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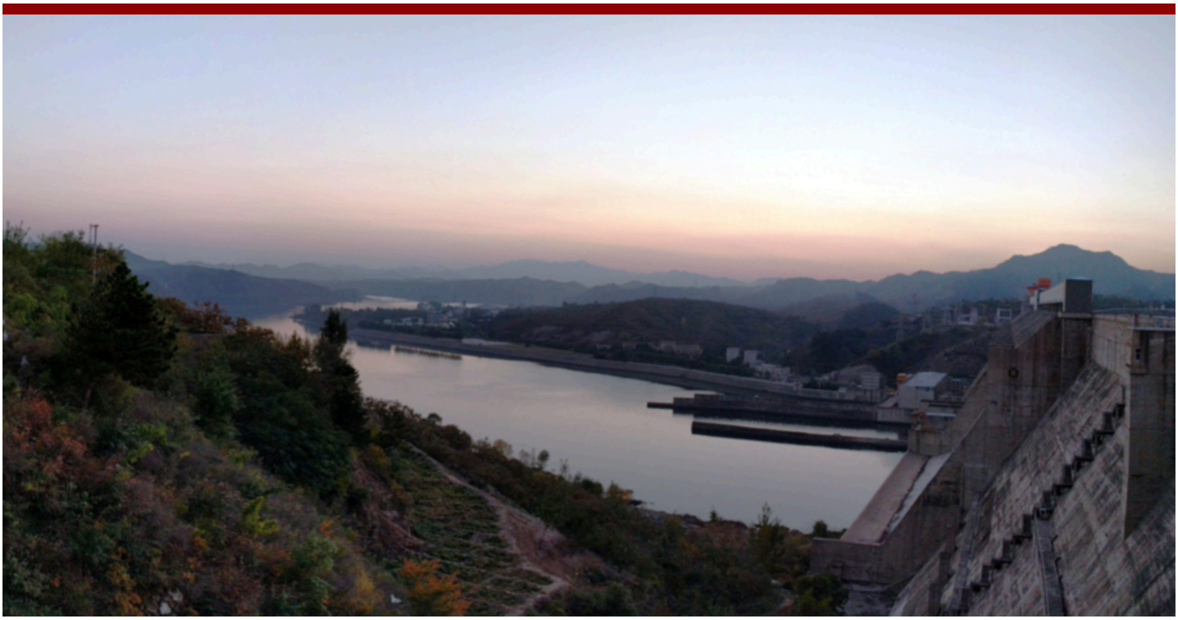

Grith Martinsen

PhD thesis
May 2019

DTU Environment
Department of Environmental Engineering

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The synopsis part of this thesis is available as a pdf-file for download from the DTU research database ORBIT: http://www.orbit.dtu.dk.

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Preface

The work presented in this PhD thesis was carried out from 1 November 2015 to 28 February 2019. It was conducted at the Department of Environmental Engineering at the Technical University of Denmark (DTU) as well as at the Institute of Geographical Sciences and Natural Resources Research at the Chinese Academy of Sciences (CAS). Over the course of the PhD study, nine months were spent in Beijing, China, at CAS. Professor Peter Bauer-Gottwein was the main supervisor, and Professor Suxia Liu and Professor Xingguo Mo from CAS were co-supervisors.

The research was funded by the Sino-Danish Center for Education and Research (SDC), Aarhus, Denmark, and the Department of Environmental Engineering at DTU and supported by the National Key Research and Development Program of China (No.2016YFC0401402) and National Natural Science Foundation of China (No.41471026).

This PhD thesis is organized in two parts: the first part provides context and background for the study and a synoptic overview of the methods and findings. The second part consists of the papers listed below. These will be referred to in the text by their paper number, written in the Roman numerals **I-III**.

I Martinsen, G., Liu, S., Mo, X., Bauer-Gottwein, P, 2019. Optimizing water resources allocation in the Haihe River basin under groundwater sustainability constraints. Journal of Geographical Sciences. In press.

II Martinsen, G., Liu, S., Mo, X., Bauer-Gottwein, P, 2019. Joint optimization of water allocation and water quality management in Haihe River basin. Science of the Total Environment. 654:72-84. DOI:10.1016/j.scitotenv.2018.11.036

III Martinsen, G., Liu, S., Mo, X., Davidsen, C., Payet-burin, R., Bauer-Gottwein, P., 2019. Assessing water resources projects with and without perfect foresight: A framework combining linear programming and model predictive control. Manuscript.

Additionally, a significant amount of information supporting the conceptual understanding of the model area is collected in appendices **IV-VII**.

In this online version of the thesis, papers **I-III** are not included but can be obtained from electronic article databases, e.g. via www.orbit.dtu.dk or on request from DTU Environment, Technical University of Denmark, Miljoevej, Building 113, 2800 Kgs. Lyngby, Denmark, info@env.dtu.dk

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During the course of this PhD study I have been fortunate to have the support and guidance from numerous people, both academically and privately. I could not have completed this task without the inspiration and guidance provided by my main supervisor Peter Bauer-Gottwein. I owe him a great amount of thanks for his patient supervision throughout this study as well as for challenging me whenever needed.

A part of this study took place in Beijing, China, under the supervision of my co-supervisors Professor Suxia Liu and Professor Xingguo Mo. I am very grateful for their enthusiasm in disseminating the work of this project in China, as well as bringing me along for meetings with Chinese water authorities, conferences and field trips. Welcoming me into their research group and supporting my research has meant a lot to me. Of my Chinese friends, I especially want to thank Xuezhi Long. He has been a great support for me during my stays in China, both academically and socially.

I also owe a big thanks to Claus Davidsen for bringing me along on one of his field trips during his own PhD study in Ziya River basin in China, when I was still a master student. It opened up my curiosity to the topic, and he has been a great inspiration and guidance for me in the earliest part of my PhD project. I would like to thank Hugo Connery for his enthusiasm in doing a one-person course with me to get me on my feet with bash, git and programming. Also thanks to Dan Rosbjerg for leading the way at several international conferences.

Working at DTU has given me tons of great colleagues. Tons of names take up too much space, but thanks to all of you for making every-day office work more interesting and cheerful. I would also like to thank Liguang for his effort in translating my summary into Chinese, and for general Chinese Office Wisdom. I owe a big thanks to the SDC Beijing crew for all the great fun during our, often smoggy, Beijing days. Especially thanks to Liz, Nina, Frodi, Mariu, Jonas and Kirstine for being “home away from Denmark”.

Most of all, I am grateful for the unconditional support and love from my family. Alice, Torben and Rune have always been there for me, as well as throughout this process. I feel lucky to have family like you. I am also lucky to have friends who supported and took interest in what kept me long hours at DTU. Your support have meant a lot to me. Last, but not least: Thank you Henning. Thanks for being there, and thanks for making me laugh. A lot!

Summary

China has experienced rapid economic growth and an increasing population over the past half century, which has put enormous pressure on its natural resources. In many regions, the rising pressure on water resources poses considerable challenges to water management. China has a long tradition of large-scale water infrastructure projects, but not until recently has the government emphasized more ‘soft’ approaches to water resources management, such as economic incentives and institutional measures. This transition has led to the formulation of several policy documents, which set new goals for capping water use and improving its quality. Among these documents is the Water Ten Plan, which identifies the Haihe River basin as one of the key regions for addressing water scarcity and pollution. The basin is one of the seven major river basins in China, and its plain area is part of the North China Plain, traditionally known as “the food basket of China”. It is intensively cultivated, and agricultural irrigation demands compete with megacities and industries for scarce water resources. This has led to an overexploitation of the groundwater resources over the past decades. In addition to water scarcity, the Haihe River basin also presently has the overall worst water quality in the country.

