal and turbine pumps fitted with diffusers for mine drainage in the 1930s. This enabled deeper underground mining below the regional water table as typified by the lead and zinc Broken Hill Mine at Kabwe, Zambia.

Prior to the 1930s, manufacturers frequently used models and prototypes to perfect the design of centrifugal and turbine vanes, impellers and shrouds. Using these methods, designers were able to produce pumps with specific yield and head performance curves. In 1932, hydraulic research that showed previous visualization of frictionless non-viscous water flow failed to represent the actual velocities and flowpaths generated by rotating pump impellers (Fischer and Thoma, 1932). This research provided a base for future perfection of submersible and line-shaft pumps. Cavitation damage to impellers was seen as a major wear factor associated with excessive vane tip speeds.

The 1930s also saw the introduction of the line shaft driven progressive cavity pumps. Technically, therefore, from around 1930, with a range of purpose designed borehole pumps and versatile well drilling machines, planners and investors had worldwide access to groundwater as typified by the groundwater development in Wadi Hadhramaut in South Yemen for the piped Tarim urban water supply commissioned in 1932.

3.5 First groundwater governance initiatives

By the middle of the 20th century no management or legal constraints had been placed on the construction and maintenance of water wells or the installation of pumps beyond the community management as typified by the Oromo in Ethiopia, the recognition of traditional water rights under Muslim Law and the creation of protection zones around public water supply wells.

Almost all users, from individual householders through irrigation and dry-land farmers to urban water supply and industrial companies had full confidence in their installed groundwater pumping equipment in terms of reliability and durability. Having had a role in selecting the equipment, they understood and accepted the operation and maintenance demands involved in the use of pumps. While for most of the general public the majority of groundwater developments stemming from these advances had largely taken place unnoticed and unremarked, there was a degree of awareness among groundwater experts of their lack of understanding of the resources being exploited. This awareness was sharpened in countries with recurrent droughts and expanding demands from growing populations and economies. It also brought existing water rights legislation into question as society adopted the view that groundwater was a common property resource. This view led to refocusing of legislation aimed at ensuring the security of supply for right holders. This required a much sounder understanding of the groundwater resources than had previously been necessary.

To fill this knowledge gap in North America and Europe, the responsibility for monitoring and evaluating of groundwater was vested in the National and State Geological Surveys or Water Resource Agencies. The first step in the UK was the1945 UK Water Act. But by not treating the surface and groundwater as single entity, this Act failed to address the impact of increased groundwater abstraction on river flows in southern England. The 1963 Water Resources Act rectified this oversight and created a Water Resources Board charged with planning the integrated development and conservation of water resources on a national scale.

3.6 Worldwide expansion of urban and rural groundwater developments

Outside North America and Europe, taking advantage of ready access to small diameter drilled water wells and line-shaft pumps, groundwater was the prime source for many of the first piped urban water supplies. By 1960, this pattern of groundwater development provided an estimated 50 percent of all urban water supplies to population centres of less than 100 000 in Africa, Asia, South America and Australia. In addition, groundwater dominated the development of rural water supplies.

In Africa, following European procedures, annual budgets were centrally allocated for the steady and systematic construction of hand-dug and drilled well programmes at sites decided at the district and provincial government level. Usually some 200 hand-dug wells and 100 to 200 boreholes (Table 1) were programmed countrywide in Southern and Central Africa (Box 4). Most boreholes were finished at 150 or 200 mm diameter and equipped with diesel powered reciprocating cylinder pumps until the 1960s when line-shaft progressive cavity pumps became more popular. The hand-dug wells were usually equipped with buckets and windlasses.

Works completed	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	Total 1942-52
Boreholes	24	18	40	38	40	89	110	178	178	148	184	1 047
Total meterage	1154	973	2019	1570	1580	3415	4372	6294	6179	4966	6478	39 000
Hand-dug Wells	114	134	105	82	54	101	163	202	219	266	237	1 767

Table 1: Summary of Groundwater Development Works, 1942 - 1952, Zambia (WDID, 1953).

Rarely, groundwater developments for rural water supplies ran into unexpected problems. During the late 1950s and early 1960s, among unreported government groundwater-based rural water supply initiatives that should have impacted on the planning of future developments was the Colonial Government's Lake Kariba resettlement scheme in southern Zambia. Some 57 000 people were moved to new government constructed villages as their traditional Gwembe Valley homeland was flooded behind the Kariba Dam. At around 20 sites following resettlement, villagers were found to be suffering from severe fluorosis. Investigations showed the new water supply boreholes to have damagingly high fluoride levels. The government was forced to destroy the affected boreholes and again move the villagers to new sites. Subsequently, water samples from all successful government-drilled domestic supply boreholes were sent to the government analyst for full chemical determinations. Decades later, under another accelerated programme in Bangladesh, groundwater from the hundreds of thousands of tube wells sunk in the 1970s, 1980s and 1990s were belatedly found to contain poisonous levels of arsenic.

Although natural contamination of groundwater is uncommon and geographically localized, there are other recognized cases. The two examples of hazardous groundwater mentioned above suggest that proof of the acceptable chemical quality of any new source should be required in administrative procedures for the granting of water rights for domestic use and, possibly, during pump purchase.

3.7 Groundwater development – The perceived rural water supply solution

From the mid-1960s, with rising populations, the newly independent nations found a steady incremental expansion in rural water supplies politically unacceptable. Accelerated programmes were needed to provide clean drinking water that would improve the nations' health and welfare. To meet this demand, the international lending and development agencies focused on rural water supplies. Groundwater had long been identified as the prime source for improved rural water supplies with hand-dug and drilled wells fitted with hand pumps as the obvious route to implementing the programmes (Wagner and Lanoix, 1959; United Nations, 1960; World Bank, 1976; McJwikin, 1977; Hughes, 2000).

Box 4: Rural Water Development – Roots of Ownership and Sustainability

Based on an annual budget, the Pre- and immediate Post Independence rural water development policy of the Zambian Department for Water and Irrigation Development (DWID) was driven by decentralized requests for improved water supplies originating from district level government committees. On receipt of the requests at regional level, the provincial DWID office undertook a feasibility survey that included an outline selection of the raw water source and preliminary costing. In practice, this approach was largely demand-driven with the Central Government supplying funds within its budget limitations.

A 1952 Report (DWID, 1953) records:

> The concrete-lined well retains its popularity as a source for domestic water supply, and there is very little reduction in the demand for wells. It is worth noting that villages are now beginning to realise that the wells are theirs and that it is their responsibility to look after them. Wells are being kept in better condition, surrounds are being kept cleaner, and there have been fewer demands on the Department for well repairs, although the number of wells in use is much higher.

The Report for the Southern Region goes further:

> Very few wells were sunk by the Department in (...) rural areas. There is an increasing tendency for this type of work to be done by local well diggers, trained by the Department. The Department provides the materials and general supervision but the community supplies the labour.

How rural development shifted from the above model to that described in the influential “Drawers of Water” (White, Bradley and White, 1972) represents a major fault line in the progress in implementing rural water supply. White, Bradley and White do not comment on this linkage between ownership and sustainability, but do suggest an approach to low-cost rural water supplies that features the same ideas:

> Individual homeowners would be systematically encouraged to make independent improvements. These include individual cisterns, shallow wells, spring protection (...). Social guides would include research on new methods, information on improving techniques, and technical assistance in design and construction.
>
> Such a policy would depart from the current tendency to focus nation efforts on rural projects directly administered by national agencies. More emphasis would be placed on stimulating individuals and community groups to make their own improvements. (Page 267)

At present it is valid to include donors and international development loan projects to national agencies in this comment. The natural wish of donors and development agencies to acclaim their works with prominent billboards at the entrance to endowed communities would seem to detract from engendering the necessary community ownership of the scheme and hence its sustainability. How much better to proclaim: *this village with the help of the xyz donor have installed their own water supply system*.

In the early 1990s, the World Bank indicated a return to a decentralized model for water supply development that embodied many aspects of the earlier Zambian DWID practices. In 1994, Zambia re-adopted decentralization and community-based projects (Harvey and Skinner, 2002), and now the Zambian Ministry of Local Government and Housing (MLGH, 2007) sets out the guidelines for community management of hand-pumps that implies total community ownership of the installations.

While virtually all externally funded development projects included counterpart training and institutional strengthening, in practice most national government organisations did not have the manpower resources or establishment to provide suitable candidates for training. This led to the projects concentrating on the technical execution of the work and the schemes subsequently proving unsustainable with local staff unable to operate or maintain the equipment. In detail, another significant problem with many accelerated programmes occurred and still occurs, when the installation of pumps in successful boreholes falls rapidly behind drilling progress until the time lag between well completion and equipping is measured in years (Box 5).

Box 5: Unequipped Boreholes and Accelerated Pump-Based Rural Water Supply Programmes

The 1960 United Nations (UN) monograph "Large Scale Ground-Water Development" presents concise guidelines and advice to all professionals engaged on groundwater programmes. It covers the phasing of groundwater developments, organizational and technical requirements, and its appendices cover a range of pumping options. It stresses the staffing required for normal development activities and recommends calling in external consultancy to help cover emergency or accelerated programmes. The one not highlighted problem area, however, that continues to hamper most rural groundwater programmes is the hiatus between the completion of a groundwater abstraction borehole and the installation of a pump.

The American drillers' view of their water well industry is summed up by their maxim: "we drill wells to sell pumps". This contrasts with the common fragmented operational model were one group drills wells – often a government drilling section or a contractor – and a second group is responsible for the task of installing pumps. While this arrangement worked reasonably when district or provincial water engineers were solely responsible and financed the drilling and equipping of wells within a single financial year, it broke down when field work was disrupted, or a financial over-spend curtailed installation work. When this happened a number of recently completed wells were left with no pumps installed at the end of that financial year and there was usually no budgetary carryover to fund their completion in the next financial year. By the time funds became available to equip these suspended wells, the installation teams frequently could not find the well or the hole was partially or totally blocked with stones.

Across Africa, the number of uncompleted, but successfully tested wells is poorly recorded. Where data is available, the figure probably represents 20 to 30 percent of the total successful drilled-wells (Table B5-1) but can be considerable more. Of 243 boreholes drilled in 1971 by the Zambian Government, 60 were dry and abandoned, 118 were equipped and 125 were unequipped (DWA,1974).

A 1987 inventory of wells in Ethiopia showed that, while the majority of the uncompleted boreholes were drilled after the end of a rural water supply programme of United Nations Children's Fund (UNICEF) in 1981, some of the successful UNICEF boreholes had stood unequipped for 12 years.

To add to this view of wasted endeavour can be added the large number of investigation boreholes drilled during Water Master Plan investigations and small town water supply feasibility studies across Africa and Asia. In 1979-82, two water master plan studies in Tanzania drilled 53 and 70 boreholes with a 65 percent success rate but no hand pumps were installed. In contrast, India Mk2 hand-pumps were installed by the drilling crew in 8 of the 20 investigation holes constructed for a Battambang Urban Water Supply study, funded by the UK Department for International Development (DfID) in 1994.

Total Boreholes drilled	**Equipped with motorised pump**	**Equipped with hand pump**	**Capped waiting pump installation**	**Abandoned**
540	97	179	135	129

Table B5-1: Status of Boreholes drilled between 1973 and 1989 in Ethiopia

A number of reasons – such as the need to know type and size of pumps and installation depth – can be given to justify this break in what should be a continuous process of well construction, testing and pump installation. In many cases, these reasons are immaterial, particularly in the case of hand-pumps, and can be short-circuited by improved management and a flexible supply chain, as suggested in the 1960 UN publication. In fact, the only acceptable constraint may concern groundwater quality, but with a borehole database this should rarely arise.

In Asia much of the work was undertaken with reasonable success by international consultants and private contractors. The first and second tube-well programmes in Bangladesh, for example, were funded by the World Bank's International Development Association. Elsewhere, the accelerated programmes were executed following European models within a receiving national government framework. The results were more mixed as the project design and programmes usually failed to take into account the local conditions, infrastructure and technical resources (Vaa, 1993). Classic examples include the access problems involved in moving 20-tonne drilling rigs though rural areas along tracks and over bridges designed for the 7-tonne trucks, farm tractors and trailers. Equally, the complexity of the drilling rigs and, even more so, the compressors were beyond the capabilities of the local mechanics. This was seen in an early, relatively large-scale UNICEF intervention in Pakistan that floundered as the receiving agency did not have the means and technical resources to deploy and utilize water supply equipment provided under the programme (Bayer, 1987).

3.8 International Drinking-Water Supply and Sanitation Decade (IDWSSD 1981-1990)

To rationalize a global approach to improving rural livelihoods by securing safe drinking water for all, the 1977 Mar del Plata World Water Conference Action Plan formulated plans leading to the UN International Drinking-Water Supply and Sanitation Decade (IDWSSD 1981-1990) with the objective to:"provide every person with access to water of safe quality and adequate quantity, along with basic sanitary facilities, by 1990."Executing this directive required coordinated action from both the supply side and the demand side.

For the first decade or so, the supply side – comprising the international and bilateral lenders and donors and the equipment manufacturers – dominated the field. The demand side comprising the beneficiaries – generally the national governments perceived as *defacto* representatives of their populations – were largely passive recipients. Given the scale of the task, close attention was given to the selection and price of equipment and materials (Weiss and Jequier, 1984; UNICEF, 1999). By the mid 1990s, the views of the community on the demand side – mainly from non-governmental organization (NGO) feedback – began to receive more attention (Carter, Tyrrel and Howsam, 1996).

A 1998 analysis prepared for the World Bank uses different terminology, with the 1978-1988 period being considered the appropriate technology phase and the 1988-1994 period as the transition from a hardware to a software phase (Black, 1998). Translated this implies recognition of the supply-side failure took 10 years and that a further 10 years were required to fully recognize that sustainable development depended not on a central government demand but on the demand at the community level.

The perceived need for an appropriate technology phase contrasts against the earlier pragmatic approaches outlined in Box 4 and with the Wagner and Lanoix (1959) guidelines for rural water supply[5].

---

[5] Wagner and Lanoix (1959) also highlighted the superior practicality of chain pumps over regular hand-pumps in terms of performance and maintenance.

3.9 Legacy of modern hand-pumps – Sustaining a rural water supply culture

In 1981, the World Bank, faced with a low success rate of completed and on-going projects, initiated the Rural Water Supply Handpumps Project aimed at identifying suitably reliable village-level operation and maintenance (VLOM) hand-pumps (Box 6). Carried out by the UK Consumers Association, the testing work largely focused on the robustness and mechanical efficiency of the pump heads designed to lift groundwater up to 60 m (World Bank, 1984).

By the mid-1980s, internal reviews of donor and lending agency rural water supply programmes began to highlight a series of sustainability problems that required a major re-think of their project approach. Among the main problems was despite intensive testing, most hand pumps installed did not meet the VLOM concept. While the high profile role of UNICEF in promoting local manufacture of variations of the India Mk2 and Mk3 hand-pumps in Africa[6] is well documented, the skill levels required for 100 percent successful installations were not always available (Harvey and Skinner, 2002).

Box 6: The Hand-pump Conundrum

During the late 1970s, the UNICEF rural water supply programme in India adopted, and helped with the development of the India Mk2 hand-pump (Mudgal, 1997). By 1980, a huge local demand for the hand-pumps and competition between manufactures brought the price of the India Mk2 with 50 m of rising main down to USD 200. It was also claimed that the pump satisfied VLOM status.

The low unit price and ready availability made the India Mk2 first choice for many of early IDWSSD projects outside India. However, removed from the mechanical support infrastructure available in India, the Mk2 pump proved difficult to install faultlessly and to subsequently maintain. There were inherent quality problems with the rising mains supplied and with other aspects of the India Mk2 pumps exported by some manufacturers, despite the controls and inspections developed between UNICEF and the Indian Standards Institute, initially, and later with the British Standards Institution and SGS – *Société Générale de Surveillance* (Jones, 1990, Baumann, 2000, Michael and Gray, 2005). However, the chain link connector between the pump arm quadrant and the pump rods is a constant cause of failure, particularly when the pumps are set at a shallow depth (Michael and Gray, 2005). Used in shallow wells, the weight of the rods is insufficient to push the plunger quickly down the cylinder as the handle is lifted: this causes the chain link to buckle. The situation is further aggravated by users developing a habit of using short quick strokes. The cost of mobilizing a technician to do the repair was many times the price of the spare part. When correctly installed deeper, the India Mk2 (>4 pump rods) can give over five years of heavy, trouble-free, performance as can the solid-link India Mk2 variant when the use of less than four pump rods is needed.

By the late 1970s, internal reviews of donor and lending-agency rural water supply programmes found that the repair of broken down hand-pumps was beyond the capabilities of most rural communities. The main problem was that despite intensive promotion, the hand-pumps did not meet the VLOM concept. In 1981, the World Bank frustrated by this low sustainability of completed and on-going projects, initiated the Rural Water Supply Handpumps Project aimed at identifying suitably reliable pumps. Many had inherent design weaknesses like the use of plastic crown wheel and retaining set screws that worked loose under use in some versions of the Mono progressive cavity pump (Jones, 1990). The rotor was also liable to become jammed in the stator if silt collected in the pump. The results of the tests and subsequent Water Aid analysis (Water Aid, 2007) are shown on Table B6-1.

Name	Type	Lift Range m.	Discharge l/min	VLOM	Origin

---

[6] UNICEF continues to fund some 20 percent of the 35 000 and 55 000 India Mk2 and Mk3 hand-pumps shipped annually to Africa between 2005 and 2009 (UNICEF, 2010).

Afridev	Deep well	7	25	45		22	15	Yes	Kenya, etc.
Afridev	Direct action	7	15		26	22		Yes	Kenya, etc.
Bucket pump	Improved bucket and rope	6	15		5	10		Yes	Zimbabwe
Consallen	Deep well	7	25	45	14	14	14		UK
India MK 2	Deep well	7	25	14	12	12	12	No	India, etc.
India MK 3	Deep well	7	25	45	50% of Mk2				India, etc.
Monolift	Deep well progressing cavity	25	45	60	16	16	9	No	UK, South Africa
Nira AF 76	Deep well	7	25		25	26		No	Finland
Nira AF 84	Deep well	7	25	45	23	22	21	No	Finland
Nira AF 85	Direct action	7	15		26	24		Yes	Finland
New No. 6	Suction pump	7			36				Bangladesh
Tara	Direct action	7	15		24	23		Yes	Bangladesh
Vergnet	Deep well diaphragm	7	45		24	25		No	France
…	Windlass and Bucket	0	45		5	15			Universal

Table B6-1: Selected hand-pump performance and VLOM characteristics (from Water Aid, 2007).

Promoters' annual reports of IDWSSD hand-pump projects, however, were quick to announce their success clusters along the lines of: *in the past year our projects provided safe drinking water to so many hundreds of thousand people*. To which, many field workers could reply: *yes, but for how long?* Figure B6-1 provides a partial reply. It shows the situation with broken down hand-pumps across a number of sub-Saharan countries. The results from elsewhere are likely to mirror these results: McJwikin, 1977, for example, highlights the weaknesses of many of the commercially manufactured hand-pumps then available.

Looking at the mechanical reasons for the breakdowns (Figure B6-2) recorded by Reynolds (1992) shows a close correlation with the earlier experience in the operation and maintenance of rural hand pumps. In the 1960s and 1970s, most problems affected, in order of frequency, plunger washers, foot valves and pump cylinders. The pump heads were then largely of the heavy-cast iron lever or rotary type.

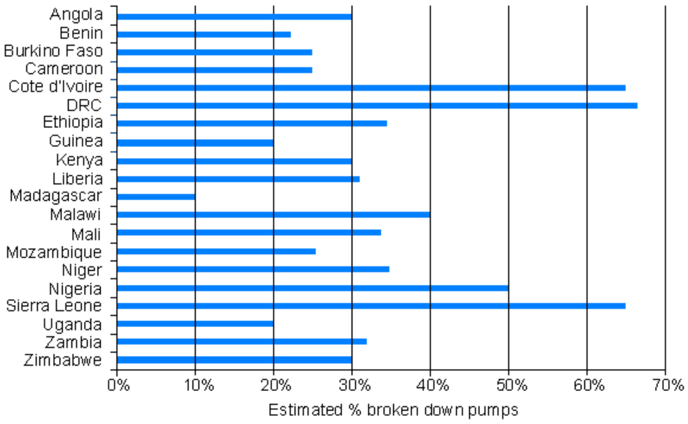
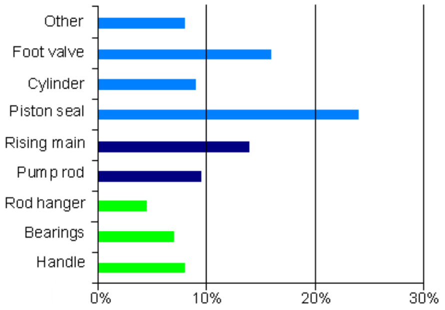


Figure B6-1: Percentage of broken down hand-pumps in selected Sub-Saharan countries (from RWSN, 2010).



Light blue - down-hole components
Dark blue – rising main components
Green – headwork components

Figure B6-2: Main causes of hand-pump breakdowns (from Reynolds, 1992).

The high frequency of down-hole component failures suggests two possible causes. The pump seals and cylinders may have reached the end of their service life or they are prematurely worn out due to the inflow of abrasive silt or sand into the pump body. This inflow would also account for jamming of the foot valve. The use of manmade materials rather than traditional leather for the pump seal or cup has not proved entirely satisfactory in terms of working life or efficiency. The self-healing nature of wet leather allows stray sand grains to embed into the seal rather than to be trapped on the surface where it can abrade the cylinder walls. The use of a short cylinder length as a cost-cutting measure has downside impacts. It makes the alignment of the piston stoke within cylinder very critical and removes the opportunity of relocating the piston movement to an unworn part of the cylinder: this is frequently done by turning the cylinder upside down.

The difficulties of replacing the down-hole components was recognized and addressed with a number of pumps having foot valves and pump plungers retrievable without removing the whole pump and rising main. This is a feature of the Afridev pump that can also be supplied with unplasticized polyvinyl chloride (uPVC) plastic rising main.

The problems with the rising main and rods can usually be traced to poor assembly during installation or poor quality materials: corrosion of badly galvanized pipes and fittings is a particularly problem. The lower percentage of breakdowns associate with the pump head suggests that accessible components are more readily repaired (Mbamali, 1998).

The criteria for judging hand-pumps performance used by the World Health Organization (WHO)/UNICEF Joint Monitoring Programme – JMP (WHO/UNICEF-JMP,2000) classifies a pump as functioning if it works for more than 70 percent of the time and it is repaired within two weeks of breaking down. Even within these generous criteria, the JMP reports that only 70percent of rural water supply systems were functioning between 1990 and 2000 in Africa and 83percent in Asia.

Irrespective of the cause of hand-pump failures, they result in endless inconvenience and added health risks to the rural communities unless a workable maintenance solution is in place. The lack of this interface lay behind the poor performance of many early IDWSSD hand-pump projects and exposed the inherent weakness of the supply-side driven projects.

