Chapter 5
Way Forward

The combination of fallowing and substituting groundwater by surface water was effective in reducing aquifer depletion in Guantao. The average annual depletion rate after 2014 was about half the value of the pre-project period 2000–2013 and basically limited to the deep aquifer. The goal of closing all deep aquifer wells has only been reached partially, their use being necessary in locations where the shallow aquifer is too saline. Ending unsustainable groundwater use in Guantao and the NCP is feasible with presently available options. It involves a set of measures, large and small, which are all needed. Uncertainty in the future role of groundwater resources is introduced by climate change and socio-economic development. The transition from small family farms to large industrial farms will increase the overall efficiency of farming including water use efficiency. Population decrease and diet change both affect food demand and thus future agricultural structure and irrigation demand. New cultivars may increase yield without increasing water needs. While the current over-pumping control heavily depends on surface water imports from the South, climate change induces uncertainty by both reducing water availability in the South and increasing water deficits of double cropping in the NCP.

5.1 Recommendations for Guantao

The situation of groundwater over-pumping in Guantao has improved since 2014. The groundwater gap of about 37 Mio. m^3/year before 2014 has been reduced to almost one half during the project. The shallow aquifer is basically in equilibrium between recharge and discharge. The remaining task is stopping the decline of piezometric levels in the deep aquifer, which implies the abandoning of all deep wells. The corresponding reduction of pumping from the deep aquifer of approximately 20 Mio. m^3/year can be implemented either by decreasing demand or increasing supply. Further fallowing of winter wheat, making better use of present surface water

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imports, adding more reliable surface water imports at time of use, and saving water through agricultural techniques certainly have the necessary potential (see analysis in Box 5.1).

In its work in Guantao, the World Bank's GEF project (Foster and Garduño 2004) stressed that only reduction of consumptive water use (i.e. transpiration and evaporation) is real water saving. This remains of course true, but looking at saving of deep aquifer water, the statement has to be modified. As there is no irrigation back flow or any other seepage back to the deep aquifer, any reduction of pumping is 100% saving of deep aquifer water, irrespective of whether it turns into evapotranspiration, seepage to the shallow aquifer, or drainage outflow.

Main aquifer rehabilitation measures, their remaining potentials in Guantao and unit costs

Reduction of groundwater abstraction can be achieved by supply side measures, adding new water resources, and by demand side measures, reducing abstractions by water saving. Costs of both can be expressed by CNY per cubic meter supplied or saved. Demand side measures (darker shading in the table) are subsidy driven. Supply side measures consist of water imports from reservoirs, the Yellow River or - via the SNWT - from the Yangtze River Basin.

Measure	Remaining Potential in Guantao (Mio. m^3/yr)	Cost/Subsidy (CNY/m^3)
Traditional water saving* (small fields and low pressured pipe irrigation)	0.4	1.6
Highly efficient water saving* (drip irrigation in green houses)	0.7	2.5
Highly efficient water saving* (sprinklers)	0.8	2.5
Mulching*	0.2	1.0
Conservation tillage* (maize)	< 1	<0.5
Conservation tillage* (wheat)	0.6	1.3
Rain fed cropping**	0.9	4.5
Water saving cultivars***	4	1.9
Fallowing of winter wheat**	10	3.0
Yellow River and reservoir water (No increase, improvement of efficiency in use of existing imports only)	< 15	0.4
SNWT Central Route (Replace remaining deep aquifer pumping for drinking water supply)	4	2.5
SNWT Eastern Route	(Extension to Hebei under construction)	< 1

* These measures contribute to water saving by reducing unproductive evaporation. If the irrigation water is taken from the deep aquifer, all reduction in pumping contributes to real water saving.

** These measures save groundwater by not pumping at all.

*** These measures save groundwater by increasing WUE of crops.

Main sources for data: a) Work experience summary of groundwater overexploitation control in Hebei Province. Jianghe Conservancy and Hydropower Consulting Center (2018). b) Self-assessment report on groundwater overexploitation control in Handan prefecture. Handan Municipal People's Government (2019-2020). c) The third-party evaluation report on the pilot project of comprehensive groundwater overexploitation control in Hebei Province (MWR/IWHR 2014). (All in Chinese).

Box 5.1: Aquifer rehabilitation measures: remaining potential in Guantao and specific costs. The box shows two prominent items, improved used of water imports from the south and increased fallowing of winter wheat, which taken together are sufficient to close a gap of 20 Mio. m^3/year. They are followed in size by water saving through new cultivars (4 Mio. m^3/year) and numerous "small" measures of water conservation, also adding up to a potential of about 4 Mio. m^3/year. Deep aquifer pumping by households and industry should be completely substituted by additional imports of 4 Mio. m^3/year of SNWT water. All measures together (30 Mio. m^3/year) should be sufficient to fill the deep aquifer gap in the coming years provided the continued commitment of the administration.

The success of the last 7 years is mainly due to the fallowing measures and the import of surface water. It does not mean that no more management of the shallow aquifer is necessary. On the contrary, only from this situation as a starting point the storage of the shallow aquifer can be managed actively, hopefully increased, as a storage device to overcome future drought years. The system in place is also important to react to more systematic changes in the future, be it a change in crop water demand due to rising temperatures or changes in recharge due to changes in rainfall and rainfall patterns. The decision support system can keep track and help in designing the right answers in an adaptive management approach charted out by the red line concept.

The metering of water use and the collection of fees either for amounts overstepping quota or for every cubic meter of water pumped certainly serves the purpose of ensuring general discipline in water use. It is however only justified if the fees lead to a reduction of pumping. This can happen either directly or indirectly by using the collected fees to subsidize water saving measures.

Metering by electricity consumption is practicable and makes economic sense. It should be developed further with the electricity company using their daily available "big data". It would be ideal if the water fee could be collected automatically together with the electricity fee saving the effort for a second fee collection system.