Methods and concepts from the field of hydroeconomic analysis were applied to the complex water challenges of the Haihe River basin, and the fundamental view of water possessing an economic value was adopted in an optimization framework. By quantifying the value of water in terms of all of its uses, socio-economic optimal management was pursued. Introducing environmental constraints to the optimization framework reflected the value of sustainable water management in economic trade-offs and shadow prices.

The model representation of the Haihe River basin water management problem was intended to be as realistic and as recognizable to the water resources managers as possible. The hydroeconomic optimization model was therefore formulated as one large linear optimization problem, assuming perfect foresight of all future hydrological events. This allowed the model to optimize numerous decision variables over a large number of time steps, without compromising system representation. By incrementally constraining groundwater end-storage, the economic trade-offs from limiting the present groundwater overdraft to long-term sustainable groundwater abstractions was found. This revealed the significant socio-economic impacts of ending groundwater overdraft in the North China Plain.

In addition to the groundwater overdraft, the issue of water pollution was also implemented in the model framework. All possible water allocations from Haihe River basin water sources, such as surface water runoff, major groundwater aquifers and inter-basin transfers, were assigned their known water quality standard. Cleaning costs were imposed on water allocations from water sources inferior to downstream water user quality demands. This ensured water allocations with fit-for-purpose quality while quantifying the economic impact of meeting downstream users' requirements. The spatial variation of water availability shadow prices, as an effect of considering water quality, could be mapped out. The model setup was used further to evaluate project benefits from managed aquifer recharge in the plain area as well as improving water quality for inter-basin transfers from the South-to-North Water Transfer Project's eastern line.

Under the assumption of perfect foresight, impacts of uncertain future hydrological events, such as droughts, cannot be analyzed. Furthermore, assuming perfect foresight might alter costs and estimated project benefits compared to a system facing uncertain future hydrology. This was addressed by wrapping a model predictive control (MPC)-inspired continuous re-optimization routine around the optimization model. In this way, optimal water management with various levels of future foresight could be simulated. The impact of future foresight on agricultural yields was captured by representing yield response to water allocations. The model framework was used to evaluate the benefits of a proposed water infrastructure project allowing for additional inter-basin transfers from the Yellow River to flow to the plain area via the Guanting reservoir. The estimated project benefits, however, were recognized as being underestimated under an assumption of perfect foresight, which highlights the importance of considering the impacts of assuming perfect foresight in a cost-benefit context.

The proposed model framework was shown to provide valuable decision support for the major water challenges of the Haihe River basin: groundwater overdraft and water quality deterioration. Present policies in China exhibit increased awareness of the need for sustainable management of river basin-scale water quantity and quality, and insights from hydroeconomic analyses can be a step towards reaching the political goals of sustainable water resources management. Moreover, experiences with the MPC framework can be transferred to any project benefit evaluation in which a dynamic system is evaluated under perfect foresight.

Dansk sammenfatning

Kina har gennem det sidste halve århundrede været igennem en drastisk økonomisk udvikling og befolkningstilvækst. Det har medført et enormt pres på landets naturressourcer. I mange områder har det skabt nye udfordringer for, hvordan man bedst håndterer vandressourceforvaltning. Kina har en lang hostorie for storstilede vandprojekter, som dæmninger og kanalsystemer. Det er først for nylig at den kinesiske regering har haft mere fokus på 'bløde' tilgange til vandressourceforvaltning som økonomiske incitamenter og institutionelle metoder. I forbindelse med denne overgang er der blevet formuleret en række politiske dokumenter, der sætter nye mål for at stoppe overforbrug af vandressourcer og forbedre den generelle vandkvalitet. Ét af disse dokumenter er "Water Ten Plan", hvori Haihe flodens opland er et af hovedindsatsområderne. Haihe er et af Kinas syv største flodoplande. Det udgør en stor del af den nordkinesiske slette, North China Plain, der ofte bliver omtalt som "Kinas brødkurv". Her konkurrerer millionbyer med det omkringliggende, intensivt opdyrkede område om de knappe vandressourcer. Dette har medført en kraftig overpumpning af grundvandsmagasinerne. Udover generel knaphed på vand er Haihe også det kinesiske flodopland med den overordnede set værste vandkvalitet.

Hydroøkonomiske metoder og koncepter blev anvendt i dette studie på de komplekse vandressourceproblematikker i Haihe. En optimeringsmodel blev formuleret med udgangspunkt i ideen om, at vand besidder en økonomisk værdi. Ved at værdisætte alle former for brug af vand, kunne en socio-økonomisk optimal fordeling af de knappe vandressourcer tilstræbes. Med miljømæssige betingelser for den optimale fordeling af vand kunne værdien af bæredygtig vandressourceforvaltning reflekteres i økonomiske trade-offs og skyggepriser.

Den hydroøkonomiske model var tilsigtet en så genkendelig og realistisk repræsentation af vandressourceproblematikkerne i Haihe som muligt. Den hydroøkonomiske optimeringsmodel blev derfor formuleret som ét stort lineært optimeringsproblem med en antagelse om perfekt fremsynethed over fremtidige hydrologiske hændelser. Dette muliggjorde en model, der kunne optimere et stort antal beslutningsvariabler over en lang række tidsskridt, uden at der skulle gås på kompromis med detaljegraden af modelområdet. Ved trinvist at begrænse overpumpningen af grundvandsmagasinerne kunne de økonomiske trade-offs af et bæredygtigt grundvandsforbrug afdækkes. Dette viste de omfattende socio-økonomiske konsekvenser af at standse overpumpningen af grundvand i North China Plain.

Udover overpumpning af grundvand blev vandkvalitetsproblematikken også implementeret i modellen. Hver enkelt flod, grundvandsmagasin og vandtilførsler fra andre flodoplande, repræsenteret i modellen, blev angivet deres kendte vandkvalitet. De allokeringer af vand, der ikke havde en tilstrækkelig høj vandkvalitet til at sikre vandkvalitetskravene nedstrøms, blev pålagt en rensningsafgift. På denne måde sikredes alle brugere den nødvendige vandkvalitet. Samtidig kunne den økonomiske effekt af at sikre tilstrækkelig vandkvalitet kortlægges gennem skyggepriser for alle vandressourcer. Modellen blev også brugt til at finde værdien af forskellige tiltag til at imødekomme knapheden og kvaliteten af vandressourcerne. Disse tiltag var kunstig grundvandsinfiltrering og forbedret vandkvalitet af den østlige kanal med vandtilførsler fra Yangtze floden.

