Chapter 1

Introduction

The depletion of aquifers by excessive pumping is one of the prominent global sustainability issues in the field of water resources. It is mainly caused by the water needs of irrigated agriculture. The North China Plain is a global hotspot of groundwater overexploitation. Since the 1980s, groundwater levels dropped by about 1 m/year mainly due to the intensification of agricultural production by a double cropping system of winter wheat and summer maize. The consequences of declining groundwater levels include the drying up of streams and wetlands, soil subsidence, seawater intrusion at the coast and rising cost of pumping. The depletion of storage makes the production system more vulnerable with respect to climatic extremes associated with climate change. Sustainable management of aquifers keeps groundwater levels between an upper and a lower red line. While the upper red line is designed to prevent soli salinization, the lower red line is motivated by ecological requirements, water quality constraints or infrastructural concerns. Global water balances are useful in identifying the scope of the problem and the size of efforts required to restore a sustainable pumping regime. Adequate local action needs a local analysis. Guantao County is selected for such a local analysis in the North China Plain.

1.1 Groundwater Over-Pumping and Consequences

Aquifer depletion caused by excessive pumping has been described in the literature over the last two decades (Foster and Chilton 2003; Kinzelbach et al. 2003; Konikow and Kendy 2005), with the Ogallala aquifer in the United States' Midwest being the first and iconic case of a large, significantly depleted aquifer (Wines 2013). The Millennium Ecosystem Assessment Report (MEA 2005) identifies more hotspots of aquifer depletion due to agricultural irrigation, including California, Spain, Pakistan, India, and the main case of interest here, the North China Plain (NCP) (Fig. 1.1). In all these cases, aquifer depletion shows through constantly declining groundwater

Fig. 1.1 Hotspots of unsustainable agricultural groundwater abstraction, indicating North China Plain, Northwest India, High Plains Aquifer and Southern California in the USA as moderate to high overdraft regions. *Source* MEA (2005)

levels. In the North China Plain, for example, rates of decline of up to 2 m per year since the 1980s have been observed.

A global vision of large-scale groundwater depletion has been provided by the Grace mission, a satellite mission, which has been measuring the gravity field of the earth and its changes in time since 2002 (<http://www2.csr.utexas.edu/grace/overview.html>).

Temporal changes of the gravitational field are caused by displacement of large water masses over time. The water losses on the landmass not only include water from the melting of glaciers but also from the depletion of aquifers. Comparison of Figs. 1.2 to 1.1 shows the coincidence of high agricultural groundwater abstraction and mass-losses (reddish tones). A thorough analysis of areas of water loss and water gain and their respective causes is given in (Rodell et al. 2018). Figure 1.3 shows the mass change in a rectangle covering the North China Plain (between 35° and 40° N and 114° and 117.5° E) using the mascon approach. The gravitational signal has been decreasing, indicating a loss of 39 cm of water column (or about 2.4 cm/year) between 2004 and 2020. The associated area is about 165,000 km².

This leads to a total mass loss of 64 km³ or an average annual loss of 4 km³/year. An analysis by Feng et al. (2013) taking into account an area of 370,000 km², identifies a storage loss of 8.3 ± 1.1 km³/year (2.2 ± 0.3 cm/year) from 2003 to 2010. Figure 1.3 shows that there is quite some variation in the decline rate, and one must be careful when comparing figures for different periods in time. Further, the attribution of the signal to an area introduces uncertainty. Ascribing the total loss of 4 km³/year to the unconfined aquifer and assuming a specific yield of 0.03, it translates to a groundwater level decline rate of about 0.8 m/year on average.

Why do we bother about aquifer depletion? Aquifer depletion inherently contains a mechanism by which abstraction will decrease with a declining groundwater table.