Much has been achieved in the last years and a combination of crop system change and South-North Water Transfer (SNWT) clearly has sufficient potential to stop aquifer depletion, not only in Guantao but in the whole of the NCP. But stopping the depletion is not enough. Even if a cone of depression is stabilized by surface water imports and a hydraulic quasi-steady state can be reached, such a closed system will salinize with time. Only if drainage outflows to the sea via canals, streams, rivers and the aquifer are restored one can truly speak of a sustainable solution. In future, the focus should turn to groundwater quality. The salinity of pumped water should be monitored at least once per year. The increased agricultural pumping in the deep aquifer of the last few years is probably already related to an increase in salinity in the shallow aquifer's cones of depression. While the end of over-pumping is within reach, the salinity problem will not go away and requires further careful management.

5.2 Agriculture and Future Groundwater Management in the NCP

Groundwater depletion in the NCP was a consequence of the governments' will to battle famine in the early 1980s. Hebei Province played an important role in feeding the country since then. It increased its yield by 2–3 times over the past 3 decades. The intensification of food production coincided with a time of decreasing rainfall, which magnified the consequences regarding groundwater levels.

The centralized governmental structure in China usually allows the Chinese leaders to mobilize a vast amount of resources to pursue a goal or solve any problem in a determined manner once an issue is confirmed as extremely important. If a problem is perceived as in conflict with other objectives of interest, any decision is essentially a trade-off. This is the case for groundwater management in the NCP because mitigating groundwater over-pumping may hurt national food security and farmers' income, which are both considered at least as important as environmental protection, if not more important. In 2021, the agricultural department again received the task of increasing crop production (http://www.xinhuanet.com/2021-01/03/c_1126940702.htm).

Population will peak between 2025 and 2030 at about 1.5 billion (Chen et al. 2020), who want to have an ever-richer diet with more meat, vegetables, and fruit. Climate change will decrease the yield of some of today's cultivars due to higher temperature and increase the water demand of crops due to higher ET (see Sect. 5.5). Water scarcity is exacerbated by deteriorating soil and water quality. Climate change may also put a question mark to the water transfers from the South, which must maintain a reserve for its own growth. So, will the solutions envisaged today still hold in 2050 or does it take more? To approach this question, a look at some trends of today is helpful.

5.2.1 Transition from Smallholder Agriculture to Larger Farms

The first trend is the transition from the present smallholder agriculture to modernized larger-scale farming in the NCP. The smallholder family farms with a cropping area of a third of a hectare, are economically unattractive and have no future. The annual income from a winter wheat and a summer maize crop on that area is less than 3000 CNY per person , which compares unfavorably with the average annual income in China of about 30′000 CNY per person. Young people leave the countryside and look for jobs in the cities. Their support of their parents is usually more significant than the parents' own income from farming. Most people working in the fields are above 45 and the question must be asked, who will produce China's food in 2050 (see Box 5.2). The situation is expected to change dramatically in the next decade(s) due to the fast change in rural population structure. With it, agricultural production activities and organization forms will change substantially too, from smallholder farming to larger farms through land aggregation.

Take Switzerland for example: For an economically viable farm of 4 persons in Switzerland a farm area of about 100 ha (300 times the area of a Chinese family farm or almost the size of the whole cropland of a village in the NCP) is necessary. It is typically managed by the family plus one additional farm hand, which is feasible due to a high degree of mechanization, applying modern technology both for remotely controllable hardware, including machinery and irrigation equipment, and for information technology harnessing information on plant health, weather and markets for example.

Chinese farming is developing in the same direction. Farm sizes in the NCP are already increasing. Big entrepreneurs lease land from individual farmers, sometimes of whole villages, to practice a larger scale and more efficient style of farming. This opens up new opportunities also for increased efficiency in water use. However, it is unclear how grain production can eventually become profitable for big farms relying on land leased from small farm households. With the current leasing cost (800–1000 CNY/mu/year), planting grain crops (wheat and maize) is not sufficiently profitable to attract farming enterprises to take over. Agricultural land ownership and the right to trade ownership in a more permanent way will become more and more a critical issue in this transition process.

Using engineering and agronomic approaches, larger farm units can fully exploit the potential for improving water use efficiency beyond today's level. While highly efficient center-pivot sprinklers are neither applicable nor affordable for today's small family farms, they can unfold their full water saving potential on farms of at least 100 ha in size. A large farm can also afford to fallow a certain percentage of its area in order to let the soil rest or to plant green manure without having to be pushed by government. Today's pioneers of big farming go into niche products such as plant seeds, health foods, medicinal plants, or farm tourism to optimize income. At the next stage, grain production should be considered for scale-up to a more efficient and profitable operation.

Greenhouses are the most profitable production units, even at the scale of a family farm. When equipped with soil moisture sensors and automatic drip- or micro-sprinkling equipment they can save significant amounts of water compared to the traditional green houses. At the same time, they can save labor, which meanwhile has become expensive in China. In the US, vertical farms are quickly expanding. They produce vegetables in hydroponic cultures close to the consumer. Their water use is minimal as most of the transpired water can be recycled. And they do not need any agrochemicals except nutrients. Economic viability relies on the consumers' demand for healthy food. China's urban elite is also conscious of food quality, which shows in collective ordering or "crowd farming" of farm products from trusted producers in the periphery.

Bigger farms allow a more scientific approach to crop production, often termed "precision agriculture", which benefits the quality of the produce as well as the environment. Drones already today apply crop protection products. In future they will be able to deposit those products on plants in need only. Similar technology can improve fertilizer application to conserve nutrients and reach more uniform production over the area.

The smart water meters, which have been successfully applied in China's West will also be sustainable in the NCP if pumping in big farms is concentrated on fewer wells. Management of water quota by a county's water resources administration will become feasible when it needs to address only a small number of large farms instead of thousands of small farms. Already during the project, the biggest farm of Guantao enthusiastically volunteered to cooperate with our metering experiment. They want to save water—and thus energy—as they are much more conscious of cost-efficiency than the smallholder farmers. Smart devices such as smart water meters with data transmission to a central server and eventually a feedback from that server to the device, mark the beginning of the Internet of Things (IoT) in agriculture.