Under antagelsen af perfekt fremsynethed kan effekterne af uforudsete hændelser, såsom tørke, ikke analyseres. Økonomiske omkostninger og værdien af tiltag vil højst sandsynligt være anderledes, hvis uforudsete hændelser medregnes. Disse hændelser blev simuleret ved at implementere en Model Predictive Control inspireret optimieringsrutine omkring modellen, der muliggjorde en kontinuerlig re-optimering. På denne måde kunne optimeringsproblemet simuleres med varierede grader af fremsynethed. Effekten af fremsynethed for udbyttet af landbrugsafgrøder blev repræsenteret ved at implementere respons i afgrødens endelige udbytte fra vandallokeringer over hele sæsonen. Modellen blev brugt til at evaluere værdien af et foreslået projekt, der ville kunne lede vandtilførsler fra den Gule Flod gennem Guanting reservoir til den vandknappe slette. Værdien af projektet viste sig at være undervurderet under antagelsen af perfekt fremsynethed. Dette understreger vigtigheden af at overveje effekterne af uforudsete hændelser i evalueringen af værdien af vandressourceprojekter.

Modellen viste sig at være et brugbart værktøj til at klarlægge de økonomiske effekter relateret til de store vandproblematikker i Haihe: overpumpning af grundvandet og forringet vandkvalitet. De nuværende kinesiske tiltag på vandområdet viser en øget opmærksomhed omkring bæredygtig vandressourceforvaltning af flodoplande. Indsigter fra hydroøkonomiske analyser kan skabe forudsætningerne for at bevæge forvaltningen af de knappe vandressourcer i en mere bæredygtig retning og derved nå de politiske målsætninger. Erfaringerne fra Model Predictive Control optimeringsrutinen kan overføres til ethvert projekt, hvor et dynamisk system evalueres under en forudsætning af perfekt fremsynethed.

总结

在过去的 50 年间，中国的经济经历了快速增长；与此同时，人口大幅增长加剧了对资源的消耗，使经济发展的自然资源基础逐渐受到威胁。在很多地区，水资源问题已经非常突出，发展态势十分严峻。虽然中国有悠久的治水历史，但新型水资源管理制度，如用水效率激励机制、市场导向的水分配机制等还不成熟。近年来，中央出台了最严格水资源管理制度，例如 “水十条”、加快推进水资源的高效利用与保护。海河流域是中国的主要粮食产区，由于干旱缺水，导致地下水严重超采、水资源供需矛盾突出、生态环境严重退化，严重制约了区域社会经济的可持续发展。

本文利用水资源经济学的概念和方法，对海河流域水资源进行优化配置。核心理论是将水资源的经济属性引入到优化配置当中。通过定量评估农业用水、工业用水、生活用水等不同用水的经济价值，建立最优水资源配置方案。同时，将生态环境约束因子引入到优化配置中，使可持续水资源管理的价值体现到经济权衡和影子价格中。

基于实用和可行性，本文建立了海河流域高维线性水资源优化配置模型。该模型基于所有的水文事件均是完美预见（perfect foresight）的假设，可以在不降低系统复杂性情况下，进行长时段多个决策变量的优化。通过渐增式约束末期地下水储量，达到当前地下水超采和地下水长期可持续开采的经济权衡。该模型很好地体现了避免地下水超采带来的显著社会经济效益。

除了地下水超采，模型也考虑水污染问题。水资源包括地表径流、地下主要含水层、跨流域调水等，所有的水资源之间的配置都考虑了水资源的水质标准。从上游向下游配置劣质水时，要支付净化成本。这样可以确保水资源配置既满足特定用途的水质标准，又考虑满足下游水质要求的经济影响。同时，根据水质影响对影子价格的影响，可以编制可用水资源的影子价格的空间变化。该模型进一步地用来评估平原区地下水回补技术和改进水质人为管理深层地下水带来的效益，以及南水北调东线工程对提高水质的作用。

由于模型建立在“完美预见”（perfect foresight）这样的前提下（即可以预见未来水资源状况），所以无法对未来不确定极端水文事件，比如干旱等影响的评估。相比于不确定未来水资源状况的情景，“完美预见”模型计算的成本和工程效益可能与真正面对不确定的水文情势的系统有差别。基

于此，本论文嵌入了一个基于*模型预测控制(Model Predictive Control(MPC))*模块,可以围绕优化模型开展一系列再优化，从而得到不同“完美预见”情景下的最优配置方案。譬如未来“预见”对农业产量的影响通过产量对水资源配置的响应关系进行评估。本文利用该模型框架对提出的“引黄济官”工程的效益进行了理论评估。结果表明，基于“完美预见”假设，“引黄济官”工程效益被低估。该结论进一步说明了在成本效益分析中应该考虑“完美预见”假设的影响的重要性。

本文构建的模型框架可以为解决海河流域地下水超采和水质恶化提供决策支持。当前中国的水资源管理政策越来越强调以流域为单元的水量、水质控制的可持续性。本文的水资源经济学分析模型可以进一步帮助政府决策部门达到水资源可持续发展的预期目标。同时，关于预测控制模型框架的应用经验可以被广泛应用其他的采用“完美预见“假设的项目效益的评估。

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Abbreviations

DP	Dynamic Programming
FAO	Food and Agriculture Organization of the United Nations
HPC	High-Performance Computer
HRWCC	Haihe River Water Conservancy Commission
LP	Linear Programming
MPC	Model Predictive Control
SDDP	Stochastic Dual Dynamic Programming
SDP	Stochastic Dynamic Programming
SNWTP	South-to-North Water Transfer Project

1 Introduction

Water scarcity is becoming an increasingly serious problem around the world (Wada et al. 2011; Liu et al. 2017). In recent history, humans have adapted to inadequate water resources by constructing reservoir storages as well as increasing groundwater abstraction (Kummu et al. 2010). The construction of reservoirs makes it possible to control and retain large amounts of water for specific purposes, such as hydropower generation, irrigation and water supply, and to modify downstream flow to avoid flooding. In the case of scarcity, various uses of water compete for available water resources. This conflict, over a common natural resource such as water, has led to the development of hydroeconomic analysis. Economics studies the response to scarcity by individuals and societies (Young & Loomis 2014). Hydroeconomic optimization merges the disciplines of hydrology, economics and mathematical optimization. With an economically sound valuation of various uses of water, the socio-economic optimal allocation of water is pursued. Model results can be used to guide and inform decision-makers in water resources management on the optimal operation of infrastructure, as well as long-term water resources planning, but the field of hydroeconomic optimization still faces some difficulties in merging concepts and approaches from different disciplines. Attributing an economic value to a common natural resource such as water can be controversial in a world where access to clean water is a human right, as declared by the UN (2010). Additionally, computational complexity often requires simple representations of real-world systems, and water managers will often find it difficult to link model results to applications (Harou et al. 2009), and may instead rely on more traditional hydrological and economic methods for decision support.

This study uses concepts and approaches from the field of hydroeconomic analysis to address practical water resources management problems in the complex Haihe River basin in China. The river basin is part of the North China Plain, known to be one of the most water-scarce regions in the world (Liu et al. 2017; Jiang 2009). Water scarcity, driven mainly by irrigation demands, has caused a dramatic overexploitation of groundwater resources in the region, and multiple water infrastructure projects have been carried out in an attempt to alleviate this issue (Jiang 2009). Additionally, the Haihe River is one of China's most polluted river basins (Ministry of Environmental Protection 2016a).

In recent years, the People's Republic of China has acknowledged its severe water challenges through policy documents, such as the No. 1 Central Document (Ministry of Agriculture of the People's Republic of China 2010), the Three Red Lines (Global Water Partnership 2015) and the Water Ten Plan (The State Council The Peoples Republic of China

2015). All of these pledge new and ambitious goals to approach water scarcity, water use efficiency as well as water pollution. Water managers responsible for the Haihe River basin face a complex situation, in that the sustainable use of available water resources will result in limited water abstraction, which in turn will result in economic impacts due to the curtailment of water demands. A hydroeconomic optimization model is developed herein to address the main challenges of the Haihe River basin, namely groundwater over-exploitation and water quality deterioration.