3.10 The ascendency of electric submersible pumps

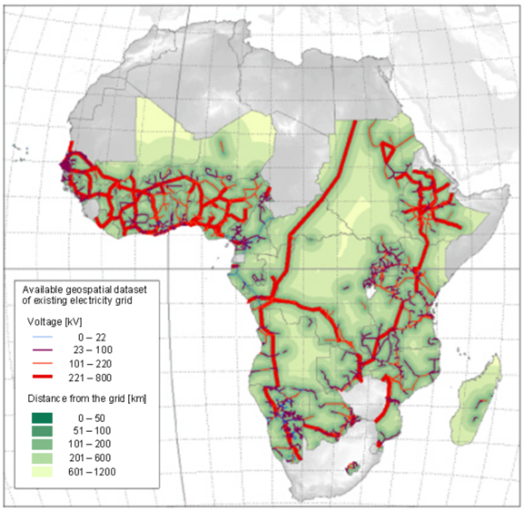
As problems with hand-pumps were emerging, progress in electric submersible borehole pumps had rapidly evolved from the late 1940s when the first 250 to 600 mm diameter pumps were developed for urban water supplies and mine dewatering. The focal design problem with the submersible pumps was creating a waterproof seal around the rotating motor shaft. Mercury-filled seals were used on the first motors but as technology advanced, closer-machined mechanical seals were developed, and finally oil-filled motors provided a robust solution to the sealing challenge. By 1960, manufacturers began to market a wide range of efficient small-diameter pumps. Commercial irrigation farmers, however, were hesitant to replace their known entities with untested pumps that required access to specialist repair facilities.

In the 1970selectric submersible pumps coupled with diesel generators were being increasingly used for rural water supply purposes in Africa and Asia with variable results. Exceptionally at Dubti in Ethiopia, in 1988 one such pumping set had been in daily use for over 14 years with the minimum maintenance and no overhaul (Jones, 1990). The normal lifespan for similar pumping sets was less than 5 years. From the mid 1970s, the expansion of rural electrification networks saw even greater use of submersible pumps (Box 7). Advances were also made with the introduction of precise, more robust and user-friendly, electronic-pump motor starter and protection switches to handle pump overloads.

Submersible pumps opened up the opportunity for solar powered photoelectric pumping with the first commercial sets being marketed in the early 1980s. Initially photovoltaic cells were expensive with a low efficiency at around 2 percent: this is has been improved to 9 percent. Matched with either DC or AC electric submersible pumps, solar power can produce up to 250 m^3/day against heads of 200 m. In areas with less dependable solar radiation, shaft driven positive-displacement, progressive cavity pumps are preferable to submersible turbine pumps as they will pump water work across a wider range of shaft rotation speeds.

Box 7: Rural Electrification – Opportunities Missed and Open

In 1988, 132 kV electric power lines, commissioned in the mid 1980s to supply the Kombolcha Textile Mill and Dese, follow 150 km of the Ethiopian Highway E1 between Shewa Robit and Dese. They passed over a string of local rural market towns and administrative centres with populations of several thousands but, with substations widely spaced, 33 kV supplies reached very few communities. This limited the number of communities that could benefit from mains electrification under the DfID Welo Well Rehabilitation Project and appeared a missed opportunity.



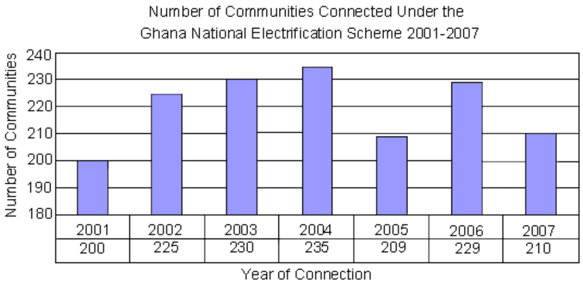


Table B7-1 (above): Progress 2001-2007 on rural electrification – Ghana. (Adapted from Abavana, 2008)

Figure B7-1 (left): Rural electrification distribution in sub Sahel Africa (from Szab´o et al., *2011)*

The design of a European Union(EU) water supply and sanitation project implemented in 40 small towns in Ghana specifically aimed to take advantage of the first phase of the rural electrification programme in the Central and Western Regions. The project followed the Western consultancy pattern with pre-feasibility, feasibility and implementation phases tailored to conform to the client's practical design, operation and maintenance guidelines. The project ran from 2000 to 2012. Preparation took 24 months, prefeasibility study and feasibility studies required 33 months and implementation lasted 54 months. The total cost was ca. 17 M Euro. The extended implementation period led to community discontent: the communities had to raise 5 percent of construction costs up front to qualify for inclusion in scheme. This was demanded during the feasibility phase and handled by community water committees who were embarrassed by the 4 or 5 years of inaction between revenue collection and the arrival of the construction consultants and contractors.

This type of development is questioned by Vaa (1993) who believes such projects should follow the 1970's World Bank Technology Advisory Group model, based on the recommendations of Sounders and Warford (1976). This model initially only aims at substantive improvement of existing supplies as opposed to fully-fledged and engineered schemes. In the EU project, each town had several existing boreholes constructed under a 1988-89 German-aid project that constructed 3 000 boreholes fitted with VLOM hand-pumps. In several cases these wells were suitable for equipping with an appropriate submersible pump for the planned urban piped-water supply but, if a lesser level of service had been agreed for the EU project, many of the frequently broke hand-pumps could have been replaced with single phase 98-mm-diameter electric submersible pumps producing 2 to 6 m^3/hour and feeding to a small storage container. As the pumping head is unlikely to exceed 50 m, the power consumption of 0,37 to 0,75 kW motors is low. A maintenance-free pump operating life in excess of 5 years plus the small diameter rising main (optimal 40 mm), are usable power cable and the possibility of using a pre-pay electricity metering (potentially including a built-in supplementary charge to cover future maintenance and replacement costs) negate many of the operational problems encountered at community level. Other advantages include rapid, low up-front, implementation costs, relatively simple technology involved with the starter switch and very little delay between community consultation and pump installation. The technology also allows the communities to consider solar and wind power alternatives and to install their own water distribution pipelines if inclined. Finally, with appropriate monitoring of the pumps and community management will provide concrete feasibility data for subsequent expansion to a full pipe supply.

The past and planned expansion of rural electrification in Ghana (Table B7-1), coupled with the newly completed comprehensive groundwater inventories for many regions and a manageable level of funding, should allow a rapid replacement of the difficult to maintain, broken hand-pumps with submersible pump installations as an intermediate step towards the implementation of fully engineered piped-water supplies. It also preserves the value of the past borehole drilling programmes. The simplicity of the scheme places it within the capabilities of community water management committees and certainly within the scope of the local supply chain. The adoption of similar pumps for rural irrigation in India shows the practicality of the model. Figure B7-1 shows the scope for similar schemes to follow on the heels of all rural electrification programmes across Africa and elsewhere.

3.11 Diesel powered shaft-driven pumps – A dying culture

With obvious efficiency and installation advantages over shaft driven pumps, by the mid1980s electric submersible pumps were replacing line-shaft pumps for urban water supplies. At the end of the 20th century, covering a very wide range of yields and heads, submersible pumps had achieved market dominance. Relatively inexpensive, easy to install and with a maintenance-free life-span of 10+ years, the use was further advanced by the spread of rural electrification.

The 1980s saw the economic assessment of groundwater production shift to whole-life costing (Hydraulic Institute, Europump and US Department of Energy, 2000). This shows the energy costs to far outstrip the capital cost of the borehole pumps. Electric submersible pumps benefit from being virtually maintenance-free compared to direct-drive diesel or liquid petroleum (LP) gas engines that require regular servicing and have a shorter working life. The 1980s, therefore, saw a rapid worldwide take-up of submersible pumps for groundwater irrigation. Coupled with centre pivots large-scale farmers were able to improve crop yields on all continents. In Nebraska, between 1972 and 1986, the number of centre-pivots in use rose from 2 700 irrigating 151 200 ha to 26 208 irrigating 1 360 000 ha (Kepfield, 1993). In Libya, submersible pumps were central to the development of the groundwater resources of Nubian Aquifer System that had been identified in the 1960s. To a large part, submersible pumps coupled with rural electrification considerably added to the productivity of India's 1970s Green Revolution.

At the close of the 20th century in India, China and the USA, the number of irrigation wells in use continued to rise. Table 2 provides a snapshot of the expansion and transitions in the irrigation pattern and costs in Nebraska. The growth in diesel-powered pumps indicates the continuing use of line-shaft pumps as new land is opened up for irrigation in response to an increase in agricultural price subsidies and a push to soya- and maize-based biodiesel production.

Year	Number of Pumps	Electricity		Diesel		Gasoline		Natural gas		LP Gas	
		Cost / ha	**ha irrigated**	**Cost / ha**	**ha irrigated**	**Cost / ha**	**ha irrigated**	**Cost / ha**	**ha irrigated**	**Cost / ha**	**ha irrigated**
1998	47 643	55,00	841 250	45,20	54 497	27,55	3 454	48,7	390 805	39,33	3 400
2003	69 583	70,00	1 168 830	74,23	920 974	113,63	551	97	483 058	73,93	214 924

Table 2: Nebraska groundwater irrigation statistics and sources of energy abstracted from the US Census of Agriculture, Farm and Irrigation Surveys of 1998 and 2003

3.12 Power supply and the electro-submersible

In India, subsidies were directed at farm inputs, mainly fertilizer and electricity. From the early 1980s, this resulted in an expansion in groundwater irrigation into areas previously limited to rain-fed or small-scale surface-water irrigation farming. Initially, electric-powered centrifugal suction pumps installed in hand-dug wells were sufficient to supply irrigation water for most farms. By the mid 1980s, farmers responded to declining groundwater levels by drilling boreholes in the bottom of hand-dug wells and setting the pumps lower in the well. As in the USA, further declining groundwater levels required a shift to shaft-driven or submersible pumps and the farmers in India were faced with the increasing costs of new equipment, higher lifting heads and longer pumping hours per day. By the late 1990s, the serious doubts voiced by the groundwater specialists about the sustainability of the groundwater abstraction were largely diverted by local politicians who relied on the goodwill of their farming electorate.

In the neighbouring countries of Bangladesh and Sri Lanka, farmers were encouraged to take up groundwater irrigation by subsidised diesel-pump purchase schemes.

Estimates by the end of the 20th century suggest as much as 20 percent of energy worldwide was used by pumps of various types (Hydraulic Institute, Europump and US Department of Energy, 2004). This high energy use brought into focus the need to improve the efficiency of both the pumps and pump motors. While there is no breakdown of what percentage was used to pump groundwater, it is possible that it was 1 or 2 percent, and almost certain that at least 75 percent of this usage was for pumping groundwater for irrigation. The remaining being split between urban and rural water supplies, land drainage, mine and construction works de-watering and a small percentage for air conditioning and heating.

3.13 Low head suction pumps – Low intensity scavenging of shallow groundwater

By 2000, various pumping technologies had been developed to skim either good quality groundwater from the top of saline groundwater bodies or hydrocarbon or other pollutants from contaminated aquifers. The skimming technology has close affinities to construction industry dewatering requirements that involve controlled lowering of groundwater levels. However, limited use is made outside the small island context of well points and suction pumps to abstract groundwater from the shoestring river alluvial tracts for piped domestic water supplies (Svubure *et al.*, 2011). In the 1970s, well points were used relatively extensively along the Zambezi floodplain in Western Province of Zambia, and the town of Mongu in Zambia was provided with such a system. To quote the 1974 Annual Report of the Zambian Department of Water Affairs (DWA):

> Under the co-operative and village water supplies programme well-point sinking and the installation of Uganda hand-pumps continued and in all 135 well-points were completed successfully, 24 more than in the previous year. There were fewer abandoned well-points as it was possible to use the small percussion rig to drill deep enough to reach the water table where the jetting method had failed. However, this is slower than jetting and expensive on labour.

Most groundwater decontamination systems depended on the steady low-yield continuous-abstraction pump characteristics of gear, peristaltic and bladder pumps. Compressed-air-powered pumps are commonly used for hydrocarbon recovery but continuous porous fibre belt recovery pumps that soak up pollutants mirror the long established rural water supply rope pump mechanism.

4. Technology Baseline and Associated Cultures of Use in the 21stCentury

4.1 Regulation and consolidation of pump manufacture

Established in 1960 by European pump manufacturers, the Europump Association now monitors industry compliance with the EU directives covering machinery efficiency that have been issued since 1989. The expansion in globalization and consolidation of the international pump industry during the first decade of the 21stcentury has seen Europump work in partnership with other manufacturing organizations including notably the United States Hydraulic Institute. Evolving improvements cover hydraulic design, motors and computerized controls aimed at improving efficiency. In many parts of the world, a range of constraints forces users to rely on the cheapest available pumps that tend to be inefficient and have a short working life. Huang, Rozelle and Hu (2007) describe the growth in response to a worldwide demand of an irrigation-pump manufacturing cluster in Daxi, China.

The 21stcentury sees emphasis placed on the sustainability for all forms of development coupled to rising concerns with resource management and climate change. The push to develop integrated water resources management plans has to be seen against the limited information on the resource base and current lack of understanding of the hydrological processes in many parts of the world.

4.2 Improved pumps and groundwater over-development, inevitable self-perpetuating trends?

The potential for expanding agricultural production is being explored against a background of almost universal groundwater level decline in existing areas of groundwater irrigation. In some developments, this has been planned for – e.g. the exploitation of the Nubian Sandstone in Libya –but in most, there has been no pre-planning and the impact of over abstraction has had major social and economic consequences. This problem becomes more pressing where uncontrolled groundwater abstraction encroaches on urban water supplies as seen in Sana'a, Yemen (Charalambous, 1982, World Bank Group, 2010).

The International Water Management Institute (IWMI, 2007a) classification of groundwater irrigation economies identifies the main indicators and economic attributes to the developments, but it does not provide a guide to the management of the resource. In addition, traditional pastoralists' livestock-watering needs have always been closer to rural domestic water supply than irrigation unless there is a heavy dependency on irrigated fodder production.

Across Peninsular India and elsewhere in Southeast Asia, the green-revolution-based groundwater irrigation, has received, and continues to receive, a high national priority. The virtually unrestrained groundwater abstraction has emerged as unsustainable in resource terms in many of the main groundwater irrigation areas (Figure 2).Seeking to control the groundwater irrigation abstraction has to recognize that the farmers' choice of crops, irrigation practices and need for water are strongly orientated by subsidies and tax breaks.

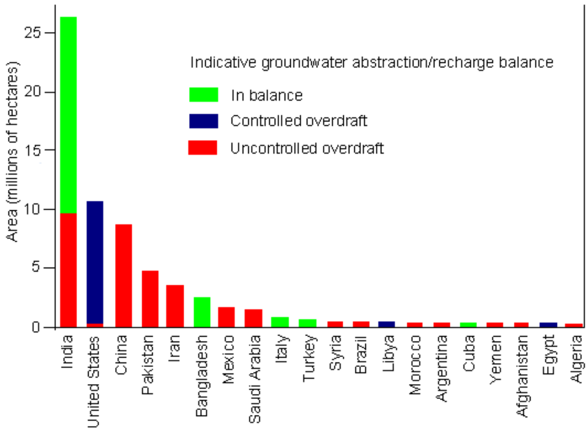


Figure 2: Area under groundwater irrigation by country: 1993-2002 with subjective view of irrigation withdrawal-recharge balance. Areas exploited under the rule of capture considered as being effectively uncontrolled developments (based on IWMI, 2007a and FAO Aquastat, 2005 data).

4.3 The US High Plains Aquifer wilful over exploitation

Since 2000, groundwater abstraction from the US High Plains Aquifer has continued to grow and groundwater levels continue to decline (Figure 3) under a regime of strong, technically-based and enforced groundwater rights legislation that, in most States, embraces controlled over-abstraction as an accepted policy. The highly motivated commercial farmers ensure high pump efficiencies and use diesel-powered line-shaft turbines to open up new areas for groundwater irrigation.

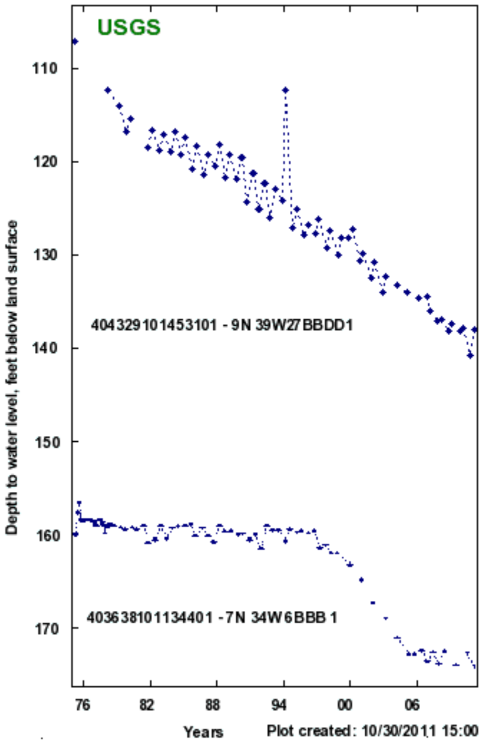
As the farmers in the Northern High Plains States continue to optimize the quantity of water available for irrigation, the municipal water supply companies are acutely concerned with the water quality. The impact of agricultural activities on both surface and groundwater quality has steadily increased since homestead farming became agribusiness. The consequences of further expansion in biofuel feedstock production may well undo any of the other environmental benefits achieved. Greater use of limited and deficit irrigation practices could lead to economies in water usage and enable an expansion in the irrigated area, but the impact of the additional agro-chemicals needed, will stretch in to the future. How much damage to the environment will take place before the “cleanest production pathways” and the lowest production carbon footprint are achieved remains to be seen (Roberts, Male and Toombs, 2007).

The situation under the rule-of-capture water rights legislation in the Texan High Plains has seen some groundwater irrigation areas retired due to uneconomic pumping costs or deteriorating water quality. The Texan Groundwater Conservation Districts (GCDs) main approach to resource conservation applies some form of depletion formula based on retaining a percentage (usually 50 percent) of the existing groundwater in storage at a certain date in the future (typically2050). In 2002, following legal and technical processes, the Mesa Water Group obtained permits in 2002 to sell 39,5 Mm^3/year of groundwater to metropolitan areas in Texas under the established (Texas) Panhandle Groundwater Conservation District regulations (Freese and Nichols, Inc., 2006). The conditions of the permit were as follows:

1. Pumping must be limited to one-acre foot per year per surface acre (3 005m^3/year).
2. Fifty percent of the 1998 aquifer volume must remain in place in 2048 (“50% Rule”).
3. Water may be sold only for municipal use within Texas.
4. Wells must be spaced and located to minimize impact on neighbours.

This represents the current limit to the control of groundwater pumping in the State of Texas and, to a large extent, worldwide where the rule of capture applies in lieu of other legislation in force.

The depth of scientific study involved in the quantification of the large-scale groundwater abstraction in the USA is huge, but the ultimate verification of the success of management plans depends on a well-funded and assiduous long-term monitoring programme. Whatever impact on-going biofuel feedstock production may have on the surface and groundwater resources, the US Geological Survey’s National Water-Quality Assessment Program (USGS – NAWQA, 2007) and the local Groundwater Management Districts (GMDs) will be engaged in monitoring quantity and quality parameters. The speed at which groundwater levels decline or recover across the High Plains will show if the GMDs depletion assessments and rules are appropriate. It seems certain farmers will maximize their abstraction rights and irrigation efficiency. It also seems certain that diffuse contamination levels in surface water and groundwater bodies will continue to spread while many of the known-point contamination sources and plumes will be contained and cleaned up.



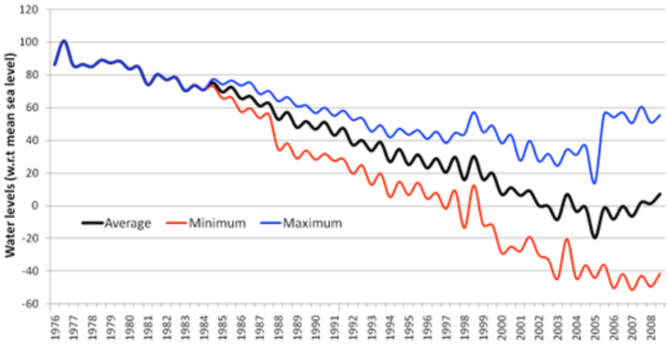


Figure 3: Groundwater Hydrographs from the High Plains Aquifer in Nebraska (left scale in feet) and Gujarat (above scale in metres) from 1976 to 2008 showing the impact of over abstraction on groundwater levels.

The lower Nebraskan example shows the rapid impact as new areas are brought under groundwater irrigation. Nebraska graphs from USGS: http://groundwaterwatch.usgs.gov/StateMaps/NE.htm and Gujarat graph from: http://water.columbia.edu/?id=India&navid=Gujarat

To achieve future equitable groundwater management, the existing water legislation in the 8 High Plains States will continue to evolve. The options available, however, are limited and will be met with objections from special interest groups and politicians. The general consensus is that groundwater levels and baseflow will continue to decline even if substantial cuts are made to groundwater irrigation (US Bureau of Reclamation, 2007). The substantive options available are:

- retirement of surface water irrigated lands;
- retirement of groundwater irrigated lands;
- retirement of groundwater irrigated lands with lagged depletions;
- introduction of interruptible water diversion rights.

All these options will involve some form of monetary compensation for surrendered water rights.

Finally, although the High Plains Aquifer provides valuable technical, legal and economic water resource development and management models that could be applied elsewhere, the regional population density has remained very low at 3,5 per km^2 since 1960. Also the differences in the climatic setting and hydrogeology must be taken into account. The Nubian Sandstone Aquifer of North Africa and large outwash tracts in Central Asia and South America are among the few potentially comparable groundwater occurrences.

4.4 Power supply and the electro-submersible – Progressive 'privatization' of supply

4.4.1 Sustainable or unsustainable, uncontrolled groundwater development in Southeast Asia

In 1960, around 100 000 centrifugal suction and low lift pumps were used for groundwater irrigation in India. With virtually no legal restrictions on groundwater abstraction, by 2000 the number of pumps had risen to over 19 million, and by 2007 over 25 million pumps were in use. The associated growth in groundwater abstraction, irrigation area and electricity usage (Box 8) has been instrumental for the steady decline in groundwater levels shown on Figure3. No distinction is made between electric pump types in published references: Many in the major river basins they are either suction centrifugal or shaft-driven turbine pumps. The number of electric submersible pumps is not recorded but their widespread used since 1980 is largely responsible for the decline in groundwater levels in many Indian Peninsular States.

Beyond the impact of the Indian pump subsidies on groundwater levels, is the question of over-irrigation. Although statistics for the area under groundwater irrigation are readily available, similar abstraction data is elusive: the Central Groundwater Board of India (CGWB), however, quotes countrywide totals of 115 km^3 in 1995 and 231 km^3 in 2004 (of which 213 km^3 is assigned to irrigation use). These equate to an annual irrigation application of 398 mm in 1995 and 564 mm in 2004.