Information technology and the full use of available information have to play a bigger role in farming. Alibaba launched the "ET Agricultural Brain". This digital tool enables farmers to raise their crop yields and income by leveraging big data. The app allows farmers to digitally record information about their yields in order to optimize their entire production cycle, raising efficiency and capacity. It was preceded by similar efforts in North America where for example Climate Corporation analyses 50 terabytes of weather data every day and sends the information to users via its Software-as-a-Service platform Climate.com. The corporation's goal is to leverage data to help farmers deal with the increasingly volatile weather caused by climate change.

Agricultural research in China is quite advanced, but it is slow in trickling down into practice. A recent example shows how it can be made available to farmers faster: Through a national campaign, about 20.9 million farmers adopted the recommendations of a study, which increased productivity and reduced environmental impacts. As a result of the intervention, farmers were together US$12.2 billion better off through savings in fertilizer and increase in yield (Cui et al. 2018). The new type of agriculture requires human resources with the relevant education. To feed China's population in 2050, a scientifically educated workforce with an agricultural background will be vital (Tso 2004).

Increase of production per ha does not automatically mean increase of production per cubic meter of water, i.e. more "crop per drop". Therefore, optimization of production must go in parallel with other options of reducing water use. Agrotechnology has still some other methods in store, which under the name of "new green revolution" will help to optimize the combined efficiency of water and nitrogen use (see Sect. 5.3).

5.2.2 Consumer Behavior and Food Demand

Water saving must include the **reduction of food waste** post-harvest, in retail and on the level of the consumer. In recent years Chinese propaganda campaigns focused on the reduction of food waste in restaurants. In Europe initiatives push smart logistics for internet-based distribution of food close to expiration date. Food saved is water saved.

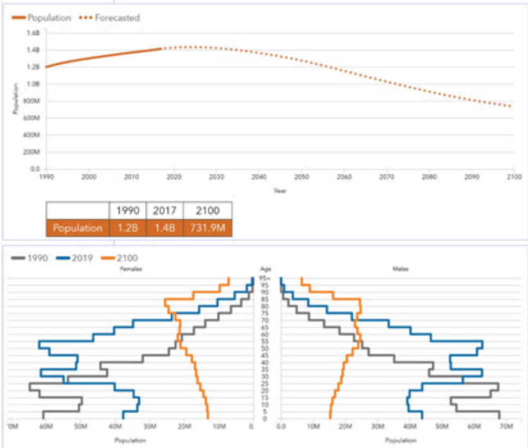
Future water demand is closely related to the diet people desire (McLaughlin and Kinzelbach 2015). Even a stagnating population will further increase water demand if the present trend towards increasing consumption of meat and milk products continues. In the past 30 years China's meat consumption has grown 2.5 fold with a population increase of about 15%, and the trend towards more meat continues, with values admittedly still low in comparison to many western countries (see Box 5.3)

China's Population

According to the Institute of Health Metrics and Evaluation (IHME) China's population will peak between 2020 and 2030 at a population of 1.5 Bio. and then gradually decease to 730 Mio. at the end of the century. This is much less than the prediction by the UN bureau of population. This development presents a big advantage for China's resource availability.

The age pyramid will also change significantly with the population over 50 being in the majority. The over-aging and lack of work force can be balanced out by more mechanization e.g. in agriculture.

Source: http://www.healthdata.org/china



Box 5.2: Development of China's population and possible consequences for agriculture.

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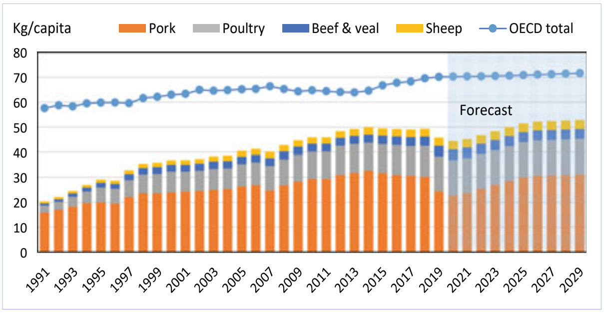
However, the trend in meat consumption could change over health concerns. Young people in the west turn to vegetarianism. While the number of vegetarians in Germany was estimated to be 0.6% in 1983, it increased to about 10% of the population in 2016, with typical vegetarians being between 19 and 29 years old (Mensink et al. 2016). The market adapted to this dietary shift and the associated new demand. Sales of meat substitutes are increasing rapidly, creating a new billion-Dollar market.

The **diet** plays an important part in determining the water demand in agriculture. Of course, its meat component impacts in the first place the production of feed grain, which grows in summer and presents a smaller potential for water saving than wheat. But **substitutes** for wheat could also be considered. Potatoes yield the largest number of calories with the least input of water per unit area. Of course, dietary changes need time for people to get accustomed to. But did China not get accustomed to wheat after centuries of millet? Potatoes, which were unknown before Columbus, are the 4th staple food crop (after rice, wheat and maize) in China since 2015 (Xinhua 2015).

Possibly China may also get used to Quinoa, which is advocated by the UN in its efforts to enhance the globe's food security while saving water (FAO 2011).

China's Diet

In 2026 an average Chinese citizen will consume about 53 kg of meat per year, 10% more than in 2017. Pork is the favorite Chinese meat making up about 60% of all meat consumption. It is followed by poultry, beef and veal, and mutton and lamb. Due to the African Swine Fever epidemic, the consumption of pork declined after 2018 and rebuilding the swine herd will still take some years.



Data source: https://data.oecd.org/agroutput/meat-consumption.htm

China is still eating less meat than others, such as the USA with an average yearly meat consumption of 100 kg/capita or the OECD countries with an average of about 70 kg/capita. This indicates that there is room for expansion.