1.1 Objectives and research questions

The motivation of this PhD study was to represent the water challenges of the Haihe River basin in a flexible and realistic model setup that is easily recognizable for decision-makers in water resources management. A single hydroeconomic optimization framework was developed to address both water scarcity and water quality demands, as well as infrastructure investments, in a setup with low computational complexity, which made it suitable for subsequent integration into a control strategy optimization framework with increased complexity. Three research objectives were formulated, each resulting in a paper publication:

- **Objective 1.** In order to address the economic trade-offs from limiting groundwater overdraft in the Haihe River basin, a realistic system representation of all major reservoirs, dynamic groundwater storages and the complex water infrastructure was modelled. The system was formalized as a Linear Programming multi-reservoir, multi-temporal hydroeconomic optimization model, solved under the assumption of perfect foresight of all future hydrological events. The model setup was used to determine shadow prices, economic costs and trade-offs from limiting groundwater overdraft (paper I).
- **Objective 2.** Limiting groundwater overdraft will cause an incentive to make best use of the renewable water resources in the region. In the Haihe River basin, which presently is one of China's most polluted basins, it important to consider joint water allocation and water quality management. The externalities of upstream polluting activities were internalized in the hydroeconomic optimization framework without introducing non-linear instream water quality parameters. In this way, basin-wide shadow prices reflected regional differences in water quality (paper II).
- **Objective 3.** The assumption of perfect foresight does not represent the actual uncertainty of future hydrological events such as drought. To explore and quantify the effect of the perfect foresight assumption on model results, the model predictive control (MPC) framework was wrapped around the perfect foresight model. Agricultural irrigation demands

were modelled by linking yield response to water allocations, which captured the value of foresight for agricultural yields. The framework was used to compare benefits from water infrastructure investments in the Haihe River basin, based on various levels of foresight, thereby demonstrating the influence of assuming perfect foresight on project benefit evaluations (paper III).

2 Hydroeconomic analysis

This section provides the context of hydroeconomic analysis. The first part introduces some basic economic concepts of valuing water, while the second part is dedicated to a systematic overview of the field of hydroeconomic optimization.

2.1 Economic valuation of water

Determining the economic value of water is an important aspect of socially optimal allocations. Scarcity is reflected in economic values (Young & Loomis 2014), and by means of economic theory the social optimal allocation of a scarce resource can be identified, along with economic trade-offs. Microeconomics describes the allocation of resources between individual agents that are either utility-maximizing consumers or profit-maximizing producers (industries, farmers, etc.) (Griffin 2006). Consumer and producer demand and supply curves can be expressed as functions of price, and in a market, they reflect the marginal benefit and cost of a good, respectively. Their intersection marks the market equilibrium, representing an efficient allocation of resources, which will, in accordance with the First Theorem, be Pareto efficient, meaning that no other agent can be better off without making another worse off (Varian 2014). However, in the case of a market failure, the intersection is no longer the socially optimal equilibrium. For water resources, several market failures exist that require a more careful valuation. Examples of market failures that apply to water resources are the public good character of water as well as externalities. A public good, in economic theory, is defined as non-rival and non-exclusive (Griffin 2006). A scarce water resource will become rival, meaning that one agent's use will diminish the resource availability for another agent. A phenomenon where individual agents ignore the social cost of their actions, such as the over-exploitation of a common resource, is described through the concept of *the tragedy of the commons* (Hardin 1968). Externalities are impacts on a third agent's utility function during the market exchange between the consumer and the producer (Freeman III et al. 2014). Examples of negative externalities include groundwater pumping interfering with another agent's well-field, or water pollution. Negative effects on a third agent's utility from water pollution include health impacts, ecosystem impacts and cleaning costs imposed on downstream users. A market where resources and environmental services are priced correctly can create economic incentives for the sustainable behavior of individual agents. **Figure 1** shows the effect of an externality causing the marginal social cost (x) to be higher than the marginal private cost (*). By imposing the cost of externalities on the producer, the market equilibrium will shift to the social optimal (from * to x). It is market failures that make the economic measures of value important, in order to guide sustainable decisions and policymaking (Freeman III et al. 2014).

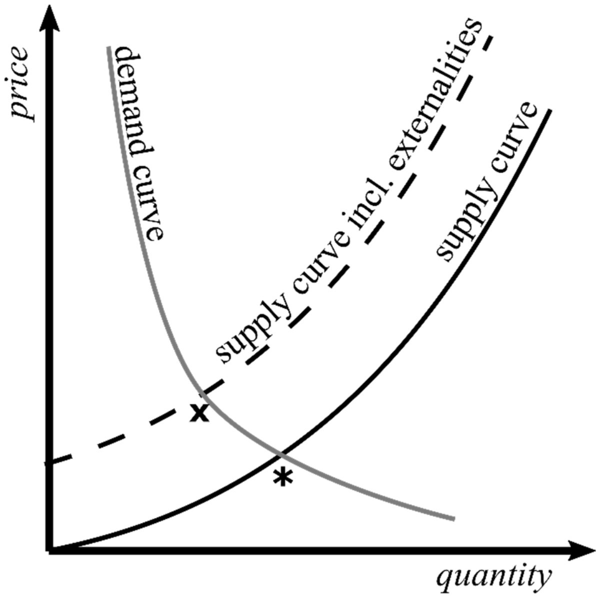

Figure 1. Conceptual illustration of the demand and supply curve at market equilibrium with (x) and without (*) considering externalities. Modified from Greenlaw and Taylor (2017).

The role of economics in the sustainable management of a resource such as water has been acknowledged internationally by the United Nations (1992):

> "[…] Past failure to recognize the economic value of water has led to wasteful and environmentally damaging uses of the resource. Managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources."
>
> **UN Dublin Statement, 1992**

There is a close link between water resources and economic activities (Brouwer & Hofkes 2008), but estimating the economic value of water is not a straightforward task, since water markets are not common, and observed prices of water are often influenced by public subsidies. In the absence of market prices for water, economists tend to express the value of water through its shadow prices (Young & Loomis 2014). Several deductive estimation methods exist in this regard, such as the residual imputation method, computational general equilibrium models (CGEMs) and mathematical programming.

The residual imputation method is an approach used widely to estimate the economic value of commodity production inputs. The value of water can be deducted from the producer benefits per allocated unit of water, and it reflects an average point estimate of its value to production (Young & Loomis 2014). As can also be the case for total household water consumption at an observed unit price of water, this can be interpreted as a point on the demand curve, as illustrated in **Figure 1**. In combination with a known price elasticity, this can be used to identify the full demand curve based on the point expansion method (Griffin 2006). These methods have been used in several hydroeconomic optimization studies to reflect the economic value of water in agricultural and industrial sectors as well as household allocations (e.g. Riegels et al. 2011; Pulido-Velázquez, Andreu, and Sahuquillo 2006).