Hidden behind these statistics are problematic facts facing the irrigators and the Indian Central and State Governments:

- Access to pumps and energy supplies;
- The wide range of farm sizes and social standing of the farmers;
- The reliability of the electricity supply;
- The energy efficiency levels of the pumps, motors and ancillary pipework;
- The role of subsidies in the agricultural sector;
- The extension of groundwater irrigation into the crystalline Basement and extrusive igneous rock areas of Peninsula.

4.4.2 Access to pumps and energy supplies

In rural India, the early, bottom-up demand created by individual investment in wells and pumps for groundwater irrigation was invigorated under the impetus of the “Green Revolution”. This led to a rapid rise in widely disperse rural agricultural energy consumption that overloaded the low tension (LT) distribution network capacity. This imbalance was entrenched by the introduction of flat rate electricity tariffs to lessen cost of metering that accounted for some 40% of the generating boards’ outgoings (Shah, Giordano and Mukherji, 2012).
Starved of investment, the generation boards in the eastern Indian States found upkeep of the LT distribution impossible and much of the system was abandoned leading to the 1985-98 rural de-electrification (Box 8).

After this rural de-electrification in the high rainfall eastern States of India diesel-pump-based irrigation became dominant (Box 8). Subsidies aimed at the poorest farming communities for well drilling and irrigation pump purchases were introduced (Shah, 2001). When implemented, the subsidy schemes in some participating eastern States were initially hampered by bureaucratic inefficiencies, and the poorer farmers preferred to purchase their own diesel pumps. After reviewing the scheme, the states adopted a system where the pump dealers became the lynchpin of the operation, handling the paperwork and organizing the drilling contractors.

Later commercial banks became involved and arranged loans to the farmers with 3 to 5 year repayment terms. The success of the scheme can be seen in the prevalence of diesel pumps shown on Figure B8-1. In West Bengal for example, the ratio of diesel to electric pumps is 9 to 1. Almost all the new electric pumps installed since 1991 belong to the wealthier landowners who could afford the high connection costs and consumption tariffs charged by the Generating Boards (Figure 4). They also frequently profit by selling irrigation water to the poorer local smaller landowners (Figure 5).

Box 8: Groundwater Irrigation in India

Countrywide in 2007, 25 percent of the farmers in India had tube wells, and an additional 50 percent bulk purchased groundwater for irrigation (Shah, 2007a). Fifty-seven percent of the pumps in use were electrically powered and 43 percent were diesel-powered. Figure B8-1 shows the distribution of these pumps in relation to the motive power. This distribution reflects past phased changes in the rural electrification network:

- Phase I:1935-1965, struggle for demand creation;
- Phase II: 1965-1975, early expansion in electric tube wells;

- Phase III: 1975-2004, take-off in GW irrigation under flat tariff;
- Phase IV: 1985-1998, de-electrification of rural eastern India;
- Phase V: 2002-to date, reversal under energy demand reduction scheme.

In areas with robust rural electric supplies, groundwater pumping accounts for around 40 percent of the energy consumed. In areas with low or poor electrical supplies the pumping accounted for around 10 percent in 1998 (CMIE, 2003). To maintain agricultural production, subsidized diesel-pump purchase was provided in the areas under the de-electrification phase. The rise in pump numbers led to increased in the area under irrigation (Figure B8-3), groundwater abstraction (Figure B8-2) and electricity usage.

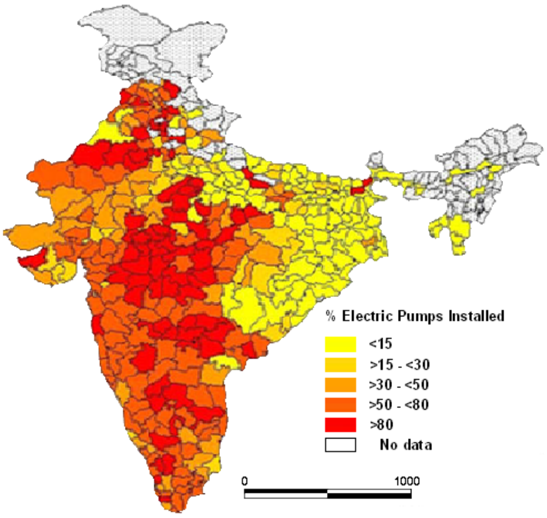


Figure B8-1: Percentage distribution of electric pumps in India (from Shah, Giordano and Mukherji, 2012).

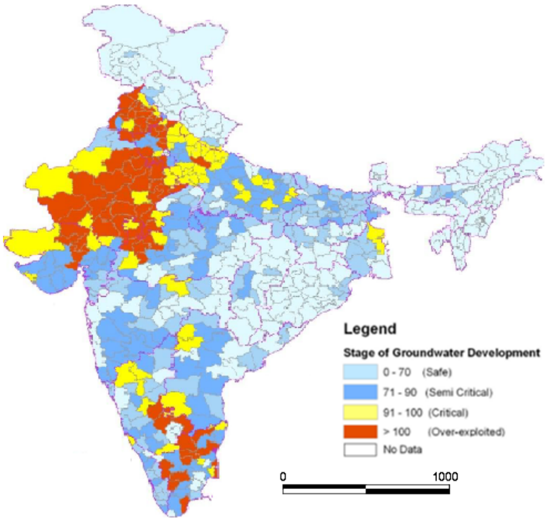


Figure B8-2: Groundwater development levels (from CGWB-MoWR (GoI), 2006).

Cuts to the rising cost of continuing the input subsidies inherent to the green revolution have to be balanced against the need to maintain social stability in the rural areas. In 2011, subsidies covering the irrigation and electricity costs reached 75 to 90 percent of the wholesale market value (Figure B8-4). Reducing the Government cost of subsidizing maintenance and expansion of groundwater irrigation is being addressed by a variety of initiatives carried out at both the State and Central level. The necessary adjustments, however, face strong local community and political resistance.

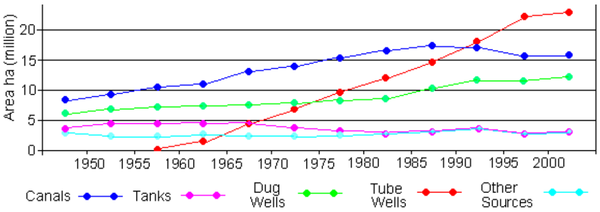


Figure B8-3: India area under irrigation and water sources (Government of India, 2003).

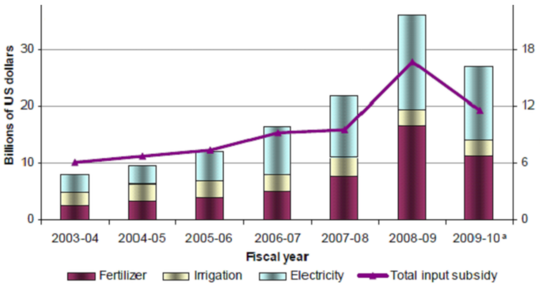
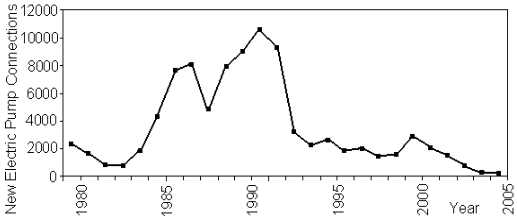


Figure B8-4: India Agricultural Input subsidies in USD and percentage of agricultural output value (Grossman and Carlson, 2011).

Faced with diesel price rises, many less affluent farmers in Assam are effectively withdrawing from irrigation and selling their irrigation pumps to newly-formed, minority, start-up farming groups. Growing social and political recognition of the need to redress the disparity between subsidized electricity and diesel costs will inevitably lead to further rethinking of the various State subsidy practices. Irrigators in eastern India are pressing for a diesel ration or a subsidized price regime.



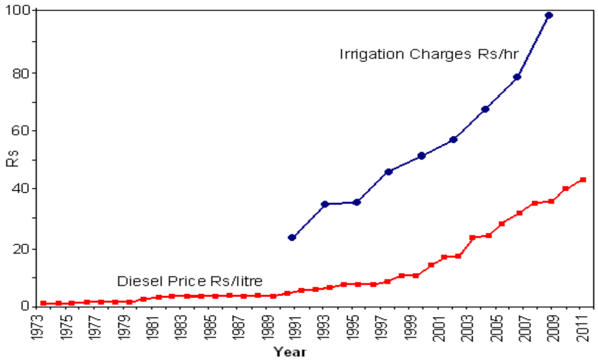


Figure 4: East Bengal new electric pump connections 1979 – 2004 (adapted from Mukherji, 2007).

Figure 5: Uttar Pradeshdiesel and irrigation water price rises (adapted from Shah, 2007b).

The results from the 1998 National Sample Survey Organization (NSSO) show the groundwater availability and electricity supply across Western and Peninsular India under significant pressure (Figure 6). The negative view of the supply situation appears to be largely unconnected to the unit cost of the agricultural electricity supply. The subsidized electricity prices below around 30 paise/kWh (ca. USD 0,007 at 2012 rates) are clearly the main reason for a wastage of resources (Shah, Giordano and Mukherji, 2012 who quote an average generating board basic unit production and delivery costs of USD 0,04.

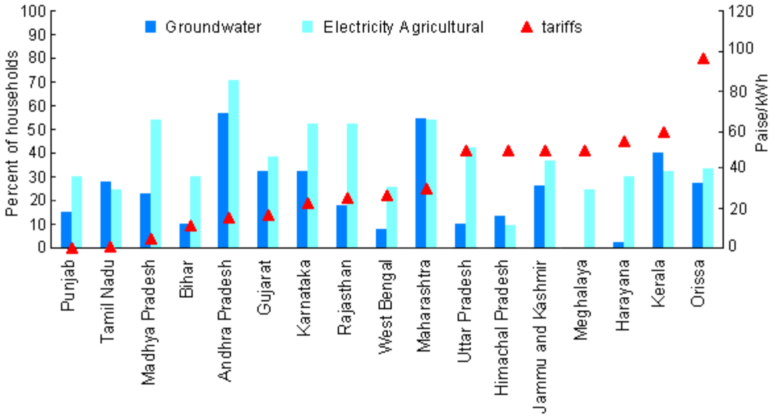


Figure 6: Farmers reporting inadequate access to groundwater and electricity in 1998. The Indian States are ranked by their agricultural electricity tariff (redrawn from Birner, Surupa and Neeru Sharma, 2011).

4.4.3 Wide range of farm sizes and social standing of the farmers

Figure 7 is based on the 2003-2004 NSSO land and livestock data and shows that these farming groups in Gujarat, Maharashtra, Andhra Pradesh and Karnataka represent more than 70 percent of the farming households and that they own less than 15percent of the land. The figures for the marginal farmers are considerably worse: they represent around 50percent of the households and own less than 5 percent of the land. Their access to groundwater is largely dictated by the geomorphological setting of the individual farms. Those close to the water divide and along the upper interfluves should receive reasonable seasonal recharge and support low yielding hand dug wells and shallow boreholes. Lands with better developed and thicker weathered regolith aquifers across the lower interfluves and on the valley floors are likely to be the target for competitive groundwater abstraction by the owners of larger farms. Marginal and small farmers with limited land in these settings are unlikely to afford the deeper boreholes and the higher cost of pumping, unless they associate with neighbouring farmers to equitably share the available resource.

The land ownership pattern and size of farms in the Ganges Basin States is shown on Figure 8. As seen across Peninsular India, the land redistribution programmes in West Bengal, Jharkhand and Bihar, and to a lesser extent in Uttar Pradesh, have benefitted the marginal, small and medium farm holdings. This contrasts with the position in Punjab and Haryana where less than 10 percent of the medium- and large-scale farmers control over 50 percent of the land.

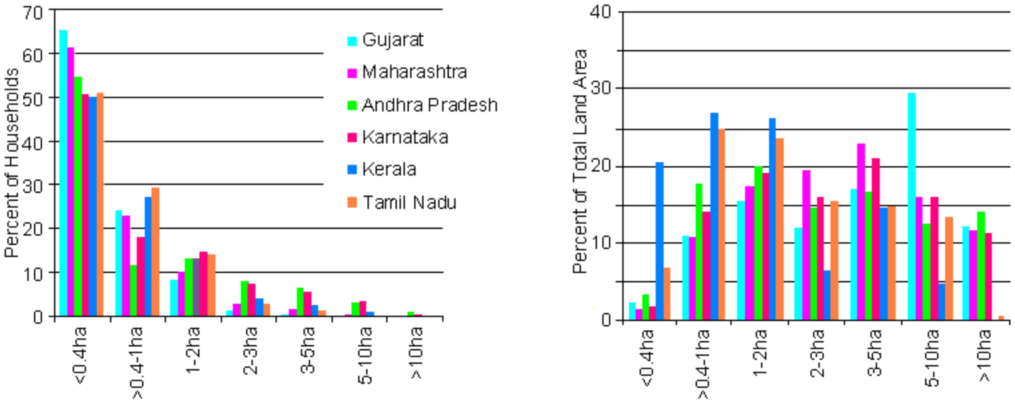


Figure 7: Peninsular Indian States – percentage distribution family farm sizes and percentage areas owned by marginal farmers (>0.4 ha), small farmers (0.4-1 ha), medium farmers (2-5 ha) and large farmers (>5 ha) (data from Rawal, 2008). The marked difference between the Kerala and Tamil Nadu family holdings reflects the State post-colonial land redistribution and the effect of the land-holding size cap.

The rural de-electrification of the eastern states of the Ganges Basin and the introduction of subsidized diesel pumps and tube-well programmes coupled with favourable hydrogeological conditions has been covered by Shah (2001 and 2007b) and Mukherji (2007). The shared consensus is that groundwater irrigation remains viable without excessive electricity subsidies. Although these analyses accept a role for a groundwater market, experience from Punjab suggests this could be socially and politically unacceptable in the long run as indicated by Sarkar (2011) who states:

> The consequences of negative groundwater draft have mostly been viewed as an ecological disaster, but the externalities of groundwater depletion pose greater concern for socio-economic equity in the access to this resource. This empirical analysis signifies the concerns for the livelihoods of farmers, when the cost of depletion is disproportionately borne by the resource-poor farmers as they are unable to invest in capital and technology and are hence denied the benefits of groundwater irrigation that is subsidised by free electricity. This situation is perpetuated with further scarcity leading to unequal economic returns and, finally, takes the most exploitative form where the "large landlords" also emerge as "water lords" through surplus accumulation, forcing the small and marginal landholders to become landless agricultural labourers.

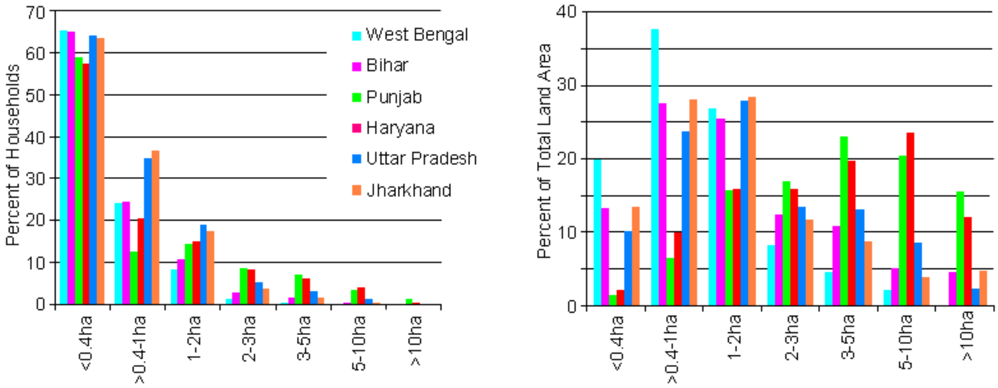


Figure 8: Indian Ganges Basin States – percentage distribution family farm sizes and percentage areas owned by marginal farmers (>0.4 ha), small farmers (0.4-1 ha), medium farmers (2-5 ha) and large farmers (>5 ha) (data from Rawal, 2008).

Table 3 presents the basis for this bleak but substantiated view of the situation in the Punjab State. The data is from three villages within the alluvial floodplain of the Ganges River system where the depth to groundwater ranges from 12 m below ground level (bgl) at Tohl Kalan to 18 m bgl at Gharinda and 46 m bgl at Ballab-e-Darya. It is considered that this analysis may well prove as valid as that for the domestic water supplies in East Africa as described by White, Bradley and White (1972).

Sarkar (2011) concludes that landowners without their own secure source of irrigation water are considerably disadvantaged. He observes that landowners or farmers leasing in land, and who are dependent of the local water market, have consistently lower crop yields than the self-sufficient landowners. This is considered to undermine the arguments that water markets work well and are largely self-regulating. As already indicated, water buyers are unlikely to have security of supply or guarantee to an equitable price (Figure 5).Singh (2007) identifies a similar potential insecurity attached to the water market available to the marginal landholders in Rajasthan.

	Marginal farmer	**Small farmer**	**Medium farmer**	**Large farmer**
Mixed irrigation village (Tohl Kalan)				
Number of farmers	18	26	38	18
Average number of operational tube wells %	0,72	0,96	1	1
Average depth of tube well m	45	58	70	98
Water purchased no.	4	5	9	2
Water sold no.	2	7	6	6
Land leased out no.	11	23	13	50
Land leased in no.	6	0	0	0
Returns on investment cost %	2,33	2,48	2,87	2,94
Tube well irrigation village (Gharinda)				
Number of farmers	4	6	32	58
Average number of operational tube wells %	1	1	1,06	1,34
Average depth of tube well m	37	56	74	96
Water purchased no.	4	6	1	0
Water sold no.	0	0	0	6
Land leased out no.	0	0	9	17
Land leased in no.	0	0	0	2
Returns on investment cost %	3,06	3,10	3,70	3,82
Tube well irrigation village with depletion problems (Ballab-e-Darya)				
Number of farmers	32	15	32	20
Average number of operational tube wells %	0,41	1	0,91	1,8
Average depth of tube well m	46	58	67	109
Water purchased no.	18	2	12	1
Water sold no.	1	1	11	12
Land leased out no.	0	0	13	20
Land leased in no.	28	7	0	0
Returns on investment cost %	1,09	1,99	2,00	2,94

Table 3: Subjective assessment of basic technical and economic factors influencing groundwater irrigation farming in 3 village communities in Punjab, India (data from Sarkar, 2011).

Key

Economic impact	Negative	Neutral	Positive
Low	🟧	🟨	🟩
Moderate	🟧	🟨	🟩
High	🟧	🟨	🟩

Paths to resolving the groundwater irrigation equalities in western Ganges Basin may include reorganizing the land holdings through land reform and/or bringing the groundwater market under an effective equitable regime. A modified West Bengal tube-well and pump subsidized scheme could be adopted to enable groups of marginal and smaller farmers to independently develop appropriately specified tube wells for groundwater abstraction on their consolidated landholdings. Ideally, over the duration of the bank loan, the construction and operation of the tube wells could be undertaken by private contractors, and the farmer group would continue to receive electricity subsidies at a steadily declining rate until the loan is repaid. Ultimately, this will mean the loss of the free electricity calculated to be worth around USD 800 per hectare (Narula *et al.*, 2011), but the investment returns shown on Table 3 suggest that such approach could be viable.

4.5 Elasticity of demand – The energy equation and alternative energy sources

Many Indian State electricity boards are responsible for providing heavily subsidized electricity to the agricultural sector. The subsidized tariffs can be a flat rate based on pump capacity or metered and, in some States, waived completely. Running at a loss, the lack of capital available to the State electricity boards means the generating capacity and distribution grids are overloaded. Attempts by the generating boards to restrict the electricity used for irrigation pumping by severely curtailing the number of hours of three-phase supply while maintaining the single- and two-phase supplies were met by widespread consumer use of phase converters to reinstate quasi-three-phase supplies for their pumps (Shah *et al.*, 2008). This substantially added to surges and dips and to frequent interruptions to the supply. These deficiencies have impacted on the farmers in their selection of pumping equipment and abstraction routines. In practice, oversized pumps are used to maximize abstraction during the periods when electricity is available and to minimize motor burnout due to supply fluctuations (Padmanaban and Sarkar, 2005). A 7,5 kVa pump with inefficient thick wire motor windings is seen as preferable to an irrigator instead of a more efficient but less robust 3,5 kVa motor.

Despite these precautions, electric motor and transformer burnouts due to supply deficiencies are still common. Irrespective of the type of pump installed, burnout electric motor rewinds seldom match the performance of the new motor (Mukherji, 2007). A frequently quoted reason for over application of irrigation water is that farmers leave the pumps switched on all the time to ensure they pump water whenever the irregular electricity supply is working.

To evade the electricity supply problems, in 2003 the State of Gujarat launched the *Jyotirgram* scheme that essentially separates the electricity supply lines to the irrigation pumps from those to other users. The scheme, initiated by an IWMI study, has enabled the State to keep irrigation supply subsidies in place while controlling pump sizes and new connections. The advantages to the irrigators are a more stable scheduled electricity supply during the 30 to 50 days of peak irrigation demand. They pay a flat-rate tariff based on pump size, which is subject to periodic escalation. Outside the peak irrigation period, only 4 to 5 hours of electricity is supplied to the pump power lines. The scheme has achieved a substantial reduction in the cost of State subsidies (Figure 9), and the removed power outages have defused complaints from the irrigators over crop losses. However, the on-going decline in groundwater levels is pushing up the energy required to lift the irrigation water to the fields (Figure 10).

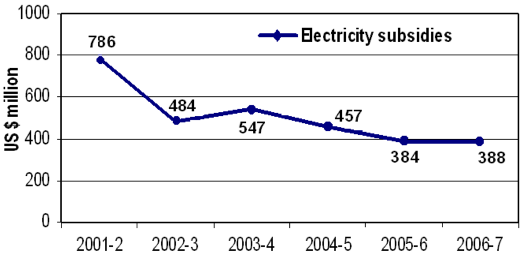


Figure 9: Decline in groundwater pumping subsidies cost to the State of Gujarat post implementation of Jyotirgram scheme (Tushaar Shah, 2007).

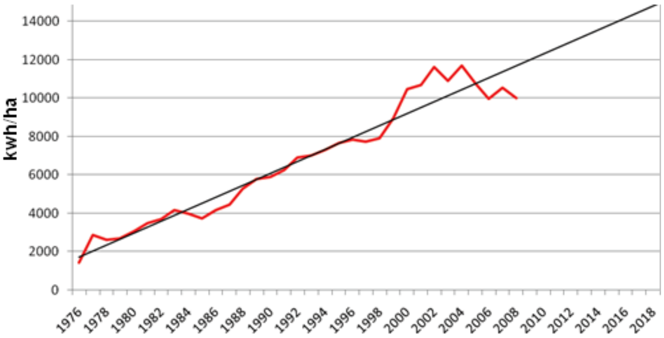


Figure 10: Gujarat – historic and projected cost per hectare of lifting 600 mm of groundwater of irrigation (from Grossman and Carlson, 2011).