Box 5.3: Development of China's meat consumption

5.3 Drought Resistant and High Yield Wheat Varieties

Managing groundwater sustainably depends to a high degree on agricultural strategies adopted in the NCP. Pursuing high yield to feed people was the major agricultural target pursued during the past 4 to 5 decades. The NCP played an important role in improving grain production during this period, when numerous high yield varieties were bred and widely cultivated. The yields of wheat and maize increased considerably from 1980 to 2010 (Fig. 5.1). They can reach 9 t/ha for wheat and 10.5 t/ha for maize today. This is much higher than the respective national average yields of 6.2 t/ha and 5.4 t/ha (2019 data) and opens up a yield gap. While the development of crop varieties has helped to achieve the goal of self-sufficiency in agricultural goods, the yield gap still presents a reserve to be activated.

The achievements in grain production were accompanied by a tremendous increase in fertilizer and irrigation water inputs, with the well-known consequences for groundwater depletion. While over the last 40 years yield increase was the primary objective, now the reduction of agricultural intensity has become an essential option to mitigate groundwater level decline.

Increasing attention has been given to the applications of biologic approaches, such as breeding of drought resistant varieties, or genetic modification and gene editing to largely improve photosynthetic efficiency. According to 30-year field experiments at the Center for Agricultural Resources Research, Institute of Genetics

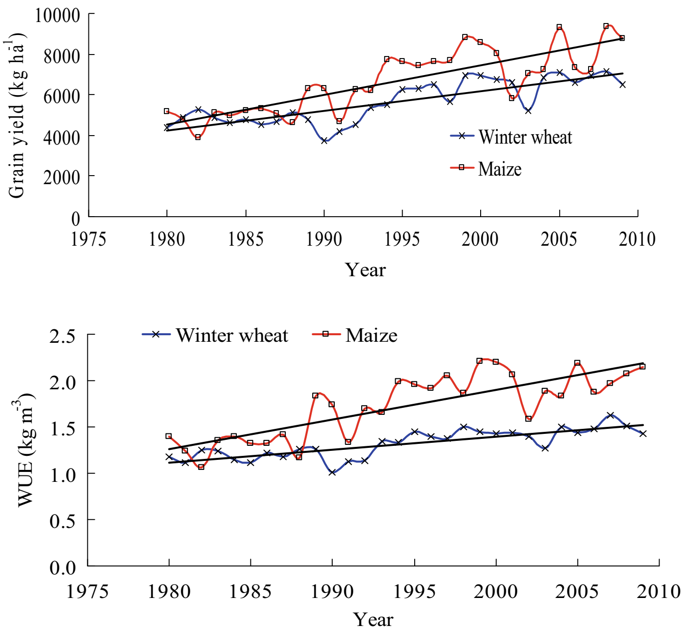


Fig. 5.1 Changes of grain yield and WUE for wheat and maize in NCP from 1980 to 2010 (Zhang et al. 2011)

and Developmental Biology, CAS, a wheat variety with high water use efficiency could save 30–50 mm of irrigation water compared to the normal varieties planted in NCP (Fang et al. 2017) with almost the same level of yield. The WUE could be improved by 21.6% maximally by adoption of highly water productive varieties for wheat. On average, adopting high WUE varieties could achieve an increase of grain yield by about 1% and an increase in WUE by 0.5% annually (Zhang et al. 2010).

A recent study revealed that nitrogen status affects rice chromatin function through the modification of histones, and some specific genes regulating tillering. The transcription factor NGR5 mediates hormone signaling and increased NGR5 levels can drive increases in rice tillering and yield without increasing nitrogen fertilization requirements (Wu et al. 2020). This kind of breakthrough in genetic or biological sciences can be expected to greatly improve water and nitrogen use efficiencies of grain crops. Therefore, another "green revolution" through genetic editing technologies may happen in the near future. It should result in new drought resistant crop varieties and varieties with higher photosynthetic ability, using less water and nitrogen fertilizer.

5.4 Importing Surface Water: Benefit and Risk

For regions lacking large rivers while suffering from severe water shortage, groundwater overdraft seems to be inevitable and importing surface water from outside of the region is the most direct and effective way to alleviate the decline of groundwater levels. Based on the experience from groundwater overdraft control in the NCP so far, importing surface water should not only increase the availability of water but also the efficiency of its use. Present use of surface water imports is extremely inefficient as the timing of water transfers depends on flows in the upstream, which are not synchronous with the irrigation calendar. Storage capacity available in the plain area is by far not sufficient to allow more efficient use of the imports. Improvement requires further updating of water infrastructure including the water system's connectivity and maintenance, e.g. by dredging river channels, renovating pools and ponds, as well as using imported water for MAR.

Import of surface water has been planned, designed, and implemented rather well compared to other methods of groundwater over-pumping control so far. Although it seems irreplaceable in the struggle to end groundwater depletion in the NCP, it is still facing considerable risks and uncertainties.

The surface water quota from the Yellow River will still be strictly limited in the near future. Due to constraints on water quota, after three years of groundwater over-pumping governance, almost all cities and counties have used up their quota of Yellow River water. However, some counties' task of cutting down on groundwater extraction has not been achieved. In Hebei Province Yellow River water has mainly been used for agricultural irrigation. If no further imports are possible, groundwater over-pumping governance can only rely on optimization of the cropping structure, which depends heavily on government subsidies. With the decline of these, the further promotion of over-pumping control action in these mainly rural areas remains challenging.

The high cost of water supply from the SNWT project brings risk and uncertainty to the groundwater over-pumping control system. One important reason is that Hebei provincial government can only spend a small portion of its whole budget for projects supporting the SNWT. 78% of the investment relies on bank loans. The construction of water treatment plants and connecting water supply pipelines is mainly supported by financing through non-governmental investors. These investors expect high returns on their investments. The above two factors result in high water supply and transfer costs for the SNWT. The water price at the entrance of the main canal of the SNWT Project into Hebei Province is 0.97 CNY/m^3, the price of water entering the surface water treatment plant is 2.76 CNY/m^3, and the water price for the consumers is 7.43 CNY/m^3, which is 24% higher than in Beijing, and 34% higher than in Tianjin. It amounts to 155% of the current average water price in urban areas, and to 210% of the current county average water price of Hebei Province.