The value of water can also be determined as an input into a regional economy from CGEMs, which link simultaneous non-linear equations describing the prices, supplies and incomes of multiple sectors (Young & Loomis 2014). A response in the regional economy to an exogenous change in water input can be used in analysing the economic value of water. Examples of CGEM applications in the hydroeoconomic analyses of water infrastructure investments include the study by Strzepek et al. (2008), investigating the impact of the High Aswan Dam on the Egyptian economy, and the economic effects of constructing the SNWTP, examined by Berrittella, Rehdanz and Tol (2006).

Mathematical programming relies on linear or non-linear optimization algorithms. An objective function, representing costs or benefits, can be minimized or maximized subject to a set of constraints (Young & Loomis 2014) that can reflect resource availability or structural constraints. Lagrange multipliers of the optimal solution reveal shadow prices of the constraints, i.e. changes in the objective from a small relaxation of the constraints. Mathematical programming can also be used in hydroeconomic optimization studies to identify optima and trade-offs in water resources management. Among numerous applications, it has been employed in large-scale river basin studies to reflect benefit opportunities from increasing water infrastructure capacities or the opportunity cost of environmental constraints (e.g. Tilmant, Marques, and Mohamed 2015; Pulido-Velázquez, Andreu, and Sahuquillo 2006). A more comprehensive review of various hydroeconomic model approaches follows in the next section.

2.2 Optimization modelling in water resources management

This section locates the three papers in a taxonomy describing the methods and approaches often used in hydroeconomic optimization, as seen in **Figure 2**. Each sub-section presents two opposites in the process used to define a hydroeconomic optimization framework. These design choices are discussed briefly and related to the existing literature. For an extensive review of optimization methods in water resources management, the reader is referred to Labadie (2004) and Rani and Moreira (2010).

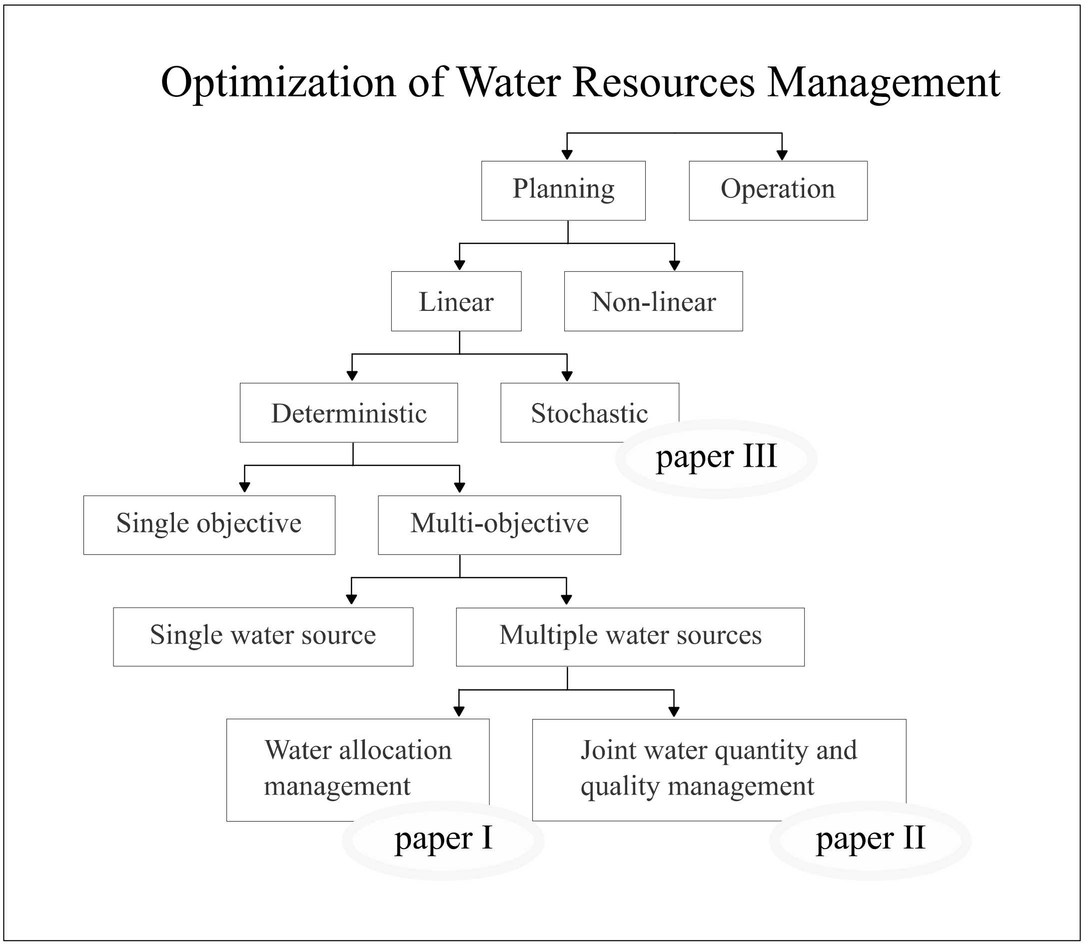

Figure 2. Taxonomy describing hydroeconomic optimization modelling approaches related to the three papers in this study.

2.2.1 Planning and operation

Water resources management problems can have different spatial and temporal scales. At the lower end of the spatial scale is the management of a single reservoir for environmental purposes, hydropower production, water supply, flood control or a combination thereof. At the high end of the spatial scale is river basin water management, where allocation schemes, pollutant loads and infrastructure investments can be addressed on medium- to long-term scales. Both are faced with the same operational problem: use water now, for immediate benefits, or save water for the future (Loucks & van Beek 2005c). This problem can be formalized into an optimization problem that can be solved and guide decision-making. The objective of such an optimization problem would often be to minimize any form of losses related to decisions, subject to a set of constraints such as water infrastructure, availability, etc. Optimization approaches are used to identify rule curves for reservoir operation, thus supporting "when" and "how much" decisions (Loucks & van Beek 2005a; Draper & Lund 2004). Optimization can also be used to address major system changes in long-term water resource management, such as benefits from new water infrastructure investments or changed allocation schemes. This study focuses on the long-term planning aspects of water resources management. The management problems addressed herein are long-term groundwater sustainability (paper I), joint water allocation and water quality management (paper II) as well as benefits from water infrastructure investments (paper III).

2.2.2 Linear and non-linear optimization models

Many water resource management problems are non-linear, examples of which include head-dependent groundwater pumping costs (e.g. Davidsen et al. 2016), water level-dependent hydropower benefits (e.g. Cai, McKinney, and Lasdon 2001) as well as water user demand curves (e.g. Huang et al. 2012). An assumption of linearity can be justified in some cases; as an example, Alemu et al. (2011) assumed a constant water-energy equivalent for a hydropower station. If linearization cannot be justified, several non-linear programming methods exist, all of which require differentiable objective functions and constraints (Labadie 2004). Non-linear Programming methods might result in a sub-optimal solution and have high computation demands, especially when applied in a stochastic framework. As a result, heuristic algorithms have become increasingly popular for dealing with non-linearity (Rani & Moreira 2010). A combination of the heuristic genetic algorithm (GA) with LP has been used in optimization of non-linear hydroeconomic models (e.g. Cai, McKinney, and Lasdon 2001). A result of the coupled LP-GA framework, in contrast to LP, is that convergence to a global optimum cannot be guaranteed (Cai et al. 2001). This PhD study works with linear optimization problems using LP. Groundwater aquifers are modelled as lumped storage, and regional variations in groundwater head from pumping activities, resulting in non-linear pumping costs, are not considered in the model.