4.6 Greater energy efficiency

Although the urban water-supply sector is currently the main beneficiary of the Distribution, Reform, Upgrades and Management (DRUM) project – funded by the United States Agency for International Development (USAID) – that is supporting the electricity generating boards, the problems facing irrigation farming are driven by a high consumer demand for a secure supply at a tariff that covers a fraction of the costs needed by the supplier to generate, maintain and feed a robust distribution network.

Most pumps are purchased from the farmers' own resources and, given the high cost of borrowing, the majority of small- and medium-scale irrigators in India are very price-sensitive. Life-cycle costs are not seen as a rational concern when purchasing electrical pumping equipment. This has opened up the market for cheap unbranded and locally manufactured pump-sets. These often come with the penalty of poor efficiency and durability (Reidhead, 2001; Tongia, 2007). With highly subsidized tariffs, the irrigators see little need to use the electricity efficiently. This problem of low irrigation-pump efficiency came to the fore in India during the early 1990s (Sant and Dixit, 1996) and remains high on the agenda. It is compounded by the use of undersized pipesand fittings that adds to hydraulic inefficiencies.

The potential for improving the estimated 27percent efficiency of electrical irrigation-pump systems has been estimated to be 7 percent, based on a number of retrofit measures (Ahluwalia and Goyal, 2003). The areas for improvement include better foot valves, replacement of high-friction loss pipework with low-friction uPVC pipes, replacing undersized pipes and fittings, using more efficient and correctly-sized pumps, motors and drive mechanisms. The impact of pipe losses is frequently overlooked by small-scale irrigators but can quickly add to the avoidable inefficiencies of their delivery systems. The savings are expected to be in the range of 30 to 35 percent and could cut pump average annual energy consumption of 4 500 kWh by 277 to 310 kWh, However, experience from the USA (Hanson, 1988) suggests that the efficiency savings will be not registered by the electricity supplier unless there are cuts in the pumping time that match the efficiency savings: this particularly applies under flat-rate tariffs.

4.7 Suction pumps – Low-lift agrarian societies

The hydrogeological conditions that support the widespread use of centrifugal suction (rotodynamic) pumps in the shallow groundwater areas of the lower Ganges Basin (Figure 11) are found across Asia outside Bangladesh and elsewhere worldwide. Although they are being seen as route to spreading small-scale irrigation developments across hydrogeologically suitable environments in Africa, suction pumps and internal combustion engine power losses (Table 4) have to be taken into account over the highlands of Central and Southern Africa.

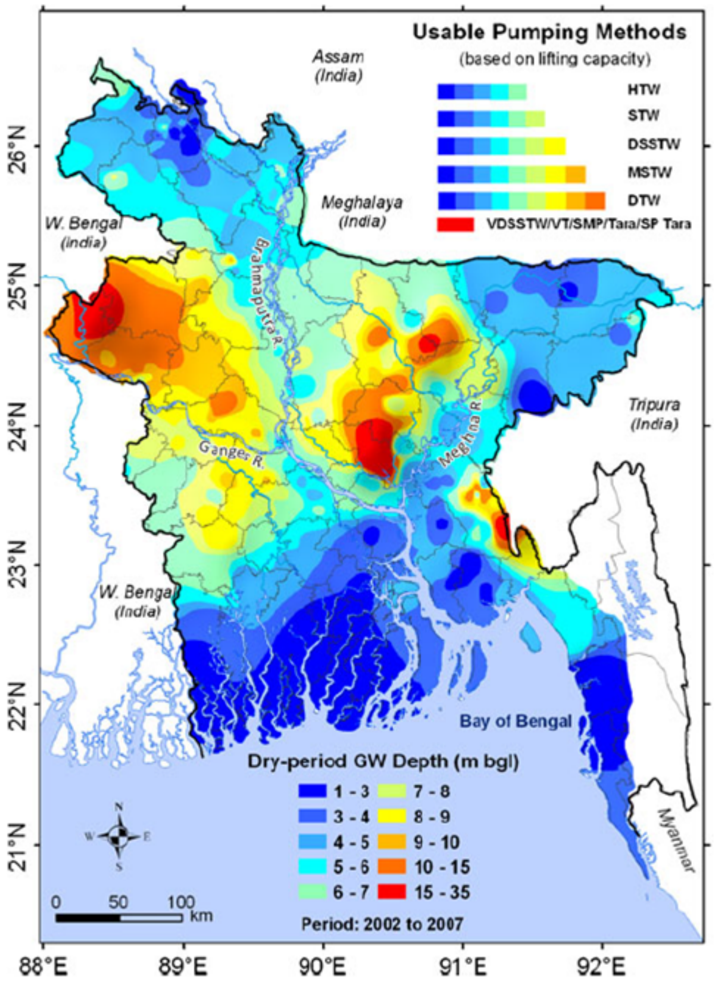


Figure 11: Distribution of static groundwater levels across Bangladesh (from Shamsudduha et al.*, 2011).*

Extract from original title: "Map shows the maximum depth (mbgl) to the recent (2002–2007) static water table in aquifers in Bangladesh. This map highlights the areas where currently available pumping technologies for drinking water and irrigation water supplies are (un?) usable during the dry season. HTW hand tubewell, STW shallow tubewell, DSSTW deep set shallow tubewell, MSTW mini-submersible shallow tubewell, DTW deep tubewell, VDSSTW very deep-set shallow tubewell, VT vertical turbine pump, SMP submersible pump, Tara Tara pump, SP Tara super Tara pump."

As the groundwater levels dropped below the range of suction pumps, users can mount the whole pump set down most hand-dug wells. However, a number of problems arise, including poor ventilation and cooling of pump motors, increased head losses and back pressures on the pump seals, vibration and difficulty in securing the pump set and finally flooding risks during high rainfall or run-off events. The historical balanced irrigation areas of Yemen have seen steadily increasing groundwater use and level declines. This has led to the replacement of the suction pumps by shaft turbine and electrical submersible pumps. Large-scale bi-lateral and international aid and loan projects since the 1970s have added to this trend.

Altitude asl m.	**NPSH m.**	**Flow reduction %**	**Discharge head reduction %**
0	7,6	100	100
600	6,7	97	96
1 200	5,9	93	91
1 800	5,3	93	87
2 400	4,7	91	83

Table 4: Effects of altitude above sea level (asl) on the Net Positive Suction Head (NPSH) and the reduction in efficiency due to the internal combustion engine power losses.

At the other end of the scale, NGOs developing groundwater for rural domestic and irrigation supplies employ a variety of man-powered pumps based on long standing designs, with the exception of the treadle pump. Based on a chain or rope pumps, treadle pumps are suitable for small-scale groundwater irrigation. Producing up to 1 l/sec they are promoted for small-holder irrigation in areas with shallow groundwater (Kay and Brabben, 2000; International Development Enterprises and Winrock International, 2002; Karekeziet *al.*, 2005; Mangisoni, 2006).

4.8 Alternative sources: solar and wind turbines

Introduced in the late 1970s (Ward and Dunford, 1984), solar voltaic pumps were initially held back by the cost of the solar panels. From the early 1980s, NGOs and bi-lateral aid grant programmes are promoting solar photovoltaic pumps (SPV pumps) and windmills as either pilot demonstration or localized development projects. These are often carried out in collaboration with specialist manufacturers. In West Africa, the Sahel region stretching from Mauritania to Niger has been the focus of a 15-year EU-supported regional solar programme– *Comité permanent Inter-Etats de Luttecontre la Sécheresse dans le Sahel* (CILSS) – that has implemented over 1 000 borehole-based rural schemes supplying between of 5 and 120 M^3/day (Figure 12).Mali has been the main beneficiary country with around 50 percent of the small piped schemes being solar powered (Gia and Fugelsnes, 2010).

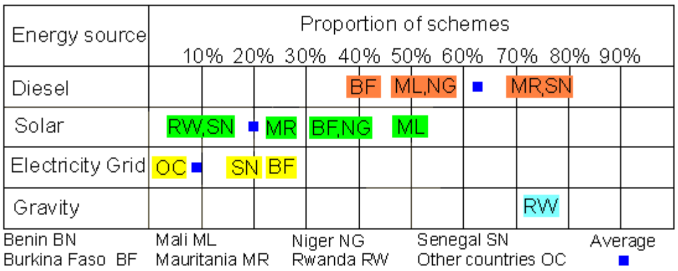


Figure 12: Energy sources for small piped water supplies surveyed in Africa (redrawn from Gia and Fugelsnes, 2010).

The first solar-powered water pumping systems in India were initiated under the Government promotion of non-conventional energy sources programme in 1993-1994 with an installation target of 50 000 units in place within 5 years. By the end of 2004, however, only 6 780 SPV pumps were installed (Purohit and Michaelowa, 2005). As cheaper and more efficient panels become available, solar-powered pumping is providing domestic and irrigation water supplies in many countries (IT Power India, 2006). Typical of the many pilot schemes is the combination of solar-panel and wind-turbine power generation for small-scale agriculture in Mali (Traore, 2010).

This indirect use of wind power supplements the existing successful windmills powering direct-drive positive-displacement pumps in a broad spectrum of geographical settings. A number of manufacturers continue to supply these classic tripod tower windmill pumps. Freed for future fuel costs and despite the relatively high purchase and installation costs, they are used for domestic water supplies, livestock watering and small-scale irrigation. However, this trend can be expected to decline as wind-powered generators producing a more flexible electrical supply take over.

In North America, the US Department of Agriculture 2003 census lists 82 solar power pumped groundwater wells in use to irrigate 1 640 ha. The spread and rise of wind-generated electric power from 2 472MW in 1999 to 43 635MW in 2011 are shown on Figure 13. In this regard, Vick (2010) describes an analysis of hybrid wind- and solar-powered centre-pivot groundwater irrigation that shows it could be economically viable in the High Plains of northern Texas if used to irrigate two crops a year.

Earlier analyses in the 1970s and 1980s had shown the use of wind-generated power was uneconomic for a single annual crop but was economic for year round irrigation of fruit orchards. Renewed studies in the late 1990s and early 2000s showed irrigation of a single annual crop remained uneconomic, as the local electricity-generating companies were unwilling to buy the farmers surplus out of season electricity at a commercially viable rate. Based on an energy requirement of 62 kWh to pump 100 m^3, the total installed capacity needed to irrigating 51 ha of a winter wheat and summer corn crop are calculated to be 196 kW from a fixed solar array, 146 kW for a single axis panning array or a total of 150 kW wind-turbine-generated power. (A two axis panning and titling solar array was found not to significantly add to the energy output).However, annual variations in the wind and solar energy inputs in northern Texas show solar energy to be a more and more constant and consistent source of energy. Further calculations showed that combining the outputs from a 90 kW single axis tracking solar array and a 50 kW wind turbine would provide sufficient energy and improve the reliable of irrigation system. For the calculations the height of the wind turbine hub was set at 25 m. For the systems to be fully commercial, there is a need to provide alternative conventional backup power and ideally generated surpluses to be used either on the farms, for greenhouse heating for example or sold into the local grid.

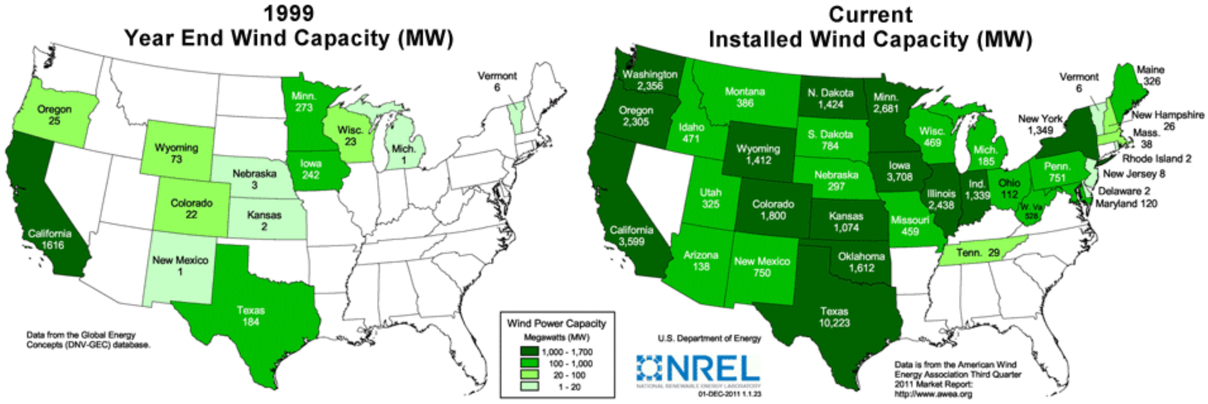


Figure 13: Growth in installed wind-powered generating capacity 1999-2011.(Adapted from US National Renewable Energy Laboratory, 2011).

4.9 Reinvigorating rural water supply programmes

The 2000 UN Millennium Summit and the follow-up 2002 World Summit on Sustainable Development set new development goals to be achieved by 2015. These included rural water supplies and sanitation as a main Millennium Development Goal (MDG).

By 1984, UNICEF, many NGOs and other agencies had moved from insular supply-side water projects to integrated health education-orientated projects involving community participation in the design, implementation, operation and maintenance of the water and sanitation elements (Bayer, 1987). The extent this could be put into practice by UNICEF and other donor agencies depended on counterpart inputs from receiving government's executive organizations. In many cases, these inputs were found to be weak or absent unless funded by the donors. When donor funds were made available, their withdrawal at the end of the project often left the client organization with well-trained staff but without recurrent funding to ensure continuing future field operations. This severely impacted on the sustainability of the project.

4.10 Improved sustainability – Community demand, management and participation keys

By the mid 1990s, mainly on NGO feedback, the views and involvement of the community demand side on the projects had become the focus of attention (Carter, Tyrrel and Howsam, 1996). Community participation was identified as the key to sustainability, typically including the election or selection of a water committee with clearly defined responsibilities, such as managing the money collected from the sale of water and organizing the operation and maintenance of the water supply system.

In the field, the effectiveness of most water committees is found to be undermined by the lack of mechanical skills, tools and access to a robust supply chain. Under decentralization reforms, tools and skills are planned to be made available at the district level, but this has yet to be widely achieved. The problems faced by the water committees can be seen with the operation and maintenance of installed hand-pumps. With the exception of rope pumps, it is widely accepted that most hand-pumps have not met the VLOM criteria.

For a successful community- and district-level-based maintenance programme, the first decision to be made is about who and how to train. Regarding who to train, many field workers advocate for the selection and training of women as they have proved competent and conscientious mechanics and have the greatest vested interest in maintaining their community water supplies (van Wijk-Sijbesma, 1998; UNDESA, 2004). The question of how to train brings in a role of the pump manufacturers and suppliers that has only been partially explored (Harvey and Skinner, 2002) but further onus to train mechanics should form an integral part of the supply chain.

Typically, up to three levels or tiers to the training programme are needed. First tier training is usually given to a responsible community member or committee. Once trained, they should be able to undertaken regular inspection of the pumps to determine if preventative maintenance is required. Although this does not require tools, it would be appropriate that the tools needed to repair the pump are held by the community water committee. The second training tier usually covers all the maintenance and repairs to the hand-pump fittings. The third tier training covers all aspects of installing and removing the hand-pump from the hand-dug or drilled well.

While ensuring the availability of spare parts should be considered by all donors, work on the supply-chain aspects shows a number of options available from a free-market solution to a fully subsidized free-supply form of distribution network. In practice the free-market solution has been found to work where the density of hand-pumps is sufficient to create a sufficient demand for spare parts. Where this condition does not exist, it has been found that some form of continued subsidized system is need. Reviews of community-based hand-pump projects, while showing range of problems, they also show numerous positive adaptive solutions to maintenance. (Harvey and Skinner, 2002; Harvey and Kayaga, 2003; Harvey, 2003).

Part 2: Diagnostic

From around 1985, many of the case histories considered in the preceding sections were based on substantial diagnostic reviews of existing and developing situations as typified by Bayer's 1987 analysis of UNICEF programmes, Black's 1998 review of World Bank-funded projects, the Trantor International's 2007 review of NORAD's Assistance to Water Supply and Sanitation in Tanzania and Kenya during the 70's, 80's and 90's, and the Giordano and Vilholth 2007 groundwater irrigation compilation. The following sections, therefore, are used to attach governance issues to the diagnostic appraisals.

5. Constraints

5.1 Institutional barriers to technology access and uptake

Obvious barriers to well-regulated groundwater abstraction include:

- insufficient monitoring and knowledge of the groundwater resource being developed;
- an entrenched prior pattern of uncontrolled groundwater abstraction and usage;
- delayed recognition of adverse impacts of prior and on-going abstraction.

As pumping technology improved from the mid 19th century onwards, this pattern of barriers developed and triggered various, but often belated, governance measures. The impact of these measures on the groundwater users frequently gave rise to varying degrees of social and political backlash.

The prime governance concerns have largely crystallized around the uncontrolled use of groundwater for irrigation. Institutionally, two basic approaches to the barrier issues have been adopted. The first is the hands-off approach where the uncontrolled development continues until abstraction becomes unviable due economics, soil salinization or water quality deterioration. The second approach is the orderly application of technically well-founded, national and local water right legislation that may be supplemented with less formal institutional tools that can provide effective local resource management steps (Theesfeld, 2008), including the following:

- improving irrigation efficiency;
- defining well spacing;
- imposing a moratorium in new borehole construction;
- restricting or banning the planting of high water demand crops, notably sugar cane;
- placing temporal limits to the groundwater irrigation cycle.

Singularly, or in conjunction, each of these measures has been demonstrated to moderate groundwater level decline (IWMI, 2007b) by a number of Indian examples and by the Mexican Aquifer Management Committee programme (Garduño and Foster, 2010). To a certain extent, these mirror the Texan GMD approach in the USA. However, where these initiatives are farming community-based, they are frequently found to be fragile arrangements that breakdown with time as community priorities change or conflicting external developments provide alternative sources of irrigation water (Shah 2001).

A number of project reviews in Central America and South Asia, point out how the benefits of many donor and central government groundwater-dependent rural water-supply programmes fail to reach the poorest in the target communities, unless founded on strong community participation and transparency throughout the project formulation and execution (Sara and Katz, 1998).

5.2 Institutional barriers to efficient use of energy in groundwater pumping

Supporting the largest areas under groundwater irrigation, the USA “Big Deal” of the 1930s and the Indian rural electrification programmes of 1965-2002 had basically same objective to improve rural livelihoods by increasing agricultural production. However, there were three major differences: (i) the very low population density in the areas served in the USA compared to India;(ii) the US cost recovery tariff structure compared to the non-commercial flat rate Indian tariffs; and (iii) differences in the nature of the groundwater occurrences.

Over the 70 years of groundwater irrigation expansion supported by large stratiform aquifers in the USA, the developments have been accompanied by on-going hydrogeological appraisals and monitoring coupled with evolving legislation and management planning.

In Peninsular India, the take up of groundwater irrigation lagged behind that in the eastern States. Again driven by individual investment and subsidized electricity, the irrigation farmers’ energy demands increasingly outstripped the capacity of the generating and distribution systems. In addition, the more limited nature of the groundwater occurrences resulted in sharply declining groundwater levels that further pushed up energy demands. By 2002, the agriculture sector reportedly used an average of 30 percent of the electricity generated in India to pump water[7]. Groundwater irrigation abstraction accounted for the majority of this usage. However, across Peninsular India, agricultural electricity usage approached 45 percent of the distributed power.

In hindsight, earlier and more effective coordination between the energy and agricultural planning sectors could have been desirable but given the scale of the development, this would probably have delayed the penetration of the benefits of the Green Revolution into the rural irrigation areas. Had monitoring of the developments been more integrated, part of the energy subsidies could have been diverted to a drive for the introduction of efficient irrigation methods and, as a separate issue, a combined tariff could have been devised linking the electricity and water usage.

However, to resolve the contemporary groundwater irrigation situation, a number of schemes have been implemented. From 2004, the USAID-funded DRUM and Water-Energy Nexus-Activity (WENEXA) projects have undertaken pilot schemes under the auspices of the Bangalore Electricity Supply Company (BESCOM), the Maharashtra State Electricity Distribution Company, Ltd. (MSEDCL) and the Madhya Gujarat Vij Company, Ltd. (MGVCL) in the Gujarat State with inputs from the US Department of Agriculture’s Rural Utility Service (RUS). One of the findings of the 2011 DRUM-WENEXA project appraisal (Warr *et al.*, 2011) highlights the insular project approach, with little or no consultation or inputs sought from the local, state or central agencies responsible for groundwater management or agricultural development.

This omission sits awkwardly with the specific objectives of the WENEXA project that are (Warr *et al.*, 2011):“to improve co-management of energy and water resources in the agricultural, urban and industrial sectors through enhanced power distribution and end-use efficiency, coupled with sound water management practices”.

However, the results from a BESCOM pilot project aimed at improving the rural groundwater irrigation energy demand side in Doddaballapur Taluk (District) near Bangalore provide concrete evidence to continue with this approach. A survey of installed pumps showed over 90 percent of the functioning pumps sets were less than 30 percent efficient. The voltage delivery of the feeder electricity lines was generally less than that required to power the pumps. Fifteen farmers received correctly-sized efficient replacement pumps in return to converting at least 0,4 ha of flood irrigated fields to drip irrigation. Most of the replaced pumps were only two years old and all were found to be oversized. Most were repaired at least once a year due to the severe voltage fluctuations. The power of new more efficient pumps was generally 1,5 kW less than the pumps they

---

[7] DRUM training programme, 2005. Annex 1: Background note Distribution Reform, Upgrades and Management (DRUM) Project.

replaced. The average installed depth was 152 m and before-and-after tests showed the combined power demand of the new pumps to be 55 300 watts after six months usage. This compares with the 72 000 watts consumed by the old pumps with the water pumped in both cases remaining approximately the same. The reported overall efficiency improvements were 70 percent in terms of energy and a 60 percent reduction in water usage. However, with 6 of the new pump motors burnt out within 9 months due to the frequent voltage fluctuations, it was clear that a simultaneous upgrading of the electricity distribution system was needed and that the efficiency saving would make for a net economic gain (Mercados, 2010).

Future WENEXA work involves developing a financially viable, sustainable and replicable pilot scheme with BESCOM in the Bangalore area with the following guidelines (Mercados, 2010):

- A high quality power distribution system is required, but this may not be financially viable for the distribution utility in the current scenario of "free" agricultural supply.
- The potential electricity conservation is highly location-specific (depending on the existing equipment in the area) and time-specific (midnight savings are worth much less than peaking power), so generalization is not possible.
- Accurate metering and regular data collection are essential[8].
- Farmers' co-operation and the participation of all stakeholders.

The WENEXA results are in line with those of Lall *et al.* (2011) who calculated a potential 30 percent water saving by using similarly efficient lower-powered pumps in combination with sprinkler and drip irrigation. The sister DRUM project is undertaking a straightforward upgrading of parts of the BESCOM rural distribution feeder network (Warr*et al.*, 2011), as well as further energy audits on installed pumps. However, coupling the WENEXA approach with the secure power line upgrade delivered under the Gujarat *Jyotirgram* scheme (Shah*et al.*, 2008) should prolong the pump motor life and enable the concept of life-cycle costs to be introduce for the economic analysis of the rural farmers' financial viability.