Due to its high price, water of the SNWT Project is not affordable for agricultural and ecological purposes. Even redundant SNWT water is too expensive to replace groundwater in agricultural irrigation and preserve the groundwater system.

If the present water price of the SNWT's Central Route of 2.5 CNY/m^3 is assumed, the water needed for irrigation of winter wheat would cost about 6′000 CNY/ha. This amount is close to the present input cost for planting one ha of winter wheat and would make wheat planting with SNWT water economically infeasible. Today, the irrigation cost of wheat with groundwater (including maintenance and labor) is about 1000 CNY/ha or 1/6th of the total input cost. The cost of water of the Eastern Route will be less than that of the Central Route, but it cannot be cheaper than groundwater as it has to be pumped up by about 100 m from the Yangtze River, about twice the lift presently necessary for deep aquifer groundwater in the NCP. If the management of all irrigation water would be put into the responsibility of one big company, they could make an average price, which would dilute the high marginal cost of the transfer water to an acceptable prize for food production.

5.5 Climate Change in the NCP

Climate change influences the fate of groundwater resources in the NCP in many ways. Precipitation determines not only groundwater recharge. It also determines the need of supplementary irrigation and therefore groundwater abstraction. Its distribution in time, extreme rain events or drought events can be as important for agricultural production as the annual total precipitation. Temperature, wind speed and radiation influence the potential evaporation, which finally determines the evapotranspiration potential of the crops and thus the water requirements. Finally, climate change may affect the flow of rivers, which are now the source of water transfers to the NCP.

The NCP has seen climate change in the past. Observations since the mid-twentieth century show that it has become warmer and drier. Most observed downward trends in annual precipitation amount were statistically significant (Chen et al. 2010; Fu et al. 2009; Liu et al. 2005; Sun et al. 2017; Wang et al. 2012). Summer precipitation, which accounts for 50–75% of the total annual rainfall in NCP, also has decreased significantly (Fan et al. 2012; Sun et al. 2020; Wang et al. 2012; Ye 2014), while precipitation in other seasons has shown contrasting trends (Fan et al. 2012; Sun et al. 2020). The decrease in rainfall led to a decrease in groundwater recharge. Significant increase was not only observed in the mean annual temperature but also in temperature during both wheat and maize seasons (Chen et al. 2010; Liu et al. 2014; Zhang et al. 2015). Surprisingly, a long-term decreasing trend has been observed in actual evapotranspiration, which can be explained by decreasing trends in precipitation, sunshine duration and wind speed which overcompensated the increase in ET due to temperature rise alone (Cao et al. 2014; Chen et al. 2010; Fan et al. 2012; Liu et al. 2014; Song et al. 2010). A recent study based on remote sensing and physical modeling found that actual evapotranspiration increased slightly since 2000, but concluded that the contribution of climate change was less than that of human activities (Chen et al. 2017). The result agrees with the measurement data of Luancheng Agro-Eco-Experimental Station of the Chinese Academy of Sciences showing that the actual seasonal ET of winter wheat and summer maize under well-watered conditions gradually increased from the 1980s to the 2000s possibly caused by the increase in leaf stomatal conductance associated with the introduction of new cultivars (Zhang et al. 2011). With global warming, more crops can be grown in Northeast China, which has better rainfall, and the recent decades already have shown some shift in production from the NCP towards the Northeast, reducing the pressure on the NCP.

The Fifth Assessment Report by the Intergovernmental Panel on Climate Change (Pachauri et al. 2014) provides the analysis of model outputs from the fifth phase of the Coupled Model Intercomparison Project (CMIP5). CMIP5 produced a state-of-the-art multi-model dataset designed to advance our knowledge of climate variability and climate change including "long term" simulations of twentieth-century climate and projections for the twenty-first century and beyond for a number of Representative Concentration Pathways (RCPs) for atmospheric greenhouse gas (GHG) concentrations (Van Vuuren et al. 2011). Annual averages of temperature and precipitation for two RCPS and a time interval at the end of the century are shown in Fig. 5.2. Looking at Eastern China for the more pessimistic RCP8.5, one can find a strong increase in yearly average temperature (5–7 °C) and an increase in annual rainfall (10–20%) compared to the baseline of 1986–2005. For a lower emission scenario, annual rainfall hardly changes, while average temperature increase is about 1 °C.

To adapt these global projections to regions, a process called downscaling is required to obtain a higher spatial resolution suited for the scale of the region. The problem with the projections is their uncertainty. While different models usually agree well as far as the projected temperature rise is concerned, predictions of rainfall are extremely uncertain reaching from increase to decrease of rainfall. This is also true for the NCP, where the ensemble of climate models shows discrepancies among GCMs and downscaling methods, concerning the projected mean and extremes of precipitation. Some studies show a likely increase in annual precipitation but at varying rates (Fu et al. 2009; Tao and Zhang 2013), while others project a decline in annual precipitation (Liu et al. 2013). Being influenced by several climate variables, evapotranspiration estimates turn out to be very uncertain, making it difficult to draw conclusions about future trends. The projected changes of evapotranspiration during the wheat or wheat–maize growth period in the NCP could either increase or decrease within a range of around ± 10% depending on the GCM and greenhouse gas emission scenario employed (Guo et al., 2010; Lv et al. 2013; Mo et al. 2013; Tao and Zhang 2013).