Fig. 1.2 Distribution of average mass change over the globe between 2004 and 2016 in cm of water equivalent per year (reddish tones: mass loss, bluish tones: mass gain). *Source* NASA (2020)

Fig. 1.3 Mass loss averaged over the North China Plain between 2004 and 2020 in monthly steps (in cm water equivalent) (Data retrieved from NASA’s GRACE data analysis tool <https://grace.jpl.nasa.gov/data-analysis-tool>, note that no data were available mid 2017 to mid 2018 before the launch of GRACE FO)

On one hand the well yields decrease with declining groundwater levels, reaching zero, when the groundwater level falls below the level of the pump. On the other hand, the energy cost of pumping increases with depth to groundwater, making water more and more expensive. Eventually, pumping will have to decrease due to economic constraints and an equilibrium is reached again, however at much lower groundwater levels. In economics, optimal use of groundwater means maximizing net present value of revenue derived from it. This implies that depleting aquifer storage today yields a higher total benefit over time than preserving it for the future, as standard discounting values production gain by irrigation today higher than the same production gain in the future. Some economists (Gisser and Sanchez 1980a, b) have argued that compared to free market forces, contributions of groundwater management to social benefit are at best marginal.

This view undervalues the negative consequences of aquifer depletion encountered before a limit for pumping is reached. In particular, it undervalues water storage of an aquifer, which provides a buffer against droughts. Depleting an aquifer allows high agricultural production and leads to a grain bubble (Lester Brown in (George 2011)). A return to sustainable groundwater abstraction is almost inevitably associated with the bursting of this bubble and a possibly disruptive reduction in agricultural production.

An aquifer in dynamic equilibrium is characterized by its average recharge being equal to its average discharge in the long term. The equilibrium is disturbed, when the recharge decreases, or the discharge increases over a prolonged period of time. Consequently, groundwater levels will decline, eventually reaching a limit. There are basically three ways in which pumping can come to an end: The first is reaching the physical limit of drying up of the aquifer. The second is reaching the water quality limit. With increasing depth to groundwater, mineralization usually increases, and when it hits a threshold unsuitable for use, pumping will stop. The third, considered in the analysis of Gisser and Sanchez, is reaching the economic limit, in which case the water price due to cost of deep-well infrastructure and energy requirements becomes unacceptable. If groundwater levels develop towards any one of these limits, abstraction is not sustainable over time. The High Plains aquifer in Kansas is the first example of an aquifer, which has been exploited to the physical limit in certain parts (Whittemore et al. 2018).

Long before reaching any of the above limits, undesirable consequences of declining groundwater levels may arise, which require a reduction of pumping.

Adverse consequences may be related to **ecological concerns**. Groundwater cannot be viewed separately from surface water. When groundwater levels fall below a streambed, groundwater discharge to the stream stops and the groundwater-dominated dry-weather stream flow is depleted, possibly disrupted completely. Stream-depletion by groundwater table decline is a serious worldwide problem (Döll et al. 2009; de Graaf et al. 2014). Springs and wetlands suffer if their groundwater feed is cut off by consumptive uses (for water use terminology see Box 1.1). With groundwater table decline, phreatophytic plants relying on a shallow depth to groundwater may no longer be able to survive. The degradation of *populus euphratica* forests in the Tarim basin of Xinjiang is a vivid example for that phenomenon (Liu et al.

2005). Generally, shallow groundwater affects terrestrial ecosystems by sustaining river base-flow and root-zone soil water in the absence of rain. 22 to 32% of global land area is of this type (Fan et al. 2013). Its decline over time is a cause for concern.

Adverse consequences may also be related to **infrastructural safety and water quality**. A common phenomenon of declining groundwater tables is soil subsidence, which is prominent if soft aquifer layers are depressurized by pumping (Herrera-García et al. 2021). In Cangzhou (a city in Hebei province, NCP, China) for example, the soil subsidence has led to a sinking of the topography by 2.5 m. All over Hebei Province, soil fissures often several kilometers long have appeared (Gong et al. 2018). The most prominent example of soil subsidence due to groundwater pumping is Mexico City, where the settling has caused immense damage to infrastructure (Ortega-Guerrero et al. 1999). At the coast, groundwater level decline may lead to seawater intrusion as it is seen for example in California (Franklin et al. 2017), and the east coasts of India and China. In Hebei Province, the saline waterfront has advanced inland by up to 50 km due to groundwater level decline (CIGEM 2019) with the subsequent pollution of wells located within that zone.

Last but not least, adverse consequences may be related to **loss of resilience**. Storage volumes of aquifers are often large compared to surface water reservoirs and therefore able to buffer multi-year droughts. Depletion of an aquifer decreases its storage and thus its ability to buffer the stochastic nature of precipitation and surface water availability. Loss of storage makes a groundwater supply system—e.g. an irrigation system—less reliable. Maintaining storage by allowing recharge in years of good rains is considered an adaptation measure to extremes associated with climate change.