This approach could also enable a tight time cap to be placed on the number of hours of groundwater pumping and attached to a flat-rate tariff. The hours of irrigation needed could be readily calculated from available objective statistics and varied to meet drought conditions. Any additional hours of pumping could be made subject to a surcharge. Although such an approach would probably slow the rate of groundwater level decline, reversing the trend will require a more drastic cut back in abstraction and in the area irrigated. The currently reported farming practice is that individual irrigators evaluate the irrigation water available for the coming season from pre-season water level measurements in their wells and then decide on the area to be planted (Lall *et al.*, 2011). A similar decision could be made if they were aware of an electricity cap.

In the other Indian States, variable tariffs are suggested to reduce irrigation pumping demands. The irrigation farmers in the eastern States do not receive subsidized electricity but pay close to cost price. All States, however, can implement the generating boards' DRUM-project recommendations to improve the efficiency of the pumps' electric motors and a repair-shop certification scheme to ensure the quality of motor rewinds.

5.3 Economic limits to pumping

Considered as a commodity, water has a market value based on its use, its production costs, the potential financial returns and its scarcity. In arid, semi-arid and sub-humid climatic zones where surface water is scarce or has a limited seasonal availability, groundwater assumes a high economic value. In sub-humid and humid zones, groundwater still has dominant economic advantages in the geomorphologically defined water divide and interfluve areas remote from the perennial water occurrences.

Attaching a role in governance to pumps requires consideration of the hierarchy of users. This has been framed under the pragmatic Wyoming surface and groundwater laws that are founded on a declared priority, which assigns the highest priority to drinking water for humans and animals, followed by municipal water

---

[8] The accuracy and precision of the measurement of results achieved will vary in direct proportion to the quality and extensiveness of metering. The ideal would be the installation of reliable meters at the consumer level, but that is a controversial issue.

supplies, then energy generation, transportation, domestic services, cooling and heating and finally industrial uses (Jacobs, Tyrrell and Brosz, 1995;BLM 2001). All other uses including irrigation are defined as non-preferred uses. This priority reflects the widely held highest social and economic valuation of secure drinking water and urban water supplies. In general, if the high price of tankered water supplies in the urban and peri-urban setting is an indicator, the limits to pumping costs have yet to be set as will be seen in the future urban developments that will be needed to resolving the water supply problems of Sana'a in Yemen where the introduction of electric submersible pumps has seen uncontrolled irrigation almost completely deplete the aquifers used for the current city water supply.

Given the lowest priority use and under most conditions, groundwater-based irrigation has high implementation and operational costs in relation to the potential profits from cropping. Groundwater irrigation is, therefore, very sensitive to the pumping costs that are directly linked to energy prices and the pumping head.

Worldwide, the vast majority of large-scale groundwater irrigation is only economically viable due to the support of significant subsidies. The energy costs for groundwater irrigation in Nebraska, USA, are shown on Table 2 above. The 2003 Nebraskan pumping costs of USD 70-75 per hectare are unsubsidized and reflect the low price of electricity, the high efficiency irrigation systems and a relatively low average pumping head (ca. 40 m). Even with this degree of efficiency, groundwater irrigation was uneconomic during the 1980s and 1990s due to low commodity prices and reduced subsidy regimes.

Field reports (Narula *et al.*, 2011) from North Gujarat in Peninsular India (Figure 10) estimate that in 2006, the energy provided for groundwater irrigation was around 10 000 kWh per hectare (unsubsidized equivalent to USD 750 per hectare). However, it is unclear whether the 10 000 kWh is measured at the point of generation or determined at the point of delivery. In the latter case, the technical transmission losses of some 30 percent and illegal connection losses at 30 to 40 percent point to an even greater demand on the generating capacity. The average power of a pump to irrigate one hectare is 7,5 kW. This suggests that the pumps are operated for the equivalent of 55 days continuous operation. If similar energy consumption levels are substantiated across the rest of Peninsular India – and indications suggest that this is the case, then the economic limits of groundwater pumping may have already been reached.

In the Ganges Basin, Scott and Sharma (2009) provide further energy data for the lower head irrigation areas that shows annual pumping costs to range from USD 150s to 250 per hectare. Despite the lower costs, there are no completely depleted aquifers, and neither has land been lost to soil salinization nor has saline intrusion occurred.

Elsewhere, propelled largely by subsidies, the planned or unplanned expansion of groundwater irrigation underpinned firstly by low cost suction pumps and, then, by deep well turbines and submersible pumps has seen alarming declines in groundwater levels in many countries. Where the energy supply for groundwater irrigation is unsubsidized, the crop value ultimately dictates the viability of the farming. In parts of Texas, USA, irrigated lands are being declared as uneconomic due to pumping costs. More frequently encountered reasons for abandoning groundwater irrigation are salinization of the land and the intrusion of saline water. Large tracts of irrigation land have been abandoned due to these causes.

No development sector shows the flexibility of the economic limits to pumping more clearly than in the deep mining of metallic minerals. An emphatic rise in copper prices has enabled the Konkola copper mine in Zambia to remain viable. Some 350 000 m^3/d of groundwater is pumped from >1 500 m below ground level to dewater the workings in one of the wettest deep mines in the world (Engineering and Mining Journal, 2011).

6. Scope for Securing Social and Environmental Benefits through Governance

6.1 Access to well informed technology options

The social and environmental benefits associated with the rural and urban water supply sectors are well established but remain to be maximized by parallel developments in the public health and sanitation programmes. Frequently, the responsibility for water supply and sanitation development rests with separate ministries or agencies. The problems this causes are understood and are being addressed at the community level but are being less well addressed at the funding level.

With access to the internet, it has to be assumed that the operators of large urban water supplies and pumping equipment agents and importers are fully informed of the improved pump performances derived for research into hydraulic design, materials and controls. With the current high power, rotation speeds and vane tip velocities, pumping heads of 850 m are being achieved by the latest single stage centrifugal impeller pumps. Computerized design studies using Computational Fluid Dynamics software (CFD) suggest an ultimate single stage 1 000 m head limit within the current level of technical knowledge.

Development of materials includes low friction internal pump coatings and the use of ceramics, tungsten and silicon carbides to reduce wear rates and to improve the performance of shaft seals. The benefits of wider use of variable speed controls to control pumping volumes include optimization of energy use and can reduce pump wear. Computerized condition monitoring provides a useful tool for programming preventative maintenance. There is also continuous assessment of improved electric motor designs including the use of the brushless inductive axle flux drives. The cost-benefit from this research, however, is relatively low and may not merit follow up unless driven by national and international energy efficiency legislation.

The situation with hand-pump research is largely static as the problems with reciprocating cylinder pumps seem technically intractable. Achieving the VLOM concept remains unlikely until the skill levels available within or to rural communities are sufficient to undertake expedient repairs to broken down pumps. The wider use of the treadle pump, however, highlights the effectiveness of the rope (or chain) pump that has been widely used for rural community water supplies in Central America and China. Also known as the Paternoster Pump and the Liberation Wheel (pump) in China, the efficiency of rope pumps ranges between 50 and 70 percent (Fraenkel and Thake, 2006). This is comparable to the reciprocating cylinder pumps. With the additional benefits of low cost, simple technology and easy maintenance, the rope pump demands further consideration. Although best suited for hand-dug wells there is scope for developing slim line rope pumps to fit 150 and 200 mm diameter boreholes. The rope pump also lends itself to retro-fitting of electric or diesel motorized power.

A further motorized pumping technology that shares the simplicity advantages of the rope pump is the combination of a surface mounted centrifugal pump and a down-hole jet or ejector pump. With no down-hole moving parts, jet pumps are more efficient than airlift devices. They are most suited to domestic water supplies where efficiency is not a paramount consideration. They also provide an interim solution to maintaining water supplies in areas where water levels are dropping below the range of suction-lift centrifugal pumps in line with the stepped development model recommended by Sounders and Warford (1976).

The technological options available to improve groundwater irrigation cover the abstraction and application efficiencies, and the crops and cropping pattern (Golden, Peterson and O'Brien, 2008). The contribution of improved pump design and construction in terms of efficiency, low maintenance costs and working life is equally available to irrigation farmers if they have the capital to upgrade their abstraction. Although this is the case in the commercial irrigation farming areas of North, Central and South America, Europe and parts of Asia and Australia, the small rural irrigators with holdings of less than one hectare lack the necessary capital and, if dependent on electricity for pumping, face two further problems: they usually are competing with neighbours for water from a common source aquifer and for electricity supplies from a tenuous distribution system.

In practice, these rural irrigation farmers have little incentive in acquiring efficient pumps instead of their more robust oversized pumps. This becomes even more justified where they pay a low flat tariffs or no tariff at all for the electricity supply. However, they do have options to improve their irrigation application efficiency, to grow crops with lower water demands and to modify their cropping pattern. Where farmers previously attempted to crop three times a year, when they adopted the first two options they frequently cut cropping to twice a year.

Ultimately, declining groundwater levels due to irrigation abstraction can be controlled or resolved by:

- introducing an equitable water rights scheme that positively discriminates in favour of the small landholder abstraction;
- placing limits to allowable borehole pump sizes compatible with the scale of the groundwater occurrence being exploited; or
- waiting until pumping of groundwater becomes totally uneconomic even with free electricity.

Given the last outcome is incompatible with the need to ameliorate rural livelihoods, the short term solution remains in improving the reliability of the energy supplies, pump efficiency and introducing an appropriate quantity based limits to abstraction and area irrigated.

6.2 Energy efficiency programmes and groundwater pumping

The vast majority of modern pumps designed to abstract groundwater are powered by internal combustion engines or electric motors. Current diesel energy efficiencies peak at around 45 percent while industrial testing suggests average efficiency clusters around 25 percent. Improvements to internal combustion engine efficiency will stem from their widespread use in transportation, and peak diesel engine efficiencies are predicted to improve to 55 percent in the foreseeable future. Irrespective of these improvements, the variable efficiency of non-branded diesel-powered pumps requires scrutiny and regulation to ensure they approach the performance of the most efficient equivalent pumps on the market.

As electric motors use about 70 percent of the general industry demand, they are the focus of European Union and other regulatory body's efficiency directives. The efficiency of induction electric motors is directly related to their rated power output as shown on Table 5. It also varies with the load as shown on Figure 14.The price premium of the most efficient motors is between 10 and 30 percent[9]. The market penetration of lower-powered motors (>3 kW) meeting these standards in the UK is less than 10 percent. While the hydraulic and mechanical efficiency and durability improvements are shared by both electric and internal combustion powered pumps, the overall energy efficiency ranges from 40 to 75percent depending on the pump size and number of stages.

The application of Variable Speed Drives (VSDs) to fluid pumping in the European Union is identified as the motor system technology having the highest significant energy savings potential as shown in Table 6.The current applications of VSDs to groundwater pumping from boreholes are limited to highly engineered urban and industrial water supplies where Pulse Width Modulation (PWM) control technology (Figure 16) can be used to produce a constant flow rate, pressure, pumping head or temperature[10].

---

[9] BNM02: Minimum Efficiency Performance Standards (MEPS) for electric motors. UK Defra v3, 2007.
< efficient-products.defra.gov.uk/spm/download/document/id/653 >

[10] See 2008Grundfos SP Engineering Manual, available online from http://www.grundfos.com/content/dam/Global%20Site/Industries%20%26%20solutions/waterutility/pdf/engineering-manual.pdf.

Power kW	Efficiency
0,75 – 3,0	78,8
3,75 – 6,75	84,0
7,5 – 14,25	85,5
15,0 – 36,75	90,2
37,5 – 100	91,7

Table 5 (above): Nominal relationship between electric motor power and efficiency

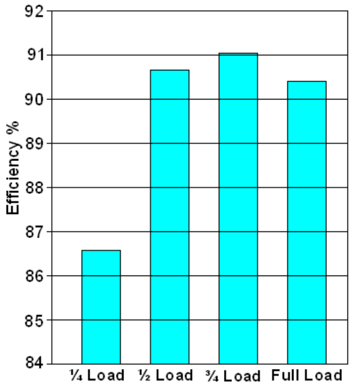


Figure 14 (right): Relationship between a Minimum Efficiency Performance Standard (MEPS) 7,5 kW electric motor working load and efficiency.

Unaddressed, in India as a whole unrestrained groundwater pumping coupled with irregular electricity supplies is possibly causing some 80 million km^3/year of excess abstraction for irrigation. This is based on the estimated groundwater abstraction of 150 km^3 in 2003 reported by Sharma (2007) compared with the CGWB's reported 231 km^3 for 2004 (CGWB-MoWR, 2006). More recent estimates of the total groundwater abstraction for irrigation hover around 200 km^3 (Aguilar, 2011 citing Ananda, 2009). This still leaves a reported in-balance over the CGWB's 231 km^3 that is in the order of one fifth of the mean annual flow of the Nile into the Mediterranean before the construction of the Aswam High Dam.

VSDs	Average Savings %	Applicability %	Already Applied %	Technical Potential %
Pumps	35	60	9	51

Table 6: Assessment of potential for energy savings by applying VSDs pumps in the European Union VSDs Pumps (from De Almeida et al.*, 2000).*

Irrespective of the availability of absolute abstraction figures, most field studies point to inefficient and over application of irrigation water in the rural areas linked to the electrical distribution networks. In Peninsular India, the largest area of unsustainable groundwater abstraction, the situation has reached crisis point. Groundwater levels are fast dropping beyond the reach of many of the small farmers' wells and pumps while the larger landowners drill deeper and install more powerful pumps to continue with the exploitation of the resource. In addition, as the groundwater occurrences approach depletion, contamination of the groundwater is occurring due to coastal saline intrusion or because poor-quality virtually connate groundwater is tapped.

However, the problems in Peninsular India are being addressed by the on-going DRUM and WENEXA programmes and the *Jyotirgram* scheme in Gujarat. These along with the University of Columbia Water Center initiative (Narula *et al.*, 2011) show the need for more coordination between the energy and agricultural sectors, if secure energy supplies and improved irrigation practices are to stabilize or modulate the groundwater level trends and improve farmers' real incomes. Equally significant is the demonstrated potential 30 to 70 percent reduction in the energy demand if the electricity supplies can be stabilized and secured (Ahluwalia and Goyal, 2003; Padmanaban and Sarkar, 2005; Shah, 2007a; Shah, Bhatt, Shah and Talati, 2008).

6.3 Reducing emissions

Other estimates of the energy savings achievable by agriculture demand-side management range from 40 to 45 percent (Warr *et al.*, 2011). If achieved, given the high agricultural electricity use, these savings will have significant impact on the ongoing emissions output of the Indian thermal generating capacity shown on Table 7.

Although water utility and industrial pumping greenhouse gas (GHG) emission assessments are the subject of national and international directives, GHG emission assessments for groundwater irrigation are still largely unexplored. However, carbon taxes could be applied to the pumping equipment but they are surely better rolled up with energy price especially as the larger pumps are considerably more efficient than smaller pumps (Table 5).

	Thermal MW & (%)				Nuclear (MW)	Hydro (MW)	Renewable (MW)	Total (MW)
	Coal	**Gas**	**Diesel**	**Total**				
All India	89,778 (47%)	17,625 (17%)	1200 (1%)	108,603 (65%)	4,560 (3%)	37,328 (22%)	16,787 (10%)	167,278

Table 7: India installed generating capacity, October 2010 (Warr et al.*, 2011).*

6.4 Institutional environments that can work – economic and environmental regulation

Halting or reversing the declining water levels across Peninsular India also requires emphatic political action including addressing existing property rights law to ensure equitable distribution of the groundwater resources to all landowners (Aguilar, 2011). The electricity suppliers are entitled to control connections to protect the integrity of their supply and to set tariffs in line with national development objectives. In parallel with scientific assessments to quantify an appropriate annual rate of groundwater abstraction, consideration of the status of prior appropriation rights in lands classified as under tribal control may yield a basis for assigning water rights.

Existing Indian environment priority legislation could possibly be applied to set limits to the size and performance of installed pumps together with setting a minimum distance between dug and drilled wells. In the case of farmers with very small landholdings, they could be encouraged to consolidate their resources to qualify and share an irrigation pump. The use of this legislation would be in line with the 2000 Millennium Declaration concerning the protection of the environment. The political solution to the objections made by medium- and large-scale farmers facing a large reduction in their current abstraction may lie with the introduction of subsidized agricultural processing plants and distribution networks that will encourage a shift into higher added-value horticulture produce grown on reduced irrigation areas.

Although the post 2002 expansion of groundwater irrigation in the State of Nebraska, USA, for biofuel crop production is regulated by the State groundwater legislation, the farmers and cooperatives are further protected by the Initiative 300 legislation[11] that is specifically designed to prevent the spread of major out-of-state agro-industrial corporations into the State. Initiative 300 was decreed in 1982 with the objectives of protecting the land from the environmental damage caused by corporate farming observed in other States in the USA. In particular, Initiative 300 was designed to forestall corporate skirting of their liabilities for the damage caused by their farming activities. This was prompted by an earlier phase of groundwater fodder irrigation for ranching developments undertaken by out-of-state corporate-driven speculation in the extensive Sandhills region of Nebraska: the irrigation fields were created by bulldozing the tops off the wind-blown sand dunes into the depressions. These developments started in the late 1960s and relied on centre-pivot groundwater irrigation. Many of the agro-industrial corporations were bankrupted by the 1980s decline in farm produce and cattle prices, and the abandoned farms, stripped of vegetation cover, suffered extensive wind erosion (Kepfield, 1993; Decision Analyst, Inc., 2003). Currently, Initiative 300 is being challenged by a new wave of agro-industrial corporations.

Although small-scale groundwater irrigation is being widely promoted across Africa, the take-up is limited. There is a strong possibility that uncontrolled development could rapidly reproduce the negative impacts observed across Peninsular India. To a very large extent in sub-Saharan Africa, the possibilities for groundwater irrigation-based industrial-agricultural systems are limited in comparison to the very large scope for small-scale farm irrigation in the humid and sub-humid zones. Given the nature of many of the groundwater occurrences in these zones, a prudent blanket permits an abstraction limit of 1,5 l/sec per km^2 to be applied until the resources are fully monitored and evaluated. While this will enable the use of two-phase electric motors or small low-powered diesel pumps, larger developments should be only considered as a

---

[11] See Center for Rural Affairs website for more information on Initiative 300 (http://www.cfra.org/I300/factsheet).

second phase development, to be started after several years of groundwater-level data has been collected and assessed. Equally the use of solar- and wind-powered pumps merits wider consideration.

Policies should aim at efficient use of the water by subsidizing the introduction of dry-season drip irrigation of around 2 ha and supplementary wet-season irrigation of 5 ha rather than permitting the use of bigger pumps and inefficient basin or furrow irrigation. With the demand for cheap pumps likely to continue to grow among the agricultural and livestock-based rural communities, national governments and funding agencies should seek to define and impose efficiency standards for imported and locally manufactured pumps and power units. Where rural electrification is in place, the network operators should collaborate by producing lists of approved and certified pumping equipment.

6.4.1 Rural water supplies, securing sustainability

Given the high MDG priority, providing sustainable drinking water supplies to rural communities has proved far from straightforward, with the hand-pump at the centre of many of the sustainability problems. Historically, hand-drawn water abstraction has had little impact on the resource base. The main development problems have been locating the groundwater and protecting it from contamination. In the humid and sub-humid tropics, most rural communities are sited along the local water divides where typically the groundwater saturated zone is thin and borehole yields correspondingly low or negligible. This even applies in the river basins of the Lake Victoria Basin in Kenya where the annual rainfall is over 1 500 mm and across the granites of the Central Region of Ghana.

At the beginning of the IWSSD, some donor projects moved into communities, constructing boreholes and wells equipped with hand-pumps with the minimum of consultation, and in the worst-case scenario no provision was made for repair or maintenance of the pumps, nor was the ownership clearly defined. Frequently this project model worked on the assumption that each hand-pump would serve populations of around 300 and that larger villages could be supplied with several pumps. With a matter of one or two years, at least 30 percent were broken down with failures often traceable to poor original installation (Jones 1990; Michael and Gray, 2005).

6.5 Institutional environment – Setting development standards

By the 1990s, many governments outside Europe and North America through national water acts, organized and empowered public and private agencies to develop urban and rural water supplies. They also imposed design and service standards.

Coupled with the World Bank push for decentralization, the Ghanaian Community Water and Sanitation Agency (CWSA) responded by preparing a series of design and construction standard guidelines, as well as operation and management manuals (CWSA, 2004). One set covers the provision of water supplies for small communities and the second set, small town piped-water supplies. Although fully justified in seeking to ensure well-engineered systems and compatible service levels across the country, certain derogations have been found necessary to optimize the supply systems. The final objective of the sector reform is that District level offices will assume full responsibility for the design and construction of all community water supplies.

The small community water supplies are generally based on drilled wells and hand-pumps and the work is most often executed by local community groups, NGOs or under bilateral grant projects. The small-town water supply projects are usually part of larger bilateral or multilateral loan or grant programmes employing qualified consultants and contractors to design and construct the electromechanical, transmission, storage and distribution works. There are only a few NGOs bridging projects that follow a sequential series of small improvements as identified in Box 7. These intermediate schemes are usually based on innovative mini-hydro, wind generators and solar power.

An early step in both sets of the CWSA guidelines is the establishment of a community water committee (board) that will take over full management after the commissioning of the works. Notionally, they will be supported at district level by water supply teams once the immediate shortages of trained manpower are overcome. However, given community problems in maintaining hand-pumps, future greater problems can be foreseen in the maintenance of borehole pumps and electromechanical equipment, unless the local supply chain is soundly established. The guidelines for small-town water supplies require the equipment suppliers to have local agents capable of providing after-sales services and relevant training support to the communities and to water sector professionals. In practice, this does not yet appear to have happened on a large scale. This raises serious concerns over the future sustainability of the systems unless the local supply chain is improved and there is more intensive training of technicians and engineers.

Another weak link in the CWSA guidelines is also found worldwide. This is the chronic non-payment of water charges by state and parastatal institutions: schools, clinics and advisory offices are almost universally in default. This is being addressed in Kenya where, in 2011, regional offices of the Water Resources Management Authority are enforcing payment of water right charges to the extent that school, industrial and urban water supply boreholes have been shut down.

6.5.1 Institutional decentralization, maximising the success

Other development models stemming from the World Bank decentralization initiative involve the Public-Private Partnership (PPP) programmes reviewed by Gia and Fugelsnes (2010) and listed on Table 8.

Country	PPP initiated	Asset holder	Regulating authority	Water provider profile	Number of operational PPPs 2009	Performance monitoring system
Benin	2006	Local Government	Ministry	PSP	130	TBI
Burkina Faso	2009	Local Government	Ministry	PSP	125	TBI
Mali	2006	Local Government	Ministry/Region	PSP	20	STEFI
Mauritania	1994	Central government	Region	PSP:ANEPA	350	CMSP
Niger	1990	Local Government	Ministry	PSP	298	BCC
Rwanda	2004	Local Government	Region	PSP	230	TBI
Senegal	2000	Central government	Ministry	CBO	183	MANOBI

Table 8: PPP water supply programmes –stakeholder profiles (adapted from Gia and Fugelsnes, 2010).
Key: Providers: PSP - private sector participation, ANEPA (Mauritania) - monopoly non-profit association, CBO - community based organisation. Performance monitoring – these broadly are designed to ensure business based cost control and recovery.