We can distinguish direct and indirect impacts of climate change on groundwater resources. Changes in the amount, intensity and frequency of precipitation directly determine groundwater recharge and indirectly influence the demand of groundwater pumping for irrigation. The direct impacts of changes in precipitation on groundwater recharge have been found to contribute less to groundwater resources than the changes in pumping, not only in the NCP but also in other regions (Larocque et al. 2019; Li et al. 2014). However, it should be noted that studies on climate change assessments usually ignore the indirect impacts of precipitation on groundwater pumping, and

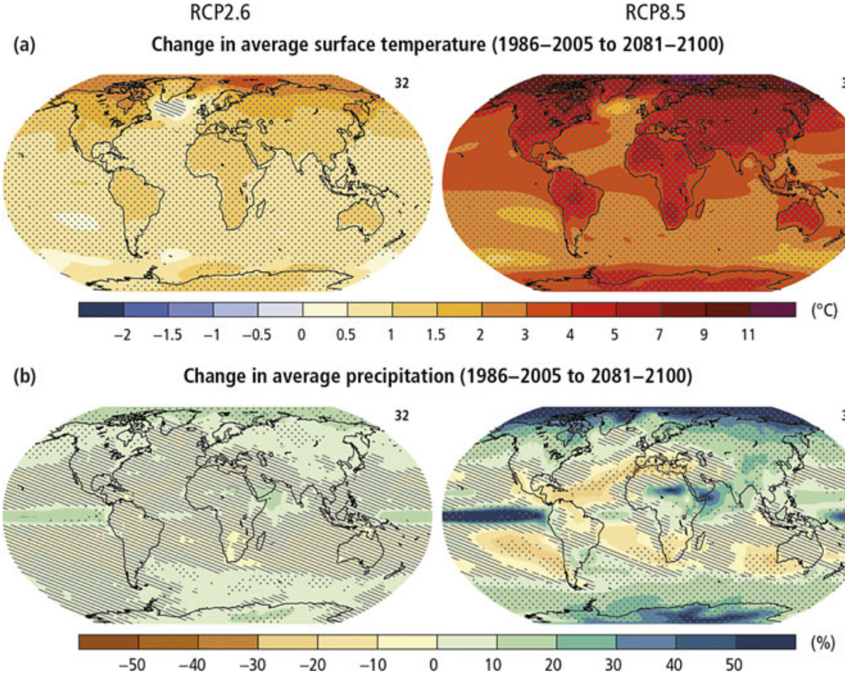


Fig. 5.2 Change in average surface temperature (a) and change in average precipitation (b) based on multi-model mean projections for 2081–2100 relative to 1986–2005 under the RCP2.6 (left) and RCP8.5 (right) scenarios (Pachauri et al. 2014). The number of models used to calculate the multi-model mean is indicated in the upper right corner of each panel. Stippling (i.e., dots) shows regions where the projected change is large compared to natural internal variability and where at least 90% of models agree on the sign of change. Hatching (i.e., diagonal lines) shows regions where the projected change is less than one standard deviation of the natural internal variability

these indirect impacts are usually connected to human activities. Similarly, evapotranspiration also directly influences groundwater recharge and indirectly determines groundwater pumping by crop water demand. Previous studies in the NCP focused on the influence of projected evapotranspiration on future crop water demand and crop yield (Tao and Zhang 2013; Xiao et al. 2020; Xiao and Tao 2016). Hardly any model takes into account the decrease of plant transpiration due to the impact of CO_2 on stomatal conduction, which also modifies estimates of irrigation water demand (Guo et al. 2010).

While an increase in transpiration will decrease recharge and instigate more pumping due to higher plant water demand, there are three mechanisms, which in other regions of the world have shown to increase groundwater recharge: The first is the increase in extremes such as strong rainfall events (Fischer and Knutti 2019). Recharge is not a linear function of rainfall. While small rain events may give zero recharge, large events lead to over-proportional recharge. The second is the decrease of average wind with global warming. As reported above, this trend has been observed in China over the last decades. If it continues, it will reduce the expected increase in evapotranspiration due to temperature increase. The third mechanism is due to the increase of winter precipitation also quoted from literature above. At warmer winter temperatures, the soil freezing depth will be reduced and more recharge will occur in the cold season when evaporation is low, especially when there is thawing snow.

To get a coherent picture for the trends in evapotranspiration and the resulting crop water demand, we did our own assessment. The results presented in Box 5.4 show that overall, the crop water deficit will increase by mid-century and increase even further by late century. The compensation by decreasing wind speed as in the past decades is not seen anymore. That means the second mechanism mentioned above will most probably not be available.

Given all the interactions and assuming that total annual precipitation will not decrease, recharge will most probably not change much compared to today. But, due to more extremes both wet and dry, the use of the aquifer as a buffering device is of growing importance in the future.

The water resources availability in the NCP is not only determined by the development in the NCP itself. As the North in recent years relies increasingly on water imports from the South, the influence of climate change on the water availability in the catchment of the Han River and the Yangtze River in general is also a relevant influence factor.

Assessment of climate change impact on crop water deficit

The assessment compares the crop water deficit under present conditions (computed from ERA5-reanalysis data) with projected conditions at mid and late century obtained from the CORDEX project. Only the two CORDEX experiments were chosen which perform well in a comparison for 2000-2013 (see table).

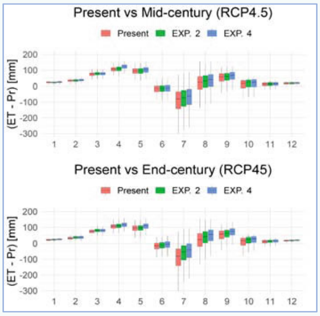
Experiment ID	GCM	RCM	Period	Scenario experiment
2	ICHEC-EC-EARTH	CLMcom-CCLM5-0-2	2035-2064 2070-2099	RCP4.5
4	MOHC-HadGEM2-ES	CLMcom-CCLM5-0-2		

Note: GCM-global climate model; RCM-regional climate model; RCP-representative concentration pathway.