A disequilibrium between recharge and discharge can be caused by decreasing recharge (e.g. due to climate change), increasing discharge (due to increased pumping) or both at the same time. Typically, a climatic change with decreasing precipitation will both decrease recharge by rainfall and increase water demand for irrigation and thus discharge by pumping. Note that not every groundwater table decline indicates over-pumping. The aquifer could just be on the way from one equilibrium to another one, trading off discharge to streams or by phreatic evaporation against discharge by pumping. We generally speak of over-pumping, when in the long term—typically decades—discharge by pumping exceeds recharge.

Estimates of global unsustainable groundwater depletion vary from about 115 km³/year (Döll et al. 2014) to 283 km³/year (Wada et al. 2010) and 362 km³/year (Pokhrel et al. 2012), with the respective authors' estimates of total global abstractions being anywhere between 600 and 1000 km³/year. These figures are of interest to scientists who estimate for example the contribution of groundwater depletion to sea level rise or the impact of decreasing groundwater availability on the global production of agricultural goods. They are less relevant for water managers caring about a single aquifer, since groundwater is essentially a local resource, which must be managed locally.

Usage or consumption? Some water terminology

Volumes of water are expressed in m^3 or km^3 , flowrates or pumping rates in m^3/s or m^3/yr .

If applied to the water delivered to our house or to an irrigated field, the colloquial word water consumption is inaccurate. Real “consumption” of water happens only when water is evaporated e.g. by the evapotranspiration of plants. This water is also not lost for the globe as it is recycled via the atmosphere. It may even be recycled locally in thunderstorms. However, usually it is lost for the catchment from which it is evaporated. In household and industry, the consumptive part of water use is small (<20%).

Water use in irrigation is mostly consumptive use (around 80%), of which again a part is productive use leading to plant growth and another part is non-productive evaporation from the soil. Irrigation water that is not consumed by evaporation or transpiration (around 20%) seeps to the underlying aquifer or flows to a drainage canal. Seepage can already happen during conveyance in an irrigation canal. Conveyance by piping reduces seepage.

Depletion of an aquifer represents consumptive water use if seepage returns to the same aquifer. All water pumped from a deep aquifer, which does not receive irrigation backflow, counts as depletion. Irrigation with surface water provides a net recharge to the underlying aquifer by seepage. Water saving in agriculture only happens if consumptive use is reduced. A reduction in water demand due to a reduction in seepage losses in the field or during conveyance saves only little water (a fraction of the 20% seepage losses). It mainly saves energy by reducing the useless cycling of water by pumping.

Water statistics of water authorities widely used in this report list total water use. Agronomists' figures usually express water consumption. A more comprehensive definition also counts water lost to sinks like the sea or rendered unusable by pollution as consumptive (Seckler 1996).

Box 1.1: Water terminology: usage versus consumption

The major user of groundwater by far is agriculture, which globally accounts for more than 70% of total water withdrawals and for more than 90% of total consumptive water use (Döll 2009). About 40% of irrigated agriculture relies on groundwater (Siebert et al. 2010). Its popularity is increasing, as it is a convenient resource, which is available throughout the year and at the location of use. Groundwater depletion due to domestic use also exists, but is usually confined to very large cities.

1.2 What Does Sustainable Groundwater Use Mean?

The most prominent sustainability problems in the field of water are related to groundwater. Besides the depletion issue, other concerns such as the reduction of low flows of rivers, the drying up of wetlands, seawater intrusion and soil salinization are related to groundwater levels (Alley et al. 1999; Kinzelbach et al. 2003; Liu et al. 2001).

Fig. 1.4 The red-lines concept defining the groundwater level range required for sustainability

Sustainable groundwater use can be defined as an abstraction regime, which keeps groundwater levels within a range bounded by an upper and a lower limit—or two red lines—which guarantee the fulfilment of sustainability criteria specific for the region considered (Fig. 1.4).