The scale of these developments bridges the small-community and small-town piped-water supplies as shown on Table 9.

Type	Characteristics	Population served	Network length	Storage capacity	Production capacity
Single public water point	No distribution network, ground or low level storage	500-1 000	< 0,1 km	0-10 m^3	5-10 m^3/day
Multiple water points	Limited gravity distribution network, limited low level storage	200-2 000	< 2 km	10-50 m^3	5-40m^3/day
Multiple water points,	Extended piped gravity	2 000-	2-10 km	10-50 m^3	20-300 m^3/day

institutional and household connections	distribution. High level storage	10 000			
Multi village schemes	Large piped scheme with long transmission lines between villages	5 000- 200 000	10-250 km	10- 50 m^3	100- 2 000 m^3/day

Table 9:Water supply scheme profiles(adapted from Gia and Fugelsnes, 2010).

The rationale for establishing the PPP model was similar to that behind the Ghanaian CWSA guidelines. However, in the seven countries reviewed, the community water committees had no legal standing and had not received sufficient guidance or expertise to undertake the community-level operation and maintenance tasks and, even with the PPP schemes in place, they have been found to suffer from the same resource and expertise problems as those found in countries with strong community management programmes in place. In addition, the PPP schemes are heavily reliant on a robust and competitive contracting and service-operating sector. Both approaches share the same governance difficulties and without the trained national manpower and local support funding, they are only partially delivering immediate benefits to the rural populations.

Major urban water utilities tend to have strong technical departments and work closely with pump manufacturers and suppliers to optimize the energy consumption. For their groundwater abstraction they rely on their own specialized engineers or qualified sub-contractors to operate and maintain the pumping equipment. The reliability and efficiency demands of the urban water operators and groundwater irrigators ensure a competitive market among borehole-pump manufactures. These operators focus heavily on lifetime cost analysis.

When weighing the balance between the main cost components – energy usage, maintenance and repair, loss of production, purchase and installation, operation, decontamination and removal – commercial groundwater irrigators have always focused on the potential loss of production costs in terms of loss of crops. As they are selling their output on an open market, the commercial irrigators can pass on rising energy and other production costs. The situation is different with the regulated urban water-supply companies, as these have appropriate backup systems to ensure continuous supply and have limited opportunity to immediately pass on rising energy costs.

7. A Rationale for Managing Demand

7.1 Absorbing actual costs at the point of supply – Spreading risks

A legacy of the rapid growth in piped urban-water supplies since 1850 is the need to generate operational and investment capital to develop new raw-water sources, to continuously maintain, upgrade and extend the treatment and distribution systems and to provide surface and waste water sewerage disposal systems. Historically, the major water companies adopted one of two charging strategies: either a flat rate charge or a charged based metered water usage. In the groundwater-stressed areas of southern England, flat-rate charging is being replaced by a sliding-scale metered usage rate. Most countries enforce water quality and pricing legislation in recognition of its importance to the common good.

Where small town water supplies are implemented under the decentralized sustainable models as seen with the Ghanaian CWSA programmes, the water charges are planned to meet the running costs, system maintenance and future expansion. Numerous willingness-to-pay surveys provide consistent evidence that rural and peri-urban communities are able to cover the basic water-supply operation and maintenance cost. However, analysis of a limited number of post completion project reviews shows considerable disparities between the performance of the community water boards with regards to financial and technical management of the resources needed to expand the commissioned water supplies: this situation is likely to improve as district- and community-level expertise develops.

Under the rule-of-capture doctrine, urban- and rural-supply operators can secure groundwater abstraction rights by appropriate land purchase: in areas of competitive groundwater usage, the land area needed can be large. This can be seen across the High Plains aquifer in the States of Texas and New Mexico, USA (Figure 15).Under other water-right doctrines, the urban and rural groundwater supplies are granted and protected from competitive users by national or state legislation: the protection from well off-setting reduces the area of land needed to be owned by the operators.

Despite obvious differences, the irrigation farmers in the State of Nebraska, USA, and in Peninsular India have invested in developing groundwater sources and rely on the productivity of their lands. The Nebraskan farmer investment and income is geared to prevailing commodity prices and shifting market conditions: past downturns in commodity price have seen farmer retrenchment and agro-industrial corporate abandonment of speculative irrigation lands.

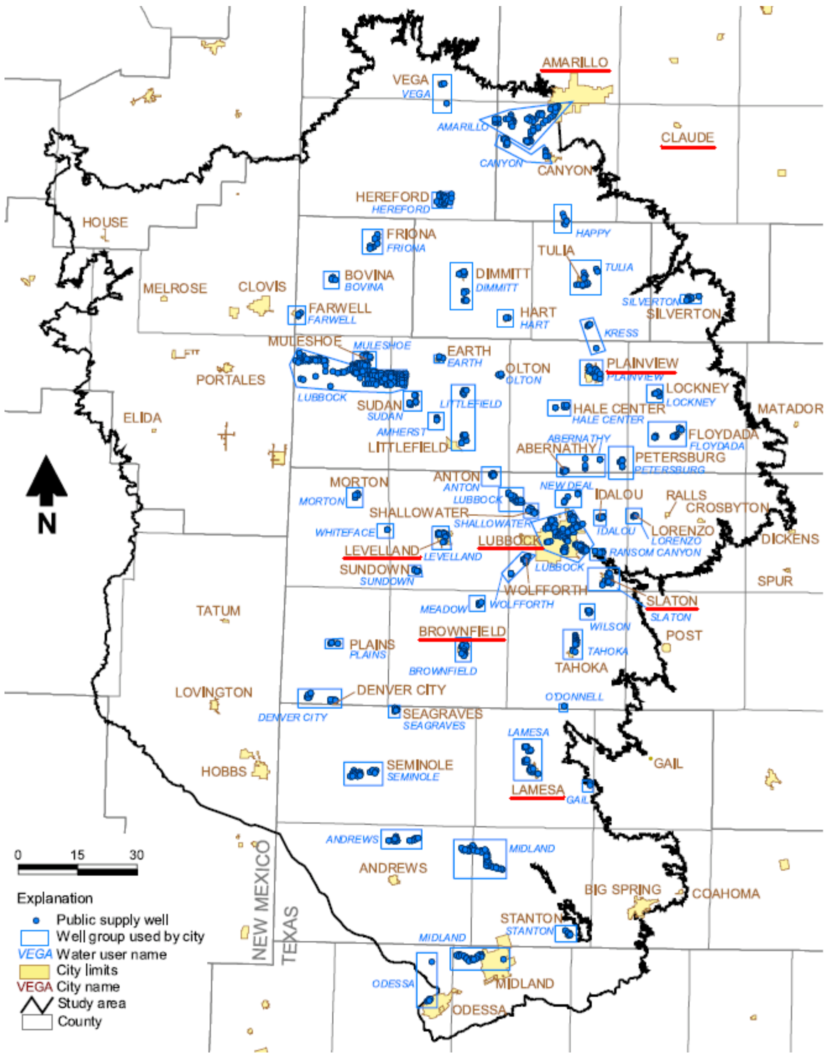


Figure 15: Texas and New Mexico southern High Plains aquifer, urban groundwater supply sources. (Canadian River Municipal Water Authority (CRMWA) cities underlined in red). (Adapted from Blandford et al., 2003.)

Across the less favourable hydrogeological terrains of Peninsular India, a large number of farmers have independently and competitively exploited the common-pool groundwater resources (Strand, 2010). With unrestrained abstraction rights based on the rule-of-capture doctrine, the farmers have little or no conservation incentives when confronted by excessive drawdowns caused by overlapping cones of influence for nearby pumping wells and boreholes. Without legislation modifying the rule of capture that removes the concept of private ownership of the groundwater, there is no scope for charging for the groundwater either directly or probably indirectly.

As already outlined, a widely accepted solution to the over abstraction is upgrading the electricity distribution networks to the well heads, replacing the flat-rate tariffs with fully commercial rates and an appropriate supply rationing schedules together with the introduction of efficient pumps. In practice, many marginal (landholding less than 0,4 ha) and small farming households (0,4 to 1 ha) are unlikely to benefit from these developments unless encouraged to pool their resources.

Part 3: Prospects

8. Projected Evolution of Pumping Technology and Cultures of Use

The current groundwater-pump market ranges from rural water supply hand-pumps, through low-powered mechanized pumps for small-scale rural and urban water supplies, to powerful electric submersible pumps for urban, irrigation, industrial and dewatering purposes.

Competition for natural resources is reflected by rising energy costs disproportionately outstripping most commodity and consumer prices. This is expected push energy efficiency higher when considering pump selection criteria. All end users expect their pumps to be efficient, durable and easy to service and operate, with minimal downtime. Amongst most informed users, the purchase price is of much lesser consideration than meeting these requirements.

Looking at the trends in the uptake of largely unregulated groundwater-based irrigation points suggests these technological developments are going to be tempered by increasing energy costs so that indirect factors a more likely to play a role in affecting regulation of groundwater abstraction.

8.1 Rural water supplies, meeting the sustainability targets

At what can be considered the bottom-end of the market, the hand-pump continues to prove an exception. Sustainability and downtime are the key selection aspects. Even with full involvement of communities through water committees, many installed hand-pumps continue to remain out of service for many weeks or month. In some cases, working parts have come to the end of the service life but more frequently there has been a premature failure of a vital part due to a manufacturing or design fault or poor pump installation. These inherent defects have been widely documented and although they should have been remedied by quality controls and inspections, in practice these are seldom enforced.

The situation is aggravated by the hands-off procurement policies adopted by most donor agencies. Numerous published and unpublished reports recommend donors should use their purchasing power to demand full compliance to manufacturing standards and to follow up the provision of training and after sales services. It is also widely recommended that the donors should provide longer term funding to establish a sustainable maintenance system. This funding should extend to covering all associated costs including transport and field allowances. In too many projects such funding ends immediately after commissioning of works.

On the design side, re-engineering of the India Mk2 and Mk3 pumps chain linkage between the pump rods and the quadrant can be considered. The use of a longer pump cylinder for example has the following advantages as it increases the piston setting-depth tolerance and if the initial setting is towards the bottom of the cylinder, this would enable the pump rod at the quadrant end to be cut and re-threaded. A second modification to eliminate the inherent difficulties of cutting threads in the field could be overcome by supplying either a fully threaded pump rod or supplying a selection of pre-cut and threaded rods of different lengths so the piston can properly located in a longer cylinder.

The implementation of the rural and peri-urban small-piped and small-town water supply schemes lags behind the MDG water target. The WHO/UNICEF, 2011 thematic report on drinking water 2011 concludes that:“at the current rate of progress, this still will leave 672 million people without access to improved drinking water sources in 2015,and possibly many hundreds of millions more without sustainable access to safe drinking water”.

8.2 Improving low-lift irrigation livelihoods

Also at, or close to the bottom end of the market, the profusion of low-powered, motorized pumps available for the rural domestic and farmer water supplies have a mixed record for durability and efficiency. Although given time, brand leaders in terms of customer satisfaction will emerge, in the near and mid-term, the interest of the low-income rural consumers should be protected by a certification system. Indeed, a formal internationally recognized testing and certification scheme is desirable for all groundwater and irrigation pumping equipment manufactured for sale under subsidized schemes or on the open market.

When groundwater levels drop below the range of suction pumping, small-scale subsistence irrigators that have experience with and own, or hire, centrifugal pumps can turn to deep-well ejector pumps that provide much cheaper alternative to the more expensive and difficult maintain line-shaft turbine pumps. Although the 20 to 30 percent pumping efficiency is down on the line shaft pumps, the benefits of having all the moving parts on the surface makes for easy maintenance. Also, if flexible hose is used, the ejectors can be readily removed from the well or tubewell for servicing or replacement.

With landholdings of less than 0,4 ha, the main buyers or hirers of small motorized pumps for irrigation cannot afford a gap in their water applications during the growing season. If a breakdown occurs, they can be forced to purchase water from surrounding irrigators or water suppliers unless they have an alternative manual pumps installed. If they were using motorized rope pumps, they could revert to a treadle mechanism to lift water to their fields. As with ejector pumps, the simplicity and ease of maintenance are the obvious advantages.

A further step available to improve both low-lift and high-lift small-scale groundwater irrigation is the use of mini-centre pivot systems by marginal and medium scale farmers in Asia and elsewhere. Currently USA manufacturers[12] are producing 27-30 m radius systems that cover around 0,25-0,4 ha. The motorized arm rotation can be solar or battery-powered. Given the economies of large-scale manufacture, the wide range of sprinkler application rates available and up to 1,8 m clearance, these systems could be considered instead of fixed sprinkler systems being proposed for cereal cropping. Combining mini-centres with the research into the use of tensiometers in flood irrigated rice fields in the Punjab State, India, (Polycarpou, 2010) should demonstrate very significant water savings.

8.3 Easing the community technology load

Groundwater developments for small-town supplies are a focal point for the many MDG projects. Using small-town water supply is shorthand to describe piped distribution schemes designed to deliver 20 litres per persons/day via communal standpipes and 60litres per person/day to house connections for communities with populations between 2 000 and 50 000. Most new schemes will follow the established development model of employing engineering consultants for the design and supervision and using qualified contractors for construction.

While the schemes are frequently devised and negotiated by central or regional government, under decentralization, commissioning and supervision of the work are undertaken at the district and community level. Analysis of this approach suggests that donors could adopt a hybrid project model as a possible way forward. This envisages a donor-funded technical assistance team designing and supervising the construction of the more technically demanding system components, the borehole drilling contract, the electro-mechanical pumping equipment, the transmission mains and the storage tank, and leave the community and the district offices to design and construction of the distribution system from the storage tank.

Regarding the availability of spare parts and technical skills, the advantages of equipment standardization are widely recognized (UNICEF, 1999). Establishing a spares exchange system where broken parts are exchanged for guaranteed refurbished parts can be considered. This should reduce the time pumps are out of service.

---

[12] See Lindsay Manufacturing website (http://www.lindsaymanufacturing.com/green_center_pvt.asp).

9. Prospects for Managing Groundwater Demand at the Point of Abstraction

Several post-commissioning, management models have been adopted for the operation and maintenance public borehole supplies. Under full decentralization, community water boards are established with full responsibility for revenue collection and handling of funds used to cover future scheme operation, maintenance and expansion. The community water boards have the option to undertake this work directly or using private companies under contract. Other models include local government management through regional water supply agencies or more centralized government water supply operators responsible for all the small towns in the country.

In addition, more effort needs to be directed to collection of long-term groundwater level data. It is in the community water boards' interest that long-term groundwater monitoring should be started as soon as possible in order that the local aquifer response to abstraction is adequately recorded. Such information will be invaluable should the town abstraction exceed the sustainable yield of the aquifer. It will reveal any long term declines in the groundwater level and firmly establish whether it is the aquifer or the borehole that is failing as discussed by Robins, Davies and Farr (2012) when considering Malawi data.

A weak link in all the small town water supply management and sustainability is the chronic non-payment of water charges by state and parastatial institutions: Schools, clinics and advisory offices are almost universally in default. This is being addressed in Kenya, where in 2011 regional offices of the Water Resources Management Authority are enforcing payment of water right charges to the extent that school, industrial and urban water supply borehole have been shut down.

Ensuring the sustainability of small-town water supplies where the schemes have only one abstraction borehole raises the issue covering pump breakdowns. If an interim replacement of existing hand-pumps with small submersible pumps had been undertaken, they would provide some form of system backup (Box 7). All management models rely on sufficient trained staffing and funds plus a robust supply chain. To avoid continuing weakness in all these areas, pumping equipment suppliers should be encouraged to offer alternative long-term leasing agreements, covering maintenance and replacement of the borehole pumps and control equipment.

10. Prospects for Regulating Energy Efficiency and Smarter 'Skimming' in Thin Aquifers

For the large urban, industrial and irrigation users, the major manufacturers will continue to develop more efficient pumps and control systems. The main areas for technical improvement focus on optimizing pumping efficiency by balancing the discharge pressure and yield to match the required operating performance. With installed pumps usually over-specified in terms of both pumping head capacity and discharge, throttling back the yield has been achieved by partially closing a control valve to choke off the flow. With rotodynamic pumps, this increases the system hydraulic losses and decreases the pumping efficiency. While this method is still widely used, a more efficient reduction of yield is achieved by fitting a bypass valve that allows part of the pumped flow to be returned down the borehole. This achieves the desired drop in yield without increasing the hydraulic losses. Both methods have been widely used to control groundwater irrigation pumping.

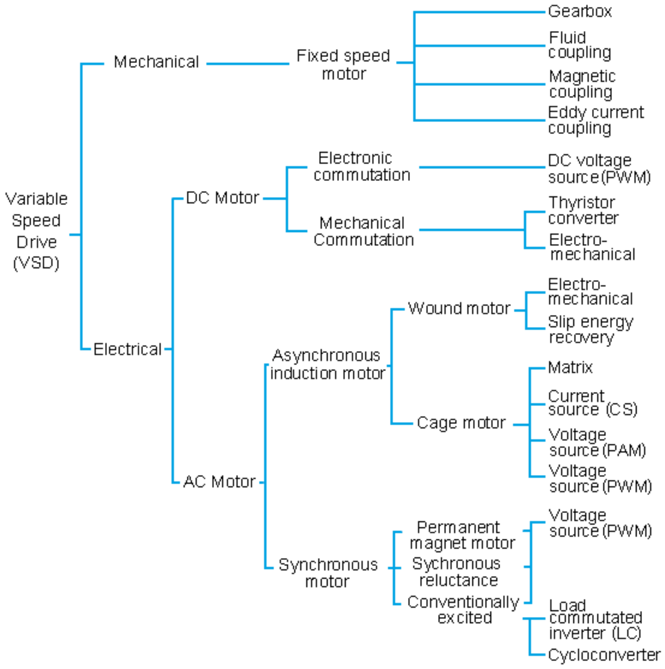


Figure 16: Variable speed drive (VSD) options and generic electric motors (redrawn from Hydraulic Institute, Europump and US Department of Energy, 2004).

PWM = Pulse width modulation (modifies AC frequency wave form by rapid on-off switching: also known as pulsed duration modulation)

PAM = Pulse amplitude modulation

The introduction of mechanical and electronic variable speed devices provides a more efficient method to control both the head and yield performance of diesel and electrically powered rotodynamic pumps. They also can be used for positive-displacement pumps as shown on Figure 16. The use of shaft-driven progress-cavity VSD pumps coupled to pressure transducers could provide the necessary steady-state drawdown conditions to control the movement of saline interfaces and for the skimming of thin aquifers.

Trails combining the two main forms of renewable energy, wind generators and solar power with VSD pumps should enhance the capacity and performance of these systems.

It is envisaged that the advances derived from the manufacturers' research and developments will be adapted by the globalization of the pump manufacture to benefit the lower end of the market. This should lead to pumps incorporating smart speed controls, and wear monitoring sensors will become widely available. Apart from offering considerable energy savings, VSD motor technology should encourage continuous steady operation of submersible pumps for both small town water supplies and small-scale low-pressure irrigation applications. With the submersible pumps operating at controlled and reduced loads will also extend the life of the pump and motor bearings. This will also reduce the additional start-up and stopping loads that can shorten motor life. Most economic analyses show the VSD technology to be cost effective.

The further efficiency gains from continuous groundwater pumping at a reduced rate are: lower well losses associated with the lower entrance velocity; lower pumping heads; and a decrease in the flow-back disturbance at the natural or artificial gravel pack well screen-aquifer interface.

11. Toward Convergence of Technology, Sustainable Use and Emissions Reduction

Whether the scope, forms and settings for governance exist at the point of groundwater abstraction has to be examined from the point of view of the main stakeholders – regulators, users and suppliers. But regulation of groundwater abstraction is usually confounded by being asked to encourage access and volume on one hand, while also judging when use becomes 'unsustainable'. For instance the universally adopted Millennium Declaration to protect the common environment specifically charges regulators: "to stop the unsustainable exploitation of water resources by developing water management strategies at the regional, national and local levels, which promote both equitable access and adequate supplies".

However, under inherited colonial legislation or deliberate policies, the regulators have been left with the intractable common-law-based rule of capture that still gives full groundwater use rights to landowners. This *de facto* private ownership and development of groundwater will continue to attract state-of-the-art drilling and pumping technology with the narrow objective of private profit without reference to the common good objectives of modern resourced governance.

11.1 Re-writing or delegating the legislative framework

Establishing the appropriate level for defining and enforcing a legislative framework appears to show that the strongest and most effective governance regimes are based on community management groups. In the drier States of Texas and New Mexico, USA, the rule of capture remains in force but the responsibilities to a virtual full adherence to the Millennium Declaration are forced on to the GMDs. Looking at the responsibilities placed on GMDs in Texas, USA shows that the role of governance on groundwater abstraction for irrigation is the same whether declared at the State, national or district level and cannot be convincingly separated. However, it appears logical to assume that the more local the governance decisions are made the more readily they are enforceable and revised as circumstances demand. For example, while the Texas State Legislature can maintain they are adhering to the declaration of property rights under the USA Constitution, in practice they are delegating the derogation of these rights down to the GMD level. In many cases, these GMDs go further the neighbouring states using the prior appropriation doctrine to water rights and, based on the "50% rule", can include the Texan GMDs dictating the size of pumps that a landowner can install and revising groundwater rights downwards to curb over-abstraction. It is noteworthy that Texan landowners are not automatically permitted to export abstracted groundwater off their lands. This contrasts with India where the rule of capture remains an unchallenged, inalienable right and landowners can profit from the sale of groundwater. This has given rise to a private water market.

Further examples of users attempting to control groundwater use within their own sphere of influence are described by van Steenbergen and Shah (IWMI, 2007b). These initiatives are almost always prompted by one three factors– declining groundwater levels, declining yields or saline intrusion – or by all three. Most self-management examples are based on community or groundwater user committees that concentrate on collective exploitation of the resource and apply restrictions on individual users and on the construction of new wells. This approach carries cost implications and, as farming and landownership patterns change over time, the community management systems are found to be unstable and break down. In many cases, the impact of outside influences and developments such as a more centralized and subsidized provision of irrigation water will accelerate the decline in what were previously workable solutions. In Mexico, more formal groundwater committees have been given responsibilities similar to those covered by the GMD legislation in Texas. Superficially many of these local initiatives mirror the traditional practices as set out in the "Alghani".

11.2 Reappraising the culture of subsidies

The regional contrasts in the application of subsidies are also instructive. Across Africa, much of the colonial water resource legislation was aimed at promoting economic growth. Annual development budgets included a variety of grants, rebates and subsidies for the borehole drilling for private individuals (e.g. Zambian DWID Report of 1953). From the late 1960s, the Asian green revolution has seen a much more extensive use of subsidies for groundwater irrigation to achieve food self-sufficiency and improve rural livelihoods.