2.2.3 Deterministic and stochastic optimization modelling

Near-future water demands can often be estimated with very little uncertainty, whereas future water availability is highly uncertain. There is a wide range of approaches in water resources optimization modelling regarding how to address the uncertainty of future hydrological events. Deterministic models assume perfect foresight of all future hydrological events, whereas stochastic models incorporate the uncertainty of future hydrology in the optimization framework. A class of optimization techniques suitable for both linear and non-linear optimization problems involves dynamic programming (DP) methods (Bellman 1966), which can reduce multi-stage non-linear problems, to multiple single-stage linear problems. Reservoirs can be represented as states with discretized storages, where all possible stages in time are solved recursively. Stochastic dynamic programming (SDP) is a modification of DP developed to represent future uncertainties. Future inflow can be represented with discrete Markov chain probabilities, and future cost functions of each stage of inflow and release decisions can be estimated in a backward-moving optimization approach. Linear cuts of the future cost functions are found by using Benders decomposition. Costs are interpolated between reservoir states, but only convex cost functions can approximate true future cost functions. Inherent in the DP method is the *curse of dimensionality* (Bellman 1961), which limits to only a few the number of reservoirs that can be optimized, since computational demands increase exponentially in line with the number of states. Pereira and Pinto (1991) introduced SDDP to surpass the *curse of dimensionality*. SDDP combines a forward-moving stochastic simulation and a backward moving deterministic optimization in an iterative approach, to find future cost functions that satisfy a specified convergence threshold between the two. Future cost functions are found by using linear extrapolation. SDDP can be applied to multi-reservoir systems, as demonstrated by Tilmant, Pinte, and Goor (2008), and SDP and SDDP are both widely applied in the water resources optimization literature, though optimization techniques are complex compared to deterministic models. Decisions based on SDDP can be very sensitive to even minimal changes in input, such as initial reservoir storage, as discussed by Rougé and Tilmant (2016). SDDP further provides the highest accuracy around the optimal solution, making it less suitable for adaptive management.

The advantage of deterministic optimization is the computational simplicity and easy application of existing efficient solvers (Harou et al. 2009). The CALVIN (Medellin-Azuara et al. 2015) and AQUATOOL (Andreu et al. 1996) models are a few examples of water resources planning models with a deterministic optimization module. Models solved in a deterministic manner represent hydrological regimes observed in the historical time series of the model. By solving a large ensemble of synthetic future inflows or a long historical time series, the deterministic optimization becomes implicitly stochastic (Labadie 2004). Model results will still only capture the statistical properties of the historical inflow data.

In optimization theory, MPC has been developed as a control strategy for dynamic systems with stochastic future disturbances (Rawlings 2000). It was originally developed for operational control in the industry, to maintain desired output trajectories despite system disturbances (Richalet et al. 1978). The principles behind MPC have been used for the optimization of energy systems (e.g. Michele Arnold and Andersson 2011), and they are also used increasingly in water resources management studies (e.g. Castelletti, Pianosi, and Soncini-Sessa 2008; Tian et al. 2017; Palmer et al. 2011). Paper I and paper II within this PhD study are both formulated as deterministic models, assuming perfect foresight. Paper III considers the stochastic nature of future water availability by wrapping a MPC framework around the deterministic optimization model of paper II, which in turn quantifies the effect of unforeseen future hydrological events and irrigation demands compared to the perfect foresight framework in paper II.

2.2.4 Single- and multi-objective optimization

Decision-makers in water systems often have to consider various stakeholders' interests as well as the multi-purpose character of water resources. If all objectives can be valued and formulated as expressions of the model's decision variables, multiple objectives can be aggregated a priori into a single overall objective. With multiple conflicting objectives, a single Pareto optimal solution cannot be found (Cohon & Marks 1975). In such cases, the trade-offs between multiple objectives can be mapped out for subsequent decision-making. By incrementally constraining the objective function, a Pareto optimal front can be mapped out, illustrating the trade-offs between the objective and the constraints. This is known as the "constraining method" (Rani & Moreira 2010; Haimes et al. 1971). Another approach is the weighting method, whereby individual weights are assigned to each objective, first presented by Gass and Saaty (1955) for a two-objective problem. With an increasing number of objectives, though, the constraining and weighting methods become challenging. Multi-objective evolutionary algorithms have been used to approximate the Pareto front in multi-objective optimization, and Reed et al. (2013) reviewed its application in water resources modelling. Another approach to multi-objective optimization is a subjective weighting of several objectives through stakeholder involvement, as well as an exploration of inferior Pareto sets. This can be a highly iterative process and an overview of the topic is provided by Loucks and van Beek (2005b). The water resources management problem of the Haihe River basin addressed in this study is multi-objective. In paper I, all water-associated costs are monetarized in the objective function while gradually constraining groundwater overdraft to introduce the objective of groundwater sustainability. Paper II adds the objective of adhering to water quality demands by adding costs associated with cleaning polluted water sources to the objective function. In this way, Pareto optimal solutions and trade-offs are mapped out and can be used for subsequent decision-making.

2.2.5 Conjunctive management of surface water and groundwater

In systems where groundwater is a dominant source of water, it is important to consider its role in optimal planning and operation of water resources systems. Groundwater modelling is complicated by aquifer heterogeneity and the impacts of abstraction. As a result, groundwater-surface water interactions are often simplified in hydroeconomic optimization models (Pulido-Velazquez et al. 2016). Since early studies on the conjunctive use of surface- and groundwater resources with DP (Burt 1964), the representation of surface water-groundwater interactions has been refined in several hydroeconomic optimization studies. In large-scale river basins, groundwater aquifers are often modelled as lumped storages with mass balances. In contrast to lumped storage, distributed groundwater modelling has also been incorporated into hydroeconomic optimization frameworks through the use of the embedding and response matrix methods (Pulido-Velazquez et al. 2016). The study by Macian-Sorribes, Tilmant, and Pulido-Velazquez (2017) is an example of embedding linear reservoir modelling of groundwater aquifers in a SDDP optimization model framework, to capture groundwater-surface water interactions. Hydrological response functions represent another approach to linking hydrological and economic models, as utilised by MacEwan et al. (2017) in a study optimizing basin-scale groundwater pumping. In this PhD study, groundwater resources are modelled holistically as time-dependent mass balances in conjunctive management with reservoir storages over the optimization period. Groundwater recharge estimates are based on numerical groundwater modelling studies and are kept constant. Groundwater-surface water interactions are assumed insignificant, because of the over-exploited nature of the groundwater aquifers.

2.2.6 Joint water quantity and quality management

Integrated water resources management must address both water scarcity as well as water quality. The aspect of water quality increases model complexity, since it is traditionally modelled by considering return flows, dilution effects and biochemical processes, which are all non-linear processes. Moreover, a wide range of pollutants exists in the aquatic environment. Water quality management can be integrated into hydroeconomic optimization models through constraints. Minimum ecological stream-flow requirements can constrain the flow of natural river stretches, and their opportunity costs can be reflected by model shadow prices (e.g. Pulido-velazquez et al. 2006). Constraints on downstream water quality offer another approach in considering the diluting effect of in-stream flows. Davidsen et al. (2015) used this approach to optimize non-linear downstream surface water quality constraints by simulating in-stream biological oxygen demand (BOD) in a single-reservoir SDP model. The non-linear model setup was solved in a coupled LP-GA optimization framework. Another study, by Peña-Haro, Pulido-Velazquez, and Sahuquillo (2018), focused on groundwater quality management. From a response matrix, based on numerical groundwater modelling, the pollution load from fertilizer application is considered through the constraints of an optimization model. Paper II approaches large-scale river basin water quality management from a different perspective. In contrast to simulating water quality, the water source qualities are fixed. The proposed model setup can determine minimum water-related costs from allocating water qualities fit for downstream purposes while adhering to long-term sustainable groundwater abstractions. In this way, the economic effect of upstream water pollution on downstream agents' quality requirements is quantified.