The upper limit has the function of preventing phreatic evaporation in agricultural regions, which leads to water logging and salinization. The upper red line in that case is located at the extinction depth of phreatic evaporation, typically between 2 and 5 m below soil surface. The lower red line could be determined by ecological criteria such as low flow requirements of streams, or the maximum root depth of phreatophytic plants. In an agricultural context, it should incorporate the requirement of minimum well yield and a reserve required to overcome a design drought. Well yield determines the time needed to pump a given amount of irrigation water. If it drops below a critical minimum, it may limit the ability to provide sufficient water to crops when it is needed (Foster et al. 2017). Close to the coast, the lower red line is determined by the seawater level. Note that the red line levels are groundwater levels as observed in observation wells, possibly averaged over a certain time and area, and not the momentary dynamic water levels in a pumping well which may be considerably lower.

There are a number of best practices recommended by groundwater managers worldwide to control groundwater levels between the two red lines. Abstraction from an aquifer should allow the establishment of an equilibrium between recharge and discharge, which respects the two red lines, not at every moment, but on the average over times on the order of a decade. Surface water and groundwater should be used conjunctively. This means that surface water is the primary source of supply in years with average and above average rainfall and associated surface water flows, allowing groundwater to recharge, while in years of low flow or zero flow, groundwater takes over the supply. The ideal use of groundwater is as a buffer, with recharge in water rich years and drawdown of groundwater levels in dry years. Theoretically, this

means that it is sufficient to design the maximum abstraction to stay below average recharge. However, in times of climate change, averages change, and management must be adaptive, correcting the average e.g. by considering moving averages or by actively controlling the groundwater level based on the red-line concept.

Real sustainability of agriculture irrigated with groundwater is achieved when water resources availability and agricultural production are in balance. Both an increase in supply and a decrease in demand can contribute to the restoration of an equilibrium between recharge and discharge in an over-pumped aquifer. This means that in the efforts to reach aquifer sustainability, an adaptation of the cropping system and a reduction of agricultural production should be taken as seriously as the search for new resources. In water scarce areas of today demand management of water resources increasingly replaces supply management.

An engineering measure of control is managed aquifer recharge (MAR), which uses excess water, e.g. surface water available outside of the irrigation season, for infiltration into the aquifer via ponds, canals, or wells. This water can then be pumped again at times of need. MAR is a promising adaptation measure to reduce vulnerability to climate change and hydrological variability. It can play a certain role in the restoration of the groundwater balance of aquifers. It can also be used to control saltwater intrusion or land subsidence. Finally, it can contribute to sustaining groundwater dependent ecosystems. The extreme form of MAR is water banking, where water is bought cheaply in times of excess, infiltrated into an aquifer, and pumped and sold in times of scarcity at the high water price associated with it. Several such schemes are working beneficially in the US and Australia. One of the first successful examples is the Arvin Edison groundwater bank in California (Scanlon et al. 2012).

Nevertheless, MAR is not a panacea. It is notoriously inefficient and plagued by clogging. It is always easier to pump water **out** of an aquifer than to put it back **into** the aquifer. Before considering such an operation the suitability of sites and methods, the costs of building and maintenance and the alternatives have to be investigated (Dillon et al. 2009). Given the order of magnitude of over-pumping in the North China Plain, the role of MAR in restoring the aquifer balance is limited. Two examples are discussed in Sect. 2.3.

1.3 Role of Irrigation in Over-Pumping in NCP

The NCP as defined in this book is bounded by the Taihang Mountains in the West, the Yan Mountains in the North, the Yellow River in the South and the Bohai Sea in the East (Fig. 1.5). Its area is about 140,000 km² and it is home to about 150 Mio. inhabitants. Due to its flat geomorphology, the NCP is one of the major agricultural areas in China. Within its boundaries, it produces 21% of China's wheat crop and 13% of its maize crop. Its climate is semi-arid with rainfall of about 500 mm/year and a potential evapotranspiration of about 1500 mm/year. There is a South-North gradient of precipitation, with higher rainfall in the South and lower rainfall in the North (Fig. 1.6). 70–80% of rainfall occurs in the summer monsoon season between

Fig. 1.5 The North China Plain (NCP) covering the sedimentary plain within the hydrogeological borders formed by the Yan mountains, the Taihang Mountains, the Yellow River and the Bohai Sea. It includes parts of Beijing, Tianjin, Hebei, Henan and Shandong Provinces

June and September.