Some subsidises are directly tied to groundwater abstraction and some indirectly impact on the pattern of irrigation. The direct subsidies cover the drilling of tube wells, provision of pumps and fixing energy costs. The indirect subsidies cover inputs – seeds and fertilizer – and outputs – largely guaranteed crop prices. They also can include tax breaks on capital investment and, more questionably, attempts to claim a groundwater depletion rebate in some States in the USA.

Often initially justifiable, subsidies have frequently become multilayered and indiscriminately applied to the extent that they can become counterproductive from the point of view of both the user and resource. The rural de-electrification across the eastern Indian States required the introduction of the diesel pump subsidies and now the irrigators are pushing for subsidized fuel or a free allowance. The steep worldwide rise in grain prices has seen simple cultivation subsidies in Nebraska, USA, of some USD 500 per hectare purely adding to the already high profit margins achieved during the currently reactivated speculative groundwater irrigations market.

Essentially the use of direct subsidies to groundwater irrigation largely undermines the legislators' ability to control the resource usage unless they are prepared to take the potentially politically damaging decisions to realign the system at a later stage. There is often strong social resistance to the inevitable readjustment or withdrawal of any subsidy. The Gujarat *Jyotirgram* scheme, however, does show that such adjustments can be made if there are positive outcomes for the users. Across Peninsular India, on the other hand, attempts to replay the rural de-electrification through neglect may prove politically difficult or more likely politically unacceptable.

11.3 Equitable redistribution and sharing of the resource

A further area that requires legislative oversight is the resource governance attached to the long term leasing of State or requisitioned community lands for agricultural development to foreign sovereign or international speculative funds. If groundwater is accepted as a common good, such requisitions have to be assessed on a user-motive basis rather than solely on a profit motive. In many cases, investments are likely to prove to be short term and environmentally damaging and, in the long term, are likely to have lasting adverse economic impacts on indigenous farmers or pastoralists. The Nebraskan Sandhills speculative developments (See Section 6.4) suggest a likely growth in social resistance.

The core of groundwater science and legislation evolved from conflicts that arose from the practice known in the early oilfield developments as "offsetting" when a landowner drilled a successful oil well near his property boundary, his neighbour responded by drilling another oil well on his own property as close as possible to the successful well. As a result, the effective doubling of the oil abstraction impacted on the yield of the first well. In the USA, where a producing oilfield was controlled by several oilfield companies or land owners, the oil-well operators rapidly became aware of the damage that well offsetting did to the reservoir and the resulting reduction in their collective oil recovery. This was predominately caused by the up-coning of saline formation water from below that broke up the continuity of the oil layer. In response to this problem the oil operators adopted a control model based on the concept of resource unitization where each operator received a prior agreed quota of the overall field production.

The practice of offsetting was repeated by groundwater irrigators and was dealt with in the first revision of the Nebraska groundwater legislation, passed in 1957. This was based on the view that groundwater was a common-pooled resource and the legislation included the registration of irrigation wells and placed a minimum 200 m well spacing. The subtle difference between the unitization development model and the common-pooled resource is that the unitization model is centred on managing the *in-situ* pore fluids to maximize their recovery for the benefit of all developers, whereas the common-pooled model concentrates on the distribution of groundwater abstraction rights. The basic features of the resource unitization model compared to the common-pooled resource model are shown on Table 10.

While there are no published examples of unitization being used to regulate groundwater abstraction, Jarvis, 2011, reports that the principles are being applied in Utah, USA, where landowners, facing a State-enforced reduction in groundwater abstraction, voluntarily pooled their groundwater abstraction rights and formed a "unit" – the Escalante Valley Water Users Association – to share the reduction in available groundwater. A similar scheme was also initiated in the over-stressed groundwater basins of the Milford Flat area in western Utah.

In areas where many landholdings are less than a hectare, interference between water wells is unavoidable, and in most cases, when more efficient pumps became available, many productive wells dried up as the cones of depression from the deeper wells dewatered the unconfined aquifers. While the prior appropriation doctrine governing water rights specifically targeted this problem, the adoption of effective solutions requires a good understanding of the resources available. In areas of deliberate groundwater over-abstraction, it has been found that water rights assigned under the prior appropriation doctrine need to be periodically adjusted to maintain the equitable allocation of the resource.

In the near future, there will be the need to address the governance of the public and private groundwater markets as they are very open to abuse. Close monitoring and auditing will be required to ensure that no entrenched monopolies develop and that profit margins are not exploitative. In the long run, however, groundwater markets could prove socially unstable and divisive, unless a new governance model is developed along the unitization development lines, as suggested by Jarvis (2011), where the benefits of the resource are jointly shared.

Principle or attribute	**Unitization**	**Common-pool resources**
Conceptual development	1890–1930s	1960–90s
Boundaries	• Voluntary units • Compulsory/conservation units • Geographic units • Geologic units	Clearly define boundaries for the user pool and the resource domain
Rules	• Pre-unit agreements at appraisal • Unitization agreement at pre-development • Redetermination during development	Appropriation rules developed for local conditions and provisional rules developed for resource maintenance
Collective action	• Collectively beneficial • Allows sharing of development infrastructure • Avoids unnecessary wells and infrastructure occurring under the competitive rule of capture	Collective-choice arrangements developed by the resource users
Monitoring	• Uses pressure maintenance on the reservoir • Uses best technical or engineering information • Provides foundation to carry out a secondary recovery programme	Monitoring programmes developed for the resource
Sanctions	• Gives all owners of rights in the common reservoir a fair share of the production	Graduated sanctions developed for "violators" of the rules
Dispute resolution	• Pre-unit agreement • Industry-standard agreements • Redetermination process	Conflict-management schemes developed
Rights of regimes	• Can be developed through voluntary or government-mandated compulsory	Rights of organized environmental regimes respected by external

	action	authorities
Administration	• Voluntary to compulsory • Other alternatives (for example, sole development, partitioned development, fixed equity, buy-out, or asset swaps)	Nested enterprises used to administer management

Table 10: Design attributes and principles of unitization versus common-pool resources (from Jarvis, 2011).

Beyond equitable sharing of the resource, users are entitled to rely on the durability and efficiency of their pumping equipment. This should be protected by governmental and industrial standards. Users also require secure access to electricity supplies or fuel and to spare parts and repair facilities. Achieving these objectives requires the attention of national regulatory bodies, as well as strong political will. The regulation and governance of pump manufacturers and suppliers is generally tied directly to industry organizations operating to and within government guidelines, as seen in the role of Europump in advising its members on compliance with the EU directives. These guidelines and regulations cover all aspects of manufactured goods, including materials, construction, efficiency and safety aspects.

The nuances of local governance in communally-owned or -managed groundwater abstraction systems have been widely analysed and solutions adopted as the result of collective community decision are seen as sound. However, several minor problems occur, particularly where small diesel-powered pumps are collectively shared amongst several users who tend to sidestep equipment maintenance. Wider adoption of equitable groundwater rights legislation will be central to realigning the role of groundwater irrigation abstraction into the future. Maintaining social cohesion will drive this need and highlight the urgency for action.

Where the distribution and quality of groundwater data and the level of understanding of the resource is weak, assigned-priority water rights legislation as applied in Wyoming, USA, is an appropriate default model. Applying this doctrine to motor-powered pumping rights will give drinking water for humans and animals the highest priority followed by municipal supplies. It also categorizes irrigation as a non-preferred use. Having stood the test of time, all hand- and animal-drawn water can be exempt from control. This will encourage the application of low technological solutions to rural water supplies and small-scale irrigation and can be extended to all groundwater developments, irrespective of the uses, through the implementation of the incrementally stepped development model (Box 7) developed by the 1970's World Bank Technology Advisory Group (Sounders and Warford, 1976).

If donors and funding agents follow this approach, the new rural water supplies will be more widely and evenly spread. This will remove one of the complaints about the selective nature of existing development programmes. It is also more suitable for the execution under the decentralization plans with limited trained manpower, given that skills and training can evolve as the level of technology applied also advances incrementally.

11.4 Future technological developments

The trends in the adoption of more precise and energy-efficient pumping technologies indicate that the global stock of groundwater pumping mechanisms can be expected to expand but that the structure will remain constant. Low-lift and low-input devices will still be needed and will service low-intensity abstractions. However, the adoption of higher capacity and higher reliability technology for high-value productive uses, including municipal water supply, industry and agriculture is likely to further concentrate intensive abstraction in aquifers that are already at risk.

Unless restricted by external controls, past experience has demonstrated that any efficiency gains achieved in groundwater pumping for irrigation are usually taken up by an expansion of the cultivated area that is likely to be coupled with negative groundwater trends. In addition, where externally-funded large-scale groundwater irrigation projects are implemented in traditional groundwater irrigation communities, they can often lead to seasonal gluts of agricultural produce that depress the local prices unless steps are taken to widen the marketing area or to feed a local food-processing sector.

Searching for future technological advances in pumping technology shows the practical uses of two materials are set to be the focus of long term electrical developments, usage and loss reduction: these are superconductors and graphene. At room temperature the normal electrical resistance losses are at least 20 percent. Initially, superconductors required cooling metals to close to zero degrees Kelvin (-273,15^0 C). Currently superconductors that work at around 70^0 Kelvin (-203,15^0 C) are available. This temperature is 7^0 Kelvin less than the boiling point of liquid nitrogen (77^0 K). Samples of superconductive material generate very strong magnetic fields, so if commercially-produced superconductor materials are developed, electric motors will be smaller, more efficient and more powerful[13].

Further approaches to superconductivity research include experiments with low-resistance, graphene nanotubes, but the main graphene applications of immediate interest are grapheme photovoltaics that promise to provide a much cheaper solution to solar power generation. Other developments already in use are the super capacitors to replace batteries for electrical storage. Currently their storage capacity is only around 50 percent of that of batteries but they can be recharged in a matter of minutes and have a recycling efficiency of over 95 percent. Future developments in this field are likely to find wide application in the storage of solar and wind power. The super capacitors are already in pilot use for electric trains and trams in China.

12. Conclusions

Within the remit, namely, *"Social adoption of groundwater pumping technology and the development of groundwater cultures: governance at the point of abstraction",* a consistent pattern is identified where early in the development cycle, the rapid and unrestrained take up of all advances in pumping technology has lead to the overexploitation of the resource base. This in turn required has prompted governments to introduce legislation to regulate groundwater abstraction. However, these initiatives have been constrained by an imperfect understanding of the groundwater occurrences.

Prior to the middle of the 19th century, the low intensity of groundwater abstraction had marginal impact on the groundwater resources and, as abstraction points were constructed and owned by individuals or communities, their rights to the groundwater were largely guaranteed by common law.

However, advances in groundwater pumping technology from the mid 19th century that helped underpin worldwide population and economic growth soon began to have unforeseen consequences. By 1900, declining groundwater levels were driving up pumping costs and reducing surface water stream flows. Investigation of these problems formed the focus of early hydrogeological studies while parallel studies of the potent health risks from groundwater contamination resulted in the introduction of the first groundwater legislation.

Within the spectrum of groundwater uses, technology has provided a continuously improving choice of more powerful and efficient pumps and the development of shaft turbine and submersible pumps throughout the 20thcentury supported the worldwide growth of groundwater-based irrigation. Initially, and in places still unregulated, this irrigation abstraction has been mainly responsible for the most heavily depleted aquifers. The necessary legislation to control overdevelopment of the resource has arguably lagged behind the rate of depletion.

The requirements of abstraction well owners are the security, reliability and economics of their groundwater supply: where security covers rights to abstract, the sustainability of the resource in terms of quantity and

---

[13] The enhanced magnetic properties of superconductors (the Meissner effect) could be used to provide highly efficient magnetic energy storage. In 2011, a number of researchers claimed to have achieved superconductivity in complex copper compounds at room temperature and if successful such enhanced electro-magnetic properties will enable pump motors to run cooler and lower the inherent energy losses associated with the rotor-stator gap. Higher rotation speeds will also be possible and enable higher vane tip velocities to be achieved in smaller diameter impellers. The vane tip velocity controls the available pumping head. Currently the maximum head for a single impeller rotodynamic pump is around 1 000m.

quality; reliability covers the robustness of the pumping equipment and power source and; economics includes the capital investment, operation and maintenance costs.

Meeting these pump owners' requirements shows the role for governments is to establish sound water rights legislation to ensure the sustainability of the groundwater supply and to set minimum efficiency and quality standards for the pump manufacturers and to ensure ready access to appropriate energy supplies. While governments have a lesser role in the economics of pumping as this should be dictated by market forces, they are seen to be considerably distorted for political purposes by a variety of subsidises.

A further important role for governments is encouraging research and innovation not just to regulate patterns of intensive abstraction for the common good but also to ensure equal access to the technology advances to the benefit all users. This is particular applicable to ensuring more efficient water usage in the irrigation sector. The research includes not only into mapping and quantifying the available groundwater resources but equally important to sound governance of groundwater abstraction is the requirement for constant monitoring of the groundwater abstraction, levels and quality.

On the legislative side, the unanimous adoption by the 193 UN member countries of 2000 Millennium Declaration on the environment has marked a turning point as both national and international attitudes recognized the need for compliance and for realignment and enforcement of groundwater resources management, which can only be achieved by the introduction of equitable water rights. However, implementation of legislation covering groundwater abstraction for irrigation has proven, and will still prove, particularly problematic as in many countries the political emphasis still remains on trying to meet farming community demands for a secure supply of groundwater from a continually declining resource.

Acronyms

AD	*Anno Domini*
Asl	Above sea level
BC	Before Christ
BESCOM	Bangalore Electricity Supply Company, India
Bgl	Below ground level
BP	Before Present
CFD	Computational Fluid Dynamics software
CILSS	*Comité permanent Inter-Etats de Luttecontre la Sécheresse dans le Sahel*
CGWB	Central Groundwater Board of India
CWSA	Ghanaian Community Water and Sanitation Agency
DEFRA	Department for Environment, Food and Rural Affairs
DfID	UK Department for International Development
DRUM	USAID Distribution Reform, Upgrades and Management project
DWA	Zambian Department of Water Affairs
DWID	Zambian Department of Water and Irrigation Development
EU	European Union
FAO	Food and Agriculture Organization of the UN
GCD	Groundwater Conservation District
GHG	Greenhouse Gas emissions
GMD	Groundwater Management District
IWMI	International Water Management Institute
IDWSSD	International Drinking-Water Supply and Sanitation Decade

JMP	WHO/UNICEF Joint Monitoring Program
MDG	Millennium Development Goal
NGO	Non-Governmental Organization
NORAD	Norwegian Agency for Development Cooperation
NSSO	National Sample Survey Organization of India
PPP	Public-Private Partnership
PWM	Pulse Width Modulation technology
SGS	*Société Générale de Surveillance*
SPV	Solar Photovoltaic water pumps
UK	United Kingdom
UN	United Nations
UNDESA	United Nations Department of Economic and Social Affairs
UNICEF	United Nations Children's Fund
uPVC	Unplasticized polyvinyl chloride
USA	United States of America
USAID	US Agency for International Development
USGS	US Geological Survey
VLOM	Village-Level Operation and Maintenance
VSD	Variable Speed Drive
WENEXA	USAID Water-Energy Nexus Activity
WHO	World Health Organization

References

Abavana, C.G., 2008. Ghana: The National Electrification Scheme (NES). Power Point Presentation, Technical Advisor, Ministry of Energy, Accra, GHANA.

Aguilar, D., 2011. Groundwater Reform in India: An Equity and Sustainability Dilemma. *Texas International Law Journal*, Vol. 46, pgs 623-653.

Ahluwalia, S. S. and A. Goyal, 2003. *Energy Efficiency and Conservation; Status and Prospects*. Report prepared for the Asian Development Bank. http://www.adb.org/Documents/Reports/Consultant/TAR-IND-4066/Energy/ahluwalia.pdf

Ananda, J., 2009. *Water Institutions in India: An Institutional Design Perspective.* In Reforming Institutions in Water Resource Management: Policy and Performance for Sustainable Policy Development, Eds. L. Crase and V. P. Gandhi eds., 2009, pgs 100-106.

Baumann, E., 2000. *Water Lifting*. SKAT Series of Manuals on Drinking Water Supplies, Vol 7, Switzerland.

Baumann, E., 2009. May-day! May-day! Our handpumps are not working! *Rural Water Supply Network, Perspectives* No 1.

Bayer, M.G., 1987. Water and Sanitation in UNICEF 1946-1986.*UNICEF History Series, Monograph Vlll*

Bazza, M., 2007. Overview of the history of water resources and irrigation management in the Near East region, *Water Sciences and Technology: Water Supply* Vol. 7, No. 1, pgs 201–209.

Behr, H.C., 1896. *Mine Drainage, Pumps, etc*. California State Mining Bureau, Bulletin 9, 240pgs. http://ia700308.us.archive.org/26/items/minedrainagepump00behrrich/minedrainagepump00behrricpdf

Birner, R., S. Gupta and N. Sharma, 2011. The political economy of agricultural policy reform in India: fertilizers and electricity for irrigation. International Food Policy Research Institute (IFPRI) research monograph

Black, M., 1998. *Learning What Works A 20 Year Retrospective View on International Water and Sanitation Cooperation*. UNDP-World Bank Water and Sanitation Program.

Blandford, T.N., D.J. Blazer, K.C. Calhoun, A.R. Dutton, T. Naing, R.C. Reedy, and B.R. Scanlon, 2003. Groundwater Availability of the Southern Ogallala Aquifer in Texas and New Mexico; Numerical Simulations Through 2050: Final Report prepared for the Texas Water Development Board. http://www.twdb.state.tx.us/gam/ogll_s/OGLL_s_FinalReport_PartA.pdf

BPMA (British Pump Manufacturers Association), 2006. *UK Guide to the Procurement of Rotodynamic Pumps*. British Pump Manufacturers Association V4/25 July 2006/DTR.

Carter, R.C., S.F. Tyrrel and P. Howsam, 1996. Strategies for Handpump Water Supply Programmes in less developed countries. *Journal of the Chartered Institution of Water and Environmental Management*, Vol. 10, No. 2, pgs130-136

CGWB-MoWR (GoI), 2006. *Dynamic Ground Water Resources of India (March 2004)*, Central Ground Water Board, Ministry of Water Resources, Government of India, Faridabad, 2006. http://cgwb.gov.in/GroundWater/GW_assessment.htm

Charalambous, A.N., 1982. Problems of groundwater development in the Sana'a basin, Yemen Arab Republic. In: *Improvements of Methods of long Term Prediction of Variations in Groundwater Resources and Regimes Due to Human Activity* (Proceedings of the Exeter Symposium, July 1982). IAHS Publ. No.136,pgs 265-274

Clutterbuck, J.C., 1842. Observations on the periodical drainage and replenishment of the subterraneous reservoir in the Chalk Basin of London. *Proceedings of the Institution of Civil Engineers*, 2, pgs155-160.

Clutterbuck, J.C., 1843. Observations on the periodical drainage and replenishment of the subterraneous reservoir in the Chalk basin of London - continuation of the paper read at the Institution, May 31st 1842. *Proceedings of the Institution of Civil Engineers*, 3, pgs156-165.

Clutterbuck, J.C., 1850. On the periodical alternations, and progressive permanent depression, of the Chalk water level under London. *Proceedings of the Institution of Civil Engineers*, 9, pgs151-180.

CMIE (Centre for Monitoring Indian Economy), 2003. Economic Intelligence Service, Mumbai. http://www.cmie.com/

Condra, G.E., 1944. *Terminology Relating to the Occurrence, Behavior and Use of Water in Nebraska*. Nebraska Water Survey, Lincoln, Nebraska: Conservation and Survey Division, Bulletin No. 1, pg 53.

Connelly, M.L., 2005.The British Campaign in Aden, 1914-1918. *Journal of the Centre for First World War Studies*, Vol. 1 No 3.pgs 65-96. http://www.js-ww1.bham.ac.uk/articles/issue3_Connelly.pdf

CWSA, 2004. *Small Town Sector Policy (Operation and Maintenance Guidelines)*. Community Water and Sanitation Agency, Accra Supply Authority, Accra, Ghana.

De Almeida, A.T., F.J.T.E. Ferreira, P. Fonseca, B. Chretien, H. Falkner, J.C.C. Reichert, M. West, S.B. Nielsen and D. Both, 2001. *VSDs for Electric Motor Systems*. European Commission, Directorate-General for Transport and Energy, SAVE II Programme 2000.

Decision Analyst, Inc., 2003. Making Nebraska The Agricultural Leader Of The 21st Century. Report prepared for the Nebraska State Department of agriculture.

DRUM training programme, 2005. Annex 1: Background note Distribution Reform, Upgrades and Management (DRUM) Project

DWA, 1974. *Annual Report of the Department of Water Affairs, 1971*. Government Printers, Lusaka.

Engineering and Mining Journal, 2011. KCM (Konkola Copper Mine) Bottoms Out New Shaft for Konkola Deep. Engineering and Mining Journal, 11 August 2011.

ENS (Environment News Service), 2007. Ethanol Production Threatens Plains States With Water Scarcity. http://ens-newswire.com/ens/sep2007/2007-09-21-091.asp

FAO (Food and Agriculture Organization), 2005a. AQUASTAT database. www.fao.org/ag/agl/aglw/aquastat/main/index.stm

Fischer, K. and D. Thoma. 1932. Investigation of the Flow Condition in a Centrifugal Pump," *Transactions of the ASME*, Vol. 54, pgs141-155.

Fouegue, J-A., 2007. *Analysis of ways to improve water supplies for sedentary cattle-owning communities: a* *case study in Rwebisengo, Sub-county of Bundibugyo District, Uganda*. MSc in Water Management: Water and Society Cranfield University, Institute of Water and Environment, School of Applied Sciences.

Fraenkel, P. and J. Thake, 2006. *Water Lifting Devices* (3rd Edition). FAO and Intermediate Technology Publications, UK.

Fraenkel, P.L., 1986. *Water Lifting Devices*. FAO Irrigation and Drainage Paper 43, FAO, Rome. 341 pgs.

Freese and Nichols, Inc., 2006, Regional Water Plan, Panhandle Water Planning Area, Amarillo, Texas. http://www.panhandlewater.org/

Garduño, H. and S. Foster, 2010. Sustainable Groundwater Irrigation approaches to reconciling demand with resources. *GWmate - Strategic Overview Series* No. 4, World Bank.

Gia, L.H. and T. Fugelsnes, 2010. Field Note: A review of progress in seven African countries Public-Private Partnerships For Small Piped Water Schemes. World Bank, Water and Sanitation Program, Nairobi, Kenya.

Gilson, P., Aistrup, J. A., Heinrichs, J. And Zollinger, B., 2001.*The Value of Ogallala Aquifer Water in Southwest Kansas*. Docking Institute for Southwest Kansas Groundwater Management District, 2001. http://www.gmd3.org/pdf/ogal1.pdf

Giordano, M. and K.G.Vilholth, 2007. *The Agricultural Groundwater Revolution: Opportunities and Threats to Development*. CABI - International Water Management Institute.