Workflow:

1. Retrieval of projection data from CORDEX project for East Asia region and extraction of gridded data points covering Guantao region only.
2. Quality control by comparing raw projection data with ERA5 reanalysis data as a proxy of gage measurements over the control period (2000-2013).
3. Computation of monthly Change Factors (CFs) for main climate variables for mid-century (2035-2064) and late century (2070-2099), respectively. Those climate variables include precipitation, min/max air temperature at 2 meter above ground, and cloud cover. The CFs are computed as difference for temperature, and as ratio for precipitation as well as cloud cover between future climate and control period.
4. Simulation of synthetic time series with the weather generator using CFs for Guantao (Peleg et al. 2017).

A water deficit indicator was computed as the difference between ET and precipitation. Presently July is the only month when rainfall is more than sufficient to cover crop evapotranspiration, while all remaining months tend to face water deficit, especially in spring season. However, this surplus is expected to decrease by mid-century, and even more so by late century, due to the increase of crop ET in July. Changes in wind speed and radiation do not compensate the increase of ET due to rising temperatures. Guantao will be facing a more severe water deficit than today.



Estimated changes of water deficit under climate projections.

Box 5.4: Influence of climate change on crop water deficit

References

Cao L, Zhang Y, Shi Y (2011) Climate change effect on hydrological processes over the Yangtze River basin. Quat. Int. 244:202–210. https://doi.org/10.1016/j.quaint.2011.01.004

Cao G, Han D, Song X (2014) Evaluating actual evapotranspiration and impacts of groundwater storage change in the North China Plain. Hydrol. Processes 28:1797–1808. https://doi.org/10.1002/hyp.9732

Chen C, Wang E, Yu Q, Zhang Y (2010) Quantifying the effects of climate trends in the past 43 years (1961–2003) on crop growth and water demand in the North China Plain. Clim Change 100:559–578. https://doi.org/10.1007/s10584-009-9690-3

Chen X, Mo X, Hu S, Liu S (2017) Contributions of climate change and human activities to ET and GPP trends over North China Plain from 2000 to 2014. J Geog Sci 27:661–680. https://doi.org/10.1007/s11442-017-1399-z

Chen Y, Guo F, Wang J et al (2020) Provincial and gridded population projection for China under shared socioeconomic pathways from 2010 to 2100. Sci Data 7:83. https://doi.org/10.1038/s41597-020-0421-y
Cui Z et al (2018) Pursuing sustainable productivity with millions of smallholder farmers. Nature 555:363–366. https://doi.org/10.1038/nature25785
Fan L, Lu C, Yang B, Chen Z (2012) Long-term trends of precipitation in the North China Plain. J Geog Sci 22:989–1001. https://doi.org/10.1007/s11442-012-0978-2
Fang Q, Zhang XY, Chen SY, Shao LW, Sun HY (2017) Selecting traits to increase winter wheat yield under climate change in the North China Plain. Field Crops Research 207:30–41. https://doi.org/10.1016/j.fcr.2017.03.005
FAO (2011). Quinoa: An ancient crop to contribute to world food security. Technical Report of the FAO Regional Office for Latin America and the Caribbean, 55 p. http://www.fao.org/3/aq287e/aq287e.pdf
Fischer EM, Knutti R (2016) Observed heavy precipitation increase confirms theory and early models. Nature Clim. Change 6:986–991. https://doi.org/10.1038/nclimate3110
Foster S, Garduño H (2004). China: Towards Sustainable Groundwater Resource Use for Irrigated Agriculture on the North China Plain. World Bank. Sustainable Groundwater Management: Lessons from Practice. GW-MATE Case Profile Collection Number 8
Fu G, Charles SP, Yu J, Liu C (2009) Decadal climatic variability, trends, and future scenarios for the North China Plain. J Clim 22:2111–2123. https://doi.org/10.1175/2008JCLI2605.1
Guo R, Lin Z, Mo X, Yang C (2010) Responses of crop yield and water use efficiency to climate change in the North China Plain. Agric Water Manage 97:1185–1194. https://doi.org/10.1016/j.agwat.2009.07.006
Handan Municipal People's Government (2020). Self-assessment report on groundwater overexploitation control in Handan prefecture (in Chinese).
Jianghe Conservancy and Hydropower Consulting Center (2018). Work experience summary of groundwater overexploitation control in Hebei Province (in Chinese)
Larocque M, Levison J, Martin A, Chaumont D (2019) A review of simulated climate change impacts on groundwater resources in Eastern Canada. Canadian Water Resources Journal/revue Canadienne Des Ressources Hydriques 44:22–41. https://doi.org/10.1080/07011784.2018.1503066
Li X, L, G, Zhang Y, (2014) Identifying major factors affecting groundwater change in the North China Plain with grey relational analysis. Water 6:1581–1600. https://doi.org/10.3390/w6061581
Liu B, Xu M, Henderson M, Qi Y (2005). Observed trends of precipitation amount, frequency, and intensity in China, 1960–2000. Journal of Geophysical Research: Atmospheres 110https://doi.org/10.1029/2004JD004864
Liu W, Fu G, Liu C, Song X, Ouyang R (2013) Projection of future rainfall for the North China Plain using two statistical downscaling models and its hydrological implications. Stochastic Environ. Res. Risk Assess. 27:1783–1797. https://doi.org/10.1007/s00477-013-0714-1
Liu Y, Yang X, Wang E, Xue C (2014) Climate and crop yields impacted by ENSO episodes on the North China Plain: 1956–2006. Reg Environ Change 14:49–59. https://doi.org/10.1007/s10113-013-0455-1
Lv Z, Liu X, Cao W, Zhu Y (2013) Climate change impacts on regional winter wheat production in main wheat production regions of China. Agric for Meteorol 171–172:234–248. https://doi.org/10.1016/j.agrformet.2012.12.008
McLaughlin D, Kinzelbach W (2015) Food Security and Sustainable Resource Management. Water Resour Res 51(7):4966–4985. https://doi.org/10.1002/2015WR017053
Mensink GBM, Lage Barbosa C, Brettschneider AK (2016). Verbreitung der vegetarischen Ernährungsweise in Deutschland. Journal of Health Monitoring 1(2). https://doi.org/10.17886/RKI-GBE-2016-033
Mo X, Guo R, Liu S, Lin Z, Hu S (2013) Impacts of climate change on crop evapotranspiration with ensemble GCM projections in the North China Plain. Clim Change 120:299–312. https://doi.org/10.1007/s10584-013-0823-3