The NCP can be divided into four hydrogeological zones: (I) the piedmont plain adjacent to the mountains in the west, (II) the central alluvial fan and lacustrine zone formed by the rivers coming from the Taihang and Yan mountains, (III) the flood plain created by the ancient Yellow River (including today's Zhang and Wei rivers) and (IV) the coastal plain bordering on the Bohai Sea in the East. Zones II and III occupy most of the NCP (Fig. 1.7).

The groundwater system of the NCP is divided into four main aquifers. The bottom of the first aquifer is at a depth of 40–60 m, the bottom of the second at 120–170 m, while the third and the fourth aquifers reach to depths of 250–350 m and 550–650 m, respectively. The first and the second aquifer are well connected and form the so-called “shallow aquifer”, while the two deep layers are known as the “deep aquifer” (Wu et al. 2010). The shallow and the deep aquifer are only connected in the piedmont region, while with distance from the mountains they are increasingly separated by thick aquitards of low hydraulic conductivity and high salinity (Fig. 1.8).

The shallow aquifer has recharge from rainfall and to a lesser extent from irrigation water backflow and river infiltration. Natural groundwater recharge by rainfall is between 10 and 30% of precipitation (Fig. 1.6). The shallow aquifer's water quality in Zones II and III is usually not up to drinking water standard as mineralization is high (1–5 g/L TDS). The deep aquifer gets its recharge only in the piedmont region

Fig. 1.6 Distribution of long-term average precipitation and groundwater recharge in the NCP. Source Cao et al. (2013)

(Zone I) on the western boundary. Its water satisfies drinking water standards with a mineralization usually well below 1 g/L. Large-scale irrigation in the NCP started in the 1950s and was based on surface water supplied through canals. The seepage losses led to a groundwater table rise and widespread soil salinization as the flat terrain did not provide an efficient drainage. This changed in the 1980s when China due to population growth had to supply more grain. The double cropping system of winter wheat and summer maize was promoted. The water demand of this crop rotation of about 900 mm/year surpasses the effective rainfall of about 500 mm/year. As rainfall is concentrated in summer, winter wheat has to rely almost completely on irrigation with groundwater (Fig. 1.9).

Thus, China's efforts to feed a growing population dramatically increased the use of groundwater since the 1980s, leading to widespread over-pumping. Typical declines in the shallow unconfined and the deep confined aquifers are shown in Figs. 1.10 and 1.11. The decline of groundwater levels in the shallow aquifer (Fig. 1.10) was fast in the 1990s and slowed down after 2000. In recent years, levels are relatively constant, apart from the seasonal variation indicating the abstraction of irrigation water. In some regions, even a rise has been observed. The same tendency

Fig. 1.7 Geological map of the NCP. *Source* Meng et al. (2015)

Fig. 1.8 Hydrogeological cross section of the NCP. *Source* Foster et al. (2004)

Fig. 1.9 Distribution of rainfall, crop water demand (crop ET) and water deficit (hatched area) over the year in the double cropping system of winter wheat and summer maize (Average data for Guantao County)

Fig. 1.10 Groundwater table decline in the shallow aquifer, using observation well in Guangzhuang, Rongcheng County, Hebei as an example

is seen in an average of 559 unconfined aquifer wells distributed over the NCP (Zhang et al. 2020). The authors ascribe local rises after 2014 to the influence of water imports by the South North Water Transfer scheme (SNWT). The decline in the 1980s and 1990s is not caused by pumping alone. It is also influenced by a

Fig. 1.11 Decline of piezometric head in deep aquifer, using the example of an observation well located in Fuwangcun, Xiong County, Hebei

decrease in rainfall (Fig. 1.12). After 2003, the decline rate of shallow groundwater levels decreased. Zhang et al. (2017) estimate that the increase of rainfall after 2002, contributed with 64% to that slowdown, while water saving contributed with 36%. Ignoring the influence of precipitation in the interpretation of groundwater levels may lead to an overestimation of the efficacy of water saving efforts.