Golden, B., J. Peterson and D. O'Brien, 2008. Potential Economic Impact of Water Use Changes in Northwest Kansas. Department of Agricultural Economics at Kansas State University. http://www.agmanager.info/policy/water/ImpactofWaterUseChanges_NW-KS.pdf

Government of India (GOI), 2003. Ministry of Agriculture, Department of Agriculture and Cooperation, Agricultural Statistics, www.agricoop.nic.in

Green, D.E., 1992. A History of Irrigation Technology Used to Exploit the Ogallala Aquifer. in David E. Kromm and Stephen E. White, eds. *Groundwater Exploitation in the High Plains* (Lawrence: University Press of Kansas, 1992), pgs 29-30.

Grossman, N. and D. Carlson, 2011. Agriculture Policy in India: The Role of Input Subsidies. USITC (United States International Trade Commission) Executive Briefings on Trade March 2011.

Hanson, B.R., 1988. Benefits and costs of improving pumping efficiency. California Agriculture, July - August 1988. http://ucanr.org/repository/CAO/fileaccess.cfm?article=68788&p=IFWWTI&filetip=pdf

Harrower, M.A., 2006. *Environmental versus Social Parameters, Landscape and the Origins of Irrigation in Southwest Arabia (Yemen).* PhD Dissertation, Ohio State University.

Harvey, P.A. and B.H. Skinner, 2002. *Sustainable Handpump Projects in Africa Report on Fieldwork in Zambia April 18 - May 4 2002*. Produced under a Knowledge and Research (KAR) project funded by the Department for International Development (DFID), UK. Contract No. R7817.

Harvey, P.A. and S.M. Kayaga, 2003. *Sustainable Handpump Projects in Africa Report on Fieldwork in South Africa May 23 – June 6, 2003*. Water, Engineering and Development Centre, Knowledge and Research (KAR) project funded by the Department for International Development (DFID), UK. Contract No. R7817.

Harvey, P.A., 2003.*Sustainable Handpump Projects in Africa Report on Fieldwork in Uganda February 10 – 14, 2003*. Produced under a Knowledge and Research (KAR) project funded by the Department for International Development (DFID), UK. Contract No. R7817.

Huang, Q., S. Rozelle and Dinghuan Hu, 2007. Pump-set Clusters in China: Explaining the Organization of the Industry that Revolutionized Asian Agriculture. *Asia-Pacific Development Journal* Vol. 14, No. 2, December 2007.

Hughes, M.V.B., 2000. *Success and Failure in Technology Transfer: The Story of the Handpump*. MA thesis, Institute for the History and Philosophy of Science and Technology, University of Toronto.

Hydraulic Institute, Europump and US Department of Energy, 2004. *Variable Speed Pumping — A Guide to Successful Applications, Executive Summary*. Hydraulic Institute, Europump, and the U.S. Department of

Energy's (DOE) Industrial Technologies Program.

Hydraulic Institute, Europump and US Department of Energy, 2000. *Pump Life Cycle Costs: A Guide to LCC Analysis for Pumping Systems*. Hydraulic Institute, Europump, and the U.S. Department of Energy's (DOE) Industrial Technologies Program.

International Development Enterprises and Winrock International, 2002. *The Smallholder Irrigation Market Initiative. Volume II*: Regional Studies and Plans (Sub-Saharan Africa, Southwest China, Deccan Plateau, Gangetic Plains, Poor Hills of Asia). Report prepared for the SIMI Network. http://www.siminet.org/documents/simi-vol2.pdf

IT Power India, 2006. *Developing Renewables, Indian Country Study: Part D RE Projects*. Report prepared for Sixth Framework Programme Priority 3, Underpinning the economic potential and cohesion of a larger and more integrated EU.

IWMI (International Water Management Institute), 2007a. T. Shah, J.J. Burke and K. Villholth. Groundwater: a global assessment of scale and significance. *Chapter 10 in Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. London: Earthscan, and Colombo: International Water Management Institute. http://www.iwmi.cgiar.org/assessment/Water%20for%20Food%20Water%20for%20Life/Chapters/Chapter%2010%20Groundwater.pdf

IWMI, 2007b, F. van Steenbergen and T. Shah. Rules rather than rights: self-regulation in intensively used groundwater systems. *Chapter 12 in Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. London: Earthscan, and Colombo: International Water Management Institute. http://www.iwmi.cgiar.org/assessment/Water%20for%20Food%20Water%20for%20Life/Chapters/Chapter%2010%20Groundwater.pdf

Jacobs, J. J., P.T. Tyrrell and D.J. Brosz, 1995. Wyoming Water Law: A Summary, Cooperative Extension Service College of Agriculture and Wyoming Water Research Center, University of Wyoming. http://library.wrds.uwyo.edu/wrp/90-17/90-17.html

Jarvis, W.T., 2011. Unitization: a lesson in collective action from the oil industry for aquifer governance, Water International, Vol. 36:5, pgs 619-630

Jones, M. J., 1990. Rural well rehabilitation and maintenance in Welo, Ethiopia. In *Water Well Monitoring, Maintenance, Rehabilitation*, Spon, London

Karaji, M. ca. 1100. *The Extraction of Hidden Waters*. (see M. Nadjiand, R. Voight, 1972. "'Exploration for Hidden Water' by M. Karaji-Oldest Textbook on Hydrology?" *Groundwater*, September-October, pgs 43-46.)

Karekezi, S., J. Kimani, A. Wambille, P. Balla, F. Magessa, W. Kithyoma and X.Ochieng, 2005.*The Potential Contribution of Non-Electrical Renewable Energy Technologies (RETs) to Poverty Reduction in East Africa. Final Regional Report,* AFREPREN/FWD. http://www.gnesd.org/Downloadables/RETs/AFREPREN%20RETs%20final%20version.pdf

Kay M. and T. Brabben, 2000. *Treadle pumps for Irrigation in Africa*. IPTRID Secretariat, FAO, Rome, 2000.

Kepfield, S. S., 1993. The Liquid Gold" Rush: Groundwater Irrigation and Law in Nebraska, 1900-93. *Great Plains Quarterly*, Center for Great Plains Studies, University of Nebraska. Fall Issue, 1993, pgs 237-250. http://digitalcommons.unl.edu/greatplainsquarterly/738

Lall, U., V. Modi, K. Narula, R. Fishman and L. Polycarpou, 2011. Addressing the Water Crisis in Gujarat, India. Columbia Water Center Earth Institute, Columbia University

Lightfoot, D.L., 2000. The Origin and Diffusion of Qanats in Arabia: New Evidence from the northern and southern Peninsula. *The Geographical Journal*166(3):215-226.

Litke, D.W. 2001, *Historic Water-Quality Data for the High Plains Region Ground-Water Study Area in Colorado, Kansas. Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming, 1930-98.* USGS Water-Resources Investigations Report 00-4254. http://pubs.usgs.gov/wri/wri00-4254/pdf/wrir00-4254.pdf

Mangisoni, J. H., 2006. *Impact of Treadle Pump Irrigation Technology on Smallholder Poverty and Food Security in Malawi: A Case Study of Blantyre and Mchinji Districts*. Report for the International Water Management

Institute (IWMI)

Mapp, H. P., 1988. Irrigated Agriculture on the High Plains: An Uncertain Future. *Western Journal of Agricultural Economics*, 13(2), 1988. http://ageconsearch.umn.edu/bitstream/123456789/3037/1/13020339.pdf

Mbamali, I., 1998. Maintainability of Rural Water Supply Bore-Holes. *Nigerian Journal of Technology and Management*, Vol. 1 No.1, pgs 34-37.

McJwikin, F.E., 1977. *Hand Pumps for Use in Drinking Water Supplies in Developing Countries.* Technical Paper Series No. 10, International Reference Centre for Community Water Supply, The Hague.

Mercados (Energy Markets India Pvt. Ltd.), 2010. *Preparing A Roadmap For Implementing Energy Efficiency Portfolio Obligation In India: Final Report*. Prepared for Climateworks Foundation USA

Michael, M. and K. Gray, 2005. Evaluation of ECHO Funded/UNICEF *Managed Emergency Health/Nutrition and Water and Environmental Sanitation Action For Conflict Affected Populations in North Darfur, Blue Nile and Unity States of Sudan*. ECHO-UNCIEF.

MLGH (Ministry of Local Government and Housing, Zambia), 2007. *National Guidelines for Sustainable Operation and Maintenance of Hand Pumps in Rural Areas*. Government of Zambia-JICA.

Molenaar, A., 1956. *Water Lifting Devices for Irrigation*. FAO Agricultural Development Paper No. 60, FAO, Rome. 76 pgs.

Mudgal, A. K., 1997. *India Handpump Revolution: Challenge and Change*. Swiss Centre for Development Cooperation in Technology and Management, HTN Working Paper: WP 01/97.

Mukherji, A. 2007. Two faces of energy irrigation nexus in West Bengal, India: high flat rate electricity tariff and escalating diesel prices**.** Invited paper presented at International Conference on Linkages between Energy and Water Management for Agriculture in Developing Countries, ICRISAT, Hyderabad, 29-30 January 2007. 35p

Mukherji, A., 2007. Against the dominant discourse: Making a case for groundwater irrigation for poverty alleviation in West Bengal, India. http://www.isid.ac.in/~planning/ConferenceDec07/Papers/AditiMukherji.doc.

Mylne, R. W. 1840. On the supply of water from artesian wells in the London Basin, with an account by W. C. Mylne of the sinking of the well at the reservoir of the New River Company, in the Hampstead Road. *Transactions of the Institution of Civil Engineers*, 3, 229-244.

Narula, K., R. Fishman, V. Modi and L. Polycarpou, 2011. Addressing the Water Crisis in Gujarat, India. White Paper. Columbia Water Center Earth Institute, Columbia University, 9 pgs. http://water.columbia.edu/sitefiles/file/Gujarat%20WP.pdf

Njalam'mano, J. B. J., 2007.*Current Status and Management of Hand Pump Equipped Water Facilities in Blantyre Rural District, Malawi: A Case Study of Kapeni and Lundu Traditional Authorities*. MSc Thesis submitted, Water Resources and Livelihood Security, Department of Water and Environmental Studies, Institute of Thematic Studies, Linköping University, Sweden.

Padmanaban, S. and A. Sarkar, 2005. *Electricity Demand Side Management (DSM) in India – a Strategic and Policy Perspective*. Office of Environment, Energy and Enterprise US Agency for International Development, New Delhi, India.

Polycarpou, L., 2010. Small is Also Beautiful – Appropriate Technology Cuts Rice Farmers' Water Use by 30 Percent in Punjab, India. Water Matters, News from the Columbia Water Center. http://blogs.ei.columbia.edu/2010/11/17/%E2%80%9Csmall-is-also-beautiful%E2%80%9D-%E2%80%93-appropriate-technology-cuts-rice-famers%E2%80%99-water-use-by-30-percent-in-punjab-india/

Purohit, P. and A. Michaelowa, 2005. *CDM potential of SPV pumps in India*. Paper No 4 by HWWI Research Programme International Climate Policy, Hamburg Institute of International Economics (HWWI)

Ramachandra Murthy, K.V.S. and M. Ramalinga Raju, 2009. Electrical Energy Loss in Rural Distribution Feeders – A Case Study. Journal of Engineering and Applied Sciences, Vol. 4 No. 2, pgs 33-37.

Rawal, V., 2008. Ownership Holdings of Land in Rural India: Putting the Record Straight. Economic & Political Weekly, March 8, 2008 pgs 43-48.

http://www.agrarianstudies.org/UserFiles/File/Rawal_Ownership_Holdings_of_Land_in_Rural_India.pdf

Reidhead, W., 2001. Achieving agricultural pumpset efficiency in rural India. *Journal of International Development*, Volume 13, Issue 2, pgs 135–151.
http://onlinelibrary.wiley.com/doi/10.1002/jid.v13:2/issuetoc

Reynolds J., 1992. *Handpumps: Towards a sustainable technology*. No: 11462. UNDP-World Bank Water and Sanitation Programme.

Roberts, M. G., Male, T. M. and Toombs, T. P., 2007. *Potential Impacts of Biofuels Expansion on Natural Resources, a case study of the Ogallala Aquifer Region, Environment Defence*.
http://www.edf.org/documents/7011_Potential%20Impacts%20of%20Biofuels%20Expansion.pdf

Robins, N., J. Davies, J. Farr, 2012. Groundwater supply and demand in the Southern African Crystalline Basement - evidence from Malawi. In press.
RWSN, 2010. *Myths of the Rural Water Supply Sector: Perspectives No 4*. Rural Water Supply Network Executive Steering Committee, Rural Water Supply Network.

Sant, G. and S. Dixit, 1996. Agricultural pumping efficiency in India: the role of standards. *Energy for Sustainable Development*, Volume III, No. 1, pgs 29-37.

Sara, J. and T. Katz, 1998. *Making Rural Water Supply Sustainable: Report on the Impact of Project Rules*. UNDP-World Bank Water and Sanitation Program.

Sarkar, A., 2011. Socio-economic Implications of Depleting Groundwater Resource in Punjab: A Comparative Analysis of Different Irrigation Systems. Economic & Political Weekly, February 12, 2011, Vol. xlvi, No. 7, pgs 59-66.
http://www.indiawaterportal.org/sites/indiawaterportal.org/files/Socioeconomic%20Implication_Depleting%20Groundwater%20Resource%20in%20Punjab_Anindita%20Sarkar_EPW_2011.pdf

Scott, C. A. and B. Sharma, 2009. Energy supply and the expansion of groundwater irrigation in the Indus-Ganges Basin. *Intl. J. River Basin Management* Vol. 7, No. 1, pgs 1-6.

Shah, T. 2001. *Wells and welfare in the Ganga basin: Public policy and private initiative in eastern Uttar Pradesh, India.* Research Report 54. Colombo, Sri Lanka: International Water Management Institute.

Shah, T., M. Giordano and A. Mukherji, 2012. Political economy of the energy-groundwater nexus in India: exploring issues and assessing policy options. Hydrogeology Journal (published online 10 January 2012).

Shah, T., 2007a. Co-management of Electricity and Groundwater: Gujarat's Jyotirgram Yojana. Powerpoint presentation to Strategic Analyses of India's NRLP Regional Workshop Hyderabad, 29 August 2007.

Shah, T., 2007b. Crop per Drop of Diesel! Energy-Squeeze on India's Smallholder Irrigation*. Proceedings of the NRLP Regional Workshop*. Hyderabad, 29 August 2007, pgs 253-270.

Shah, T., S. Bhatt, R. K. Shah and J. Talati, 2008. Groundwater governance through electricity supply management: Assessing an innovative intervention in Gujarat, western India, *Agricultural Water Management* (2008), 10 pgs.

Shamsudduha, M., R.G. Taylor, K.M. Ahmed and A. Zahid, 2011. The impact of intensive groundwater abstraction on recharge to a shallow regional aquifer system: evidence from Bangladesh. Hydrogeology Journal (2011) 19: pgs 901–916

Sharma, K.D., 2007. Groundwater Governance: The Indian Scenario. In Groundwater Governance Ownership of Groundwater and Its Pricing : *Proceedings of the 12 National Symposium on "Hydrology" November 14-15, 2006*; Eds. K.D. Sharma, N.C. Ghosh, S. Romani, Y.B. Kaushik, Capital Publishing Company, New Delhi.

Singh, D., 2007. Who Gains and Who Loses in the Game of Groundwater Markets in Water-scarce Regions. Agricultural Economics Research Review Vol. 20 July-December 2007 pgs 345-360.

Sounders, R.J. and J.J. Warford, 1976. *Village Water Supply: Economics and Policy in the Developing World.* World Bank Research Publication, Johns Hopkins University Press, Baltimore and Londonhttp://www-wds.worldbank.org/servlet/WDSContentServer/WDSP/IB/2002/11/28/000178830_98101911002968/Rendered/PDF/multi0page.pdf

State of California, 1931. *Report on Irrigation Districts in California for the Year 1930.* Department of Public

Works, Bulletin no. 21-b. http://ia700200.us.archive.org/8/items/reportonirrigati211930sacrrich/reportonirrigati211930sacrrich.pdf

Stephenson, R. 1841. *London Westminster and Metropolitan Water Company*. Second Report to the Directors. London.

Strand, J., 2010. *The Full Economic Cost of Groundwater Extraction*. Development Research Group, Environment and Energy Team, The World Bank.

Svubure, O., T. Gumbo, G. Soropa, F. Rusere, A. Ndeketeyaand D. Moyo , 2011. Evaluation of the Sand Abstraction Systems for Rural Water Supply: the case of Lupane District, Zimbabwe. *International Journal of Engineering Science and Technology (IJEST)*,Vol. 3 No. 1, pgs757-765.

Szab´o, S., K B´odis, T Huld and M Moner-Girona, 2011. Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension. Environmental Research Letters No. 6, 034002, IOP Publishing, 9pgs.

Theesfeld, I., 2008. Institutional aspects of groundwater governance. In *Conceptualizing Cooperation on Africa's Transboundary Groundwater Resources*, German Development Institute, pgs 307- 338.

Thresh, J.C. and Beale, J.F. 1925. *The Examination of Waters and Water Supplies*. 3rd Edition. J & A Churchill, London.

Tongia, R., 2007. The political economy of Indian power sector reforms. *In:* D.G. Victor and T.C. Heller, eds.,*The political economy of power sector reform : the experiences of five major developing countries.* Cambridge, New York: Cambridge University Press.

Trantor International, 2007. *Fiction, Facts & Future: Norad's Assistance to Water Supply and Sanitation in Tanzania and Kenya during the 70's, 80's and 90's*. Report prepared for NORAD by Tranor International under contract to NTU. Norad Report 16/2008 Discussion.

Traore, D., 2010. Solar & small wind turbine water pumping hybrid system as a tool to combat poverty in Mali. Presentation to 1st World Summit on Small Wind Turbines Germany

UNDESA (United Nations Department of Economic and Social Affairs), 2004. *A Gender Perspective on Water Resources and Sanitation*. Background Paper No.2, Submitted by: Interagency Task Force on Gender and Water, UN Department of Economic and Social Affairs, DESA/DSD/2005/2

UNICEF (United Nations Children's Fund), 1999. *Towards better programming A Water Handbook*. Water, Environment and Sanitation Technical Guidelines Series - No. 2

UNICEF 2010. *UNICEF Water, Sanitation and Hygiene Annual Report 2009*. UNICEF New York.

United Nations, 1960. *Large-Scale Ground-Water Development*. Water Resources Development Centre, New York.

US Bureau of Reclamation, 2007. Environmental Consequences, Republican River Basin Water Management Study. http://www.usbr.gov/gp/nepa/rep_riv_feis/feis_chap4.htm

USGS – NAWQA, 2007. The National Water Quality Assessment Program – Informing water-resource management and protection decisions, US Geological Survey, 2007. http://water.usgs.gov/nawqa/xrel.pdf

US National Renewable Energy Laboratory, 2011. U.S. Installed Wind Capacity. U.S. Department of Energy. http://www.windpoweringamerica.gov/wind_installed_capacity.asp

Vaa, M, 1993. *Towards More Appropriate Technologies? Experience from the Water and Sanitation Sector*. The Scandinavian Institute of African Studies, (Nordiska Afrikainstitutet), Uppsala, Research Report No 94.

Van Niekerk, T. and D.A. Still, 2002. Handpumps in Kwazulu-Natal: Still the most important water supply methodology. Water Institute of Southern Africa, Biennial Conference, Durban, May 2002.

Van Wijk-Sijbesma, C., 1998. *Gender in Water Resources Management, Water Supply and Sanitation, Roles and Realities Revisited*. IRC International Water and Sanitation Centre, Delft, the Netherlands.

Vick, B.D., 2010. Developing a Hybrid Solar/Wind Powered Irrigation System for Crops in the Great Plains. SOLAR 2010, American Solar Energy Society, National Solar Conference Proceedings, Phoenix, Arizona, May

2010.

Wagner, E.G. and J.N. Lanoix, 1959. *Water Supply for Rural Areas and Small Communities*. World Health Organization Monograph Series 42, Geneva

Walters, R.C.S., 1936. The Nation's Water Supply. Ivor Nicholson and Watson Limited, London.

Ward P.R.B. and W.G.Dunford, 1984. Solar powered groundwater pumping for medium heads. *Challenges in African Hydrology and Water Resources* (Proceedings of the Harare Symposium, July 1984). IAHS Publ. no. 144.

Warr, K., M. Gaffen, A. Rajagopaland M. Mishra, 2011. *Evaluation of DRUM and WENEXA: Assessing the impact of USAID/India's Distribution Reform, Upgrades and Management Program and its Water and Energy Nexus Program*. Prepared for United States Agency for International Development

Water Aid, 2007.WebTechnology notes, Section 8: Handpumps
http://www.wateraid.org/documents/plugin_documents/technology_notes_07_web_1.pdf

WaterAid, 2011. *Sustainability framework*. WaterAid

Watercentre.org, 2011. Speakers' Abstracts. WASH2011 Conference, Brisbane, Australia.

WDID (Water Development and Irrigation Department), 1953.*Annual Report for the Year 1952*. Government Printer, Lusaka.
http://www.bgs.ac.uk/sadc/fulldetails.cfm?id=ZM1084

Weiss, C. and N. Jequiereds., 1984.*Technology, Finance and Development: An Analysis of the World Bank as a Technological Institution.* Toronto: Lexington Books.

White, G.F., D.J. Bradley and A.U. White, 1972. *Drawers of Water, Domestic Water Use in East Africa*. The University of Chicago Press.

WHO/UNICEF, 2011. Drinking Water Equity, Safety and Sustainability: Thematic report on drinking water 2011: Joint Monitoring Programme for Water Supply and Sanitation (JMP).
http://bit.ly/u1kw2l

WHO/UNICEF-JMP, 2000. *Global Water Supply and Sanitation Assessment 2000 Report*   WHO and UNICEF Joint Monitoring Programme for Water Supply and Sanitation (JMP), WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation. (ISBN 92 4 1562021)

World Bank Group, 2010. *Sustaining Water for All in a Changing Climate*. World Bank, World Bank Group Implementation Progress Report of the Water Resources Sector Strategy, 57125

World Bank**,** 1976.*Village Water Supply.* The World Bank, Washington.

World Bank, 1984. *Handpumps Testing and Development: Proceedings of a Workshop in China*. G. Tschannerl and K. Bryan, editors, World Bank Technical Paper Number 48, RWS Handpumps Project.

WSP (2010) *Majini Maisha: Innovative finance for community water schemes in Kenya*.
http://www.wsp.org/index.cfm?page=page_disp&pid=22053

WSTB (Water Science and Technology Board of the National Research Council), 2007. (source Tilman, Hill and Lehman, 2006), Carbon-negative Biofuels from Low-input High-diversity Grassland Biomass. Science 314:1598–1600.
http://www.sciencemag.org/cgi/content/full/314/5805/1598?rss=1

Yazdi, A.A.S., 2006. A Survey of the Historical Evolution of Qanats in Iran. Power Point Presentation a G-Wadi meeting on Water Harvesting, Aleppo, Syria, November 2006 and accompanying text.