MWR/GIWP (2019) Comprehensive Control of Groundwater Overdraft in Hebei Province. Report of GIWP (in Chinese)

MWR/IWHR (2014). The third-party evaluation report on the pilot project of comprehensive groundwater overexploitation control in Hebei Province. Report of IWHR (in Chinese)

Pachauri RK, Allen MR, Barros VR, Broome J, Cramer W, Christ R, Church JA, Clarke L, Dahe Q, Dasgupta P, et al. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Peleg N, Fatichi S, Paschalis A, Molnar P, Burlando P (2017) An advanced stochastic weather generator for simulating 2-D high-resolution climate variables: AWE-GEN-2d. J Adv Model Earth Syst 9:1595–1627. https://doi.org/10.1002/2016MS000854

Song Z, Zhang H, Snyder RL, Anderson F, Chen F (2010) Distribution and trends in reference evapotranspiration in the North China Plain. J Irrig Drain Eng 136:240–247. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000175

Sun J, Lei X, Tian Y, Liao W, Wang Y (2013) Hydrological impacts of climate change in the upper reaches of the Yangtze River Basin. Quat Int 304:62–74. https://doi.org/10.1016/j.quaint.2013.02.038

Sun J, Wang X, Shahid S (2020) Precipitation and runoff variation characteristics in typical regions of North China Plain: a case study of Hengshui City. Theor Appl Climatol 142:971–985. https://doi.org/10.1007/s00704-020-03344-8

Sun Q, Miao C, Duan Q (2017) Changes in the spatial heterogeneity and annual distribution of observed precipitation across China. J Clim 30:9399–9416. https://doi.org/10.1175/JCLI-D-17-0045.1

Tao F, Zhang Z (2013) Climate change, wheat productivity and water use in the North China Plain: a new super-ensemble-based probabilistic projection. Agric for Meteorol 170:146–165. https://doi.org/10.1016/j.agrformet.2011.10.003

Tso TC (2004) Agriculture of the future. Nature 428:215–217. https://doi.org/10.1038/428215a

Van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque JF (2011) The representative concentration pathways: an overview. Clim Change 109:5–31. https://doi.org/10.1007/s10584-011-0148-z

Wang HJ, Sun JQ, Chen HP, Zhu YL, Zhang Y, Jiang DB, Lang XM, Fan K, Yu ET, Yang S (2012) Extreme climate in China: Facts, simulation and projection. Meteorol Z 21:279–304. https://doi.org/10.1127/0941-2948/2012/0330

Wang Y, Liao W, Ding Y, Wang X, Jiang Y, Song X, Lei X (2015) Water resource spatiotemporal pattern evaluation of the upstream Yangtze River corresponding to climate changes. Quat. Int. 380–381:187–196. https://doi.org/10.1016/j.quaint.2015.02.023

Wu K, Wang S, Song W, Zhang J, Wang Y, Liu Q, Yu J, Ye Y, Li S, Chen J, Zhao Y, Wang J, Wu X, Wang M, Zhang Y, Liu B, Wu Y, Harberd NP, Fu X (2020). Enhanced sustainable green revolution yield via nitrogen-responsive chromatin modulation in rice. Science 367(6478):eaaz2046. https://doi.org/10.1126/science.aaz2046

Xiao D, Tao F (2016) Contributions of cultivar shift, management practice and climate change to maize yield in North China Plain in 1981–2009. Int J Biometeorol 60:1111–1122. https://doi.org/10.1007/s00484-015-1104-9

Xiao D, Liu D, Wang B, Feng P, Bai H, Tang J (2020). Climate change impact on yields and water use of wheat and maize in the North China Plain under future climate change scenarios. Agric. Water Manage. 238:106238https://doi.org/10.1016/j.agwat.2020.106238

Xinhua (2015). Potato upgraded as new staple crop. China Daily 2015-01-08. https://www.chinadaily.com.cn/china/2015-01/08/content_19269910.htm

Xu Y, Xu C, Gao X, Luo Y (2009) Projected changes in temperature and precipitation extremes over the Yangtze River Basin of China in the 21st century. Quat Int 208:44–52. https://doi.org/10.1016/j.quaint.2008.12.020

Yang W, Di L, Sun Z (2021) Groundwater variations in the North China Plain: monitoring and modeling under climate change and human activities toward better groundwater sustainability.

Chapter 5 in: Mukherjee A, Scanlon BR, Aureli A, Langan S, Guo H, McKenzie AA (eds), Global Groundwater. Elsevier, pp 65–71
Ye JS (2014) Trend and variability of China's summer precipitation during 1955–2008. Int J Climatol 34:559–566. https://doi.org/10.1002/joc.3705
Zhang XY, Chen SY, Sun HY, Wang YM, Shao LW (2010) Water use efficiency and associated traits in winter wheat cultivars in the North China Plain. Agric Water Manag 97:1117–1125. https://doi.org/10.1016/j.agwat.2009.06.003
Zhang X, Chen S, Sun H, Shao L, Wang Y (2011) Changes in evapotranspiration over irrigated winter wheat and maize in North China Plain over three decades. Agric Water Manage 98:1097–1104. https://doi.org/10.1016/j.agwat.2011.02.003
Zhang HL, Zhao X, Yin XG, Liu SL, Xue JF, Wang M, Pu C, Lal R, Chen F (2015) Challenges and adaptations of farming to climate change in the North China Plain. Clim Change 129:213–224. https://doi.org/10.1007/s10584-015-1337-y
Zou Y, Yang X, Pan Z, Sun X, Fang J, Liao Y (2008) Effect of CO_2 doubling on extreme precipitation in Eastern China. Adv Clim Change Res (Chinese Edition) 4(2):84–91