The piezometric levels of the deep aquifer (Fig. 1.11) are not related to local precipitation as the aquifer receives little local recharge. The levels have been falling

Fig. 1.12 Development of rainfall since 1961 (Example Guantao County). Trends are clarified by taking a 5-year moving average

continuously since the nineties due to pumping of water not only for irrigation but also for households and industry. The decline even accelerated in recent years, which is also seen by an increasing seasonal amplitude.

The head difference between the two aquifers is ever increasing, which conjures up the danger of polluting the deep aquifer by saline water intruding from the aquiclude. This danger has previously been indicated by Foster et al. (2004) and may prevail much longer than the present over-pumping issue. The processes involved are depicted in Fig. 1.13. In the NCP, evidence of increasing leakage recharge from the shallow aquifers to the deep aquifers has been found after 2000 (Cao et al. 2013; Huang et al. 2015). While the quantities are far too small to effectively recharge the deep aquifer, they present a danger for its water quality.

The distribution maps of groundwater levels and piezometric heads (Figs. 1.14 and 1.15) show the overexploitation zones as pronounced cones of depression, both

Fig. 1.13 Processes leading to salinization of groundwater resources. *Source* Foster et al. (2004)

Fig. 1.14 Spatial distribution of observed water levels in the shallow aquifer in the North China Plain in 2019 (Cones of depression marked with red contours) (Groundwater levels in m asl, in steps of 5 m from -75 m asl to 70 m asl). *Source* CIGEM (2019)

in the shallow and the deep aquifers. The over-pumping is clearly more serious in the deep aquifer, even though its abstractions are only about a quarter of the abstractions in the shallow aquifer. It is a confined aquifer, which consequently has a very small storage coefficient. Therefore, a relatively small abstraction already causes a large drawdown. The deep aquifer is not only used by agriculture but also by households and industry because of its drinking water quality.

A rough water balance has been suggested in various groundwater-modelling efforts. Results for the period 2002 to 2008 from (Cao et al. 2013) and for 2002 to 2003 from (Wang et al. 2008) are shown in Table 1.1. Note that fluxes are not unique,

Fig. 1.15 Spatial distribution of observed piezometric levels in the deep aquifer in the North China Plain in 2019 (Cones of depression have joined to a large depression zone. Draw-down zones of different intensity are marked with red and black contour lines) (Piezometric levels in m asl, in steps of 10 m from -120 m asl to 60 m asl). *Source* CIGEM (2019)

even if they manage to reproduce observed head changes.

The depletion of storage in both models is close to the estimate made based on GRACE data (Fig. 1.3). It indicates the gap between discharge and recharge, which has to be closed in order to return to a sustainable mode of resource use. Even if abstractions could be reduced to achieve zero storage change within a few years, the restoration of groundwater levels requires much longer times. A storage change of zero would freeze present average groundwater levels. Only an excess of recharge over discharge, which is bound to be small, would allow to gradually refill

Table 1.1 Water balance of the NCP aquifer system

Item	Flux (in km ³ /year) (+in, -out) average 2002–2008 (Cao et al. 2013)	Flux (in km ³ /year) (+in, -out) average 2002–2003 (Wang et al. 2008)
Recharge by precipitation and irrigation backflow	+18.71	+20.77
Boundary flux and river seepage	+2.21	+2.60
Pumpage (shallow aquifer)	–17.70	–17.52
(deep aquifer)	–5.01	– 3.11
Phreatic evaporation and outflow to the sea	–2.58	–6.32
Storage change	–4.37	–3.58

the accumulated depletion of 40 years. A return to the shallow aquifer's groundwater levels of 1980 is not desirable as they were so high that they led to water logging and soil salinization.

While the global consideration of Table 1.1 gives a feeling for the order of magnitude of the problem and the efforts needed in its solution, it is not useful for the planning of concrete management measures. Figures 1.14 and 1.15 show clearly that aquifer depletion is not distributed homogeneously over the NCP. They also show that the situation of the deep aquifer is more severe than the situation of the shallow aquifer. The adverse consequences of long-term groundwater overexploitation such as land subsidence, ground fissures, rivers drying up, wetland degradation and seawater intrusion are also area specific. Finally, zero storage change for the whole aquifer system could hide deterioration in some locations by improvement in others. This means that for the efficient restoration of a sustainable pumping regime a thorough, spatially resolved analysis is necessary. For an example of such a local analysis, we turn to the pilot area of Guantao County, which is a typical county in the NCP.