3 Water resources management in China

Several analyses in the past have identified the complex and fragmented institutional setup in Chinese water resources management as the key to many water challenges (e.g. Ongley and Wang 2004; Jiang 2015; B. Liu and Speed 2009; Shen 2009). **Figure 3** provides an overview of the regional levels of, and relations between, the various governing bodies in this regard.

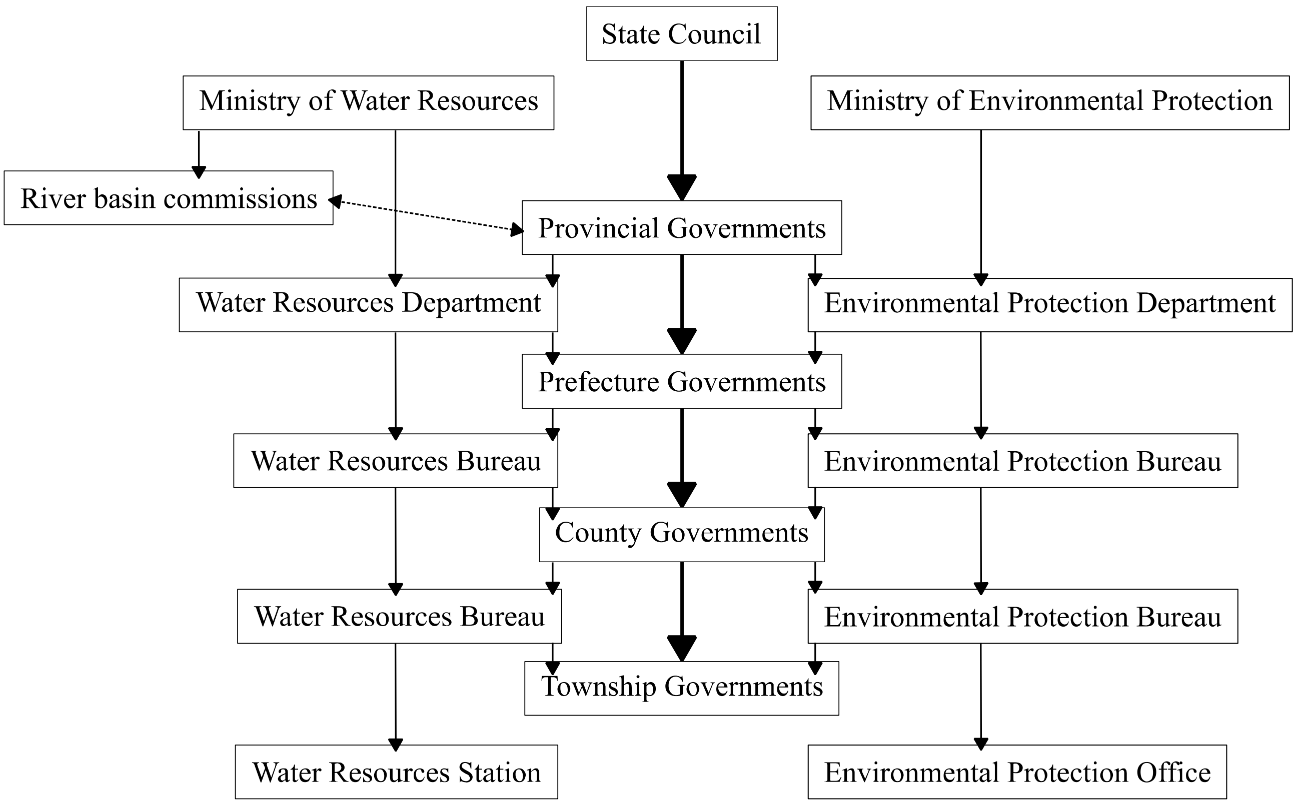

Figure 3. Main institutions involved in Chinese water resources management Modified from Song et al. (2010).

The Ministry of Water Resources and the Ministry of Environmental Protection are the two departments involved mostly in water resources management. Their main responsibilities are listed below (Khan & Liu 2008):

- Ministry of Water Resources
    - Surface water and groundwater management

    - Flood control
    - Water and soil conservation
- Ministry of Environmental Protection
    - Prevention and treatment of water pollution

Water quantity management is solely the responsibility of the Ministry of Water Resources, separating it from water quality monitoring, which is managed by the Ministry of Environmental Protection. The river basin commissions, under the jurisdiction of the Ministry of Water Resources, work on a river basin scale, compared to the administrative regions governed by the various departments and bureaus under the two ministries. River commissions exist for all major river basins in China, but they have various levels of influence in the present institutional framework, dealing mainly with flood protection and trans-boundary water resources management overlapping province borders. A meeting with the Haihe River Water Conservancy Commission (HRWCC) during this study confirmed their limited power and that "the policies from HRWCC are not legally binding and therefore only guidance. Local governments are responsible for the final decisions" (Appendix IV). Despite this fragmented system, no institution is responsible for coordination and communication between all of the involved departments in the implementation of government laws and guidelines. The structure of the institutional framework makes it vulnerable to failures and inefficiencies as a result of overlapping responsibilities on various administrative levels (Jiang 2015). The main water consumer, agricultural irrigation, is rarely metered, and in-stream water quality is badly monitored (Liu & Speed 2009), as witnessed on a field trip in the northern regions of the Haihe River basin. Here, farmers often reported that surface water pollution was one of the reasons for them using groundwater pumping for irrigation instead of surface water abstractions (Appendix V).

In the past, the focus has mostly been on water supply management, but from 1990 to 2010, Chinese water resources management went through a transition. The Chinese government started this reform with an increased emphasis on economic incentives and institutional management (Liu et al. 2013). The milestone political laws and documents during this transition period are listed below:

- **1984** amended in 1996 and 2008: **Water Pollution Prevention and Control Law** (Peoples Republic of China 2008). Sets responsibilities for water quality monitoring and aims to regulate waste water discharges (Shen 2009; Liu & Speed 2009).

- **1988** amended in 2002: **Water Law** (Peoples Republic of China 2009). China's key water legislation. A comprehensive framework for integrated water management. Specifies general guidelines but leaves implementation to local governments (Shen 2009; Liu & Speed 2009).
- **2010**: **No. 1 Central Document for 2011** (Ministry of Agriculture of the People's Republic of China 2010). A government plan to achieve sustainable use of water resources. Promotes water savings and increased investments in water conservancy technologies (Jiang 2015). Mostly focused on water quantity (Liu & Yang 2012).
- **2011**: **Three Red Lines**. Guidelines for water use, water use efficiency and water pollution, respectively. Targets of all three aspects set for 2015, 2020 and 2030 (Global Water Partnership 2015).
- **2015**: Water Pollution Prevention and Control Action Plan, also known as **"Water Ten Plan"** (The State Council The Peoples Republic of China 2015). Sets 2020 and 2030 targets for overall surface water and groundwater quality. In seven key river basins (among these Haihe River basin), >70% of surface water should have water qualities of grade I-III and less than 10% of grade V or lower. Targets to reduce over-pumping and the pollution of groundwater (The State Council The Peoples Republic of China 2015).

These laws and guidelines show an increased focus on linking water resources and quality management, as well as managing water resources on the river basin scale. A press release from the Chinese government on June 1st 2018 (Xinhua News 2018) revealed an institutional reform into which "government organizations with overlapping functions and work [had] been smoothly integrated". The new Ministry of Eco-Environment might be a step towards an environmentally friendly institutional setup. This study aims at the same targets and ambitions for sustainable water resources management laid out by the Chinese government. In the current management system, river basin commissions have limited power, but the work of this thesis is suitable for the future needs of integrated basin-scale water resources management in China.

4 Case study: the Haihe River basin and its water challenges

4.1 The Haihe River basin

The Haihe River basin is one of China's seven major river basins. It is located in the north-eastern part of the country and mainly covers Hebei, Beijing and Tianjin provinces (**Figure 4**). At the foot of the Yanshan Mountains, to the north and the Taihang Mountains and to the west, stretches the plain area. The alluvial plain area (Chen et al. 1996) covers approximately 40% of the $33.8 \cdot 10^4$ km^2 large river basin and is the hub of economic activity in the region.

Figure 4. Map of the Haihe River basin including provinces, major cities, major reservoirs and inter-basin transfers from the South-to-North Water Transfer Project (SNWTP) and the Yellow River.

The plain area is densely populated, and megacities such as Beijing and Tianjin count populations of 21.7 and 15.6 million, respectively. Outside the cities, an intensively cultivated landscape is predominant. The plain area of the Haihe River basin is a part of the North China Plain, a region often referred to as the "food basket of China". Agriculture is a big part of the economy in the river basin, and it supplies around 10% of China's total agricultural output (White et al. 2015). A double-cropping system is widespread, especially in the plain area. Summer maize is traditionally grown in rotation with winter wheat, and the region is located in the temperate zone with a semi-arid continental monsoon climate (Lu et al. 2014), resulting in limited winter precipitation. The widespread double-cropping practices of the region therefore add pressure to the scarce water resources during winter months.

4.1.1 Water scarcity

One of the key challenges in the Haihe River basin is water scarcity. Compared to China's average yearly water availability per capita of 2,100 m^3 (Ministry of Water Resources 2016), water availability is less than 279 m^3 in Haihe River basin (National Bureau of Statistics of China 2017), and as a result, groundwater resources have been over-exploited. Large-scale cones of depression have been observed in both the shallow and deep aquifer layers of the plain area, and an overall groundwater depletion rate of 8.3 km^3/year, from 2003 to 2010, has been found for the North China Plain (Feng et al. 2013). Furthermore, the groundwater overdraft has resulted in severe land subsidence (Chen et al. 2016), as well as seawater intrusion in coastal areas (Zheng et al. 2010). As a remedy, several inter-basin transfer projects, such as the prestigious SNWTP, have been constructed for supply augmentation.

4.1.2 Water pollution

In addition to water scarcity, the Haihe River basin has overall the worst surface water quality in the country. **Table 1** presents the surface water quality class demands for different purposes, adopted from the Ministry of Environmental Protection (2002), according to which 36.8% of the monitored river network in the Haihe River basin is polluted or highly polluted and has a quality class of V or >V (Ministry of Environmental Protection 2016b). Groundwater quality is also an issue, and the Ministry of Environmental Protection (2011) reports that only 62.7% of the groundwater areas of Hebei province meet water quality standard classes I-III.

Table 1. Water quality standards and their respective qualifications for use. Adopted from the Ministry of Environmental Protection (2002).

Surface water quality class	Qualify for use in
I	Head waters and national nature reserves
II	First-class protected areas of surface water sources for drinking water
III	Ecological demands
IV	General industry
V	Agriculture

4.2 Conceptual model of the Haihe River basin

In order to formalize the water resources management problem relating to the Haihe River basin, a conceptual model needs to be developed which will summarise major water resources, water users and the infrastructure connecting them. Defining the conceptual model of the Haihe River basin was an iterative process driven by an increased system understanding evolved through literature studies, data collection, field trips (Appendix V) and meetings with water resources managers in the region of interest (Appendix IV).

Figure 5. Village upstream of Guanting reservoir with small-scale farming and industries. Visited to conduct farmer interviews and make observations of irrigation facilities during the field trip (see Appendix V).

4.2.1 Sub-basin delineation

The nine largest reservoirs of the Haihe River basin, with capacities above 1,000 km^3, were considered in the model. These reservoirs are Panjiakou, Miyun, Guanting, Xidayang, Wangkuai, Gangnan, Huangbizhuang and Yuecheng, shown in **Figure 7**. The nine upstream sub-basins were the major sources of surface water runoff. The delineation of the model sub-basins was confirmed with data from the Haihe River Water Conservancy Commission (2013). In addition to the nine upstream sub-basins, the model included five downstream plain area basins and two basins covering the Beijing and Tianjin provinces.

4.2.2 Water demand aggregation

Water demands for all major water user groups, identified from the National Bureau of Statistics of China (2015), were aggregated in each sub-basin, in which the seven water user groups, namely domestic, industrial, ecological and agricultural water demands for wheat, maize, orchards and vegetables, were represented. All user groups were assumed to be capable of accessing groundwater resources. The water users in each sub-basin were modelled with access to groundwater aquifers with an overlapping recharge area (see **Figure 7**). On the field trip, farmers reported that maize was mostly rain-fed, but no farmers seemed to have difficulties accessing irrigation facilities during drought events (Appendix V). **Figure 6** shows examples of irrigation facilities observed in the field.

a) b) c)

Figure 6. Examples of irrigation facilities observed on the field trip. A) centre-pivot, b) groundwater irrigation and c) pump house.

4.2.3 Water infrastructure connectivity

The water infrastructure connectivity of the Haihe River basin was conceptualized in order to identify all possible allocations, from water sources to sub-basin water demands. Water scarcity in the Haihe River basin has promoted a highly engineered system, in that inter-basin transfers from neighboring river basins, as well as between the model sub-basins, make it possible to allocate water from one sub-basin to the other in times of scarcity. SNWTP's eastern and mid-line connects the Haihe River basin with Yangtze River water resources and terminates in Tianjin and Beijing, respectively. The lower reaches of the Yellow River define the southern border of the Haihe River basin and feed some of the southern Haihe River basin areas, as well as the distant Tianjin along the SNWTP east line. From the Wanjiazhai reservoir further upstream the Yellow River, water is transferred via underground pipe systems to the Datong region upstream of Guanting reservoir (see **Figure 4**). Within the Haihe River basin, the water infrastructure is well connected. As an example, an underground pipe system can transfer water from Yuecheng reservoir to Handan city (Davidsen 2015). Likewise Panjiakou reservoir is connected to Yuqiao reservoir, to allow water to flow downstream to Tianjin, as indicated on **Figure 7**. Appendix VI provides an overview of the whole Haihe River basin water infrastructure and its connectivity, and the sources of information used to define the conceptual understanding of this complex water infrastructure.