1.4 Requirements for Sustainability in NCP and Guantao as an Example

Guantao County, located in Handan Municipality of Hebei Province, is a typical county of the NCP (Figs. 1.5 and 1.16). It was chosen as pilot region for the implementation of the Sino-Swiss groundwater project. It had been the object of an earlier study funded by the World Bank under a GEF project (Foster and Garduño 2004). Its long-term average annual precipitation is 525 mm with an annual potential evapotranspiration of 1516 mm. Annual average temperature is 13.4 °C. Guantao has a population of 363,000, an area of 456 km² and an irrigated agricultural area of

Fig. 1.16 Guantao County map (left) and remote sensing image (right)

almost 300 km². The total annual water use is about 123 Mio. m³, of which agricultural irrigation covers 82%, industrial water use 4%, domestic and other water use 14%.

The main planting area is dedicated to the double cropping of winter wheat and summer maize. The main crops, their planting areas, and calendars as well as their irrigation norms are listed in Table 1.2.

The crop water supply depends on three sources: precipitation, the exploitation of shallow and deep groundwater layers through about 7300 shallow and 300 deep wells, and surface water provided both from the Weiyun River and from the Yellow River via Weidaguan Canal and Minyou Canal. For household and industry, the SNWT scheme has been providing 4 Mio. m³ per year since 2014. This allowed a reduction of deep-aquifer abstractions for households and industry by about one half.

Wells are operated and managed by well managers, who are owners of a well or take care of a well co-owned by several households. A household of four persons is allocated a planting area of about 1/3 of a hectare. A well typically covers about 3 ha of cropland. All wells are powered by electricity and equipped with an electricity meter. Village electricians collect electricity fees based on the readings of electricity meters by well managers, who organize the recording of irrigation electricity use and collect electricity fees from farming families sharing the same well. The collected fees include the rural, subsidized electricity fee (0.5115 CNY/kWh) for pumping and in some regions an additional fee (about 0.3–0.5 CNY/kWh depending on the farmland's distance from the well) charged for the service of the well manager.

Table 1.2 Main crops and their respective planting area, growth period, planting month, harvesting month and irrigation norm. (Data supplied by Guantao Department of Water Resources based on the local year book for 2012.)

Crop type	Total planting area (ha)	Growth period (days)	Planting month	Harvest month	Irrigation norm (mm)
Winter wheat	20,570	240	October	June	247.5
Summer maize	16,663	120	June	October	75
Cotton	5,730	210	April	November	150
Oil crop (soy)	1,025	120	June	October	150
Oil crop (peanut)	3,761	160	April	October	90
Tomato	325	60	March	May	300
Tree garden	1,000				
Orchard (apple)	1,615	210	March	October	180
Orchard (pear)	500	210	March	October	225
Orchard (wine)	350	100	April	September	150
Orchard (peach)	200	100	March	July	180
Millet	157	120	June	October	75
Vigna radiate	33	100	April	August	75
Fall sweet potato	211	120	June	October	150
Vegetables	7,675	140	February	July	375
Melons	183	120	April	July	375

Note Due to double cropping, the sum of planting areas is larger than Guantao's agricultural area

To reach the goal of sustainable groundwater use, a management system has been set up in Guantao, integrating policy with data-based decision support. It comprises three modules: data monitoring, decision support by modelling, and implementation of policies in the field (Fig. 1.17). Monitored items include groundwater levels, pumping rates, and land use. In addition, data on surface water imports and meteorological quantities are collected. All data are transferred to a server, where they are analyzed by various models and policy options are identified. The chosen policies are then implemented in the field. Success or failure can be assessed via the monitoring data in the following year. The management cycle is gone through annually, decisions being taken before the winter wheat planting in October.

The following chapters demonstrate how such a management system can be successfully implemented. This includes a review of the policy options used in

Fig. 1.17 Architecture of a real-time groundwater management system, including real-time data monitoring and transmission, modelling for decision support, and policy implementation in the field, with feedback by data monitored

the NCP to control groundwater over-pumping, the evaluation of the most effective control measures in the field, the farmers' feedback obtained from a household survey and a policy test based on game playing. Eventually the above-mentioned management system was set up in Guantao through an integrated decision support platform.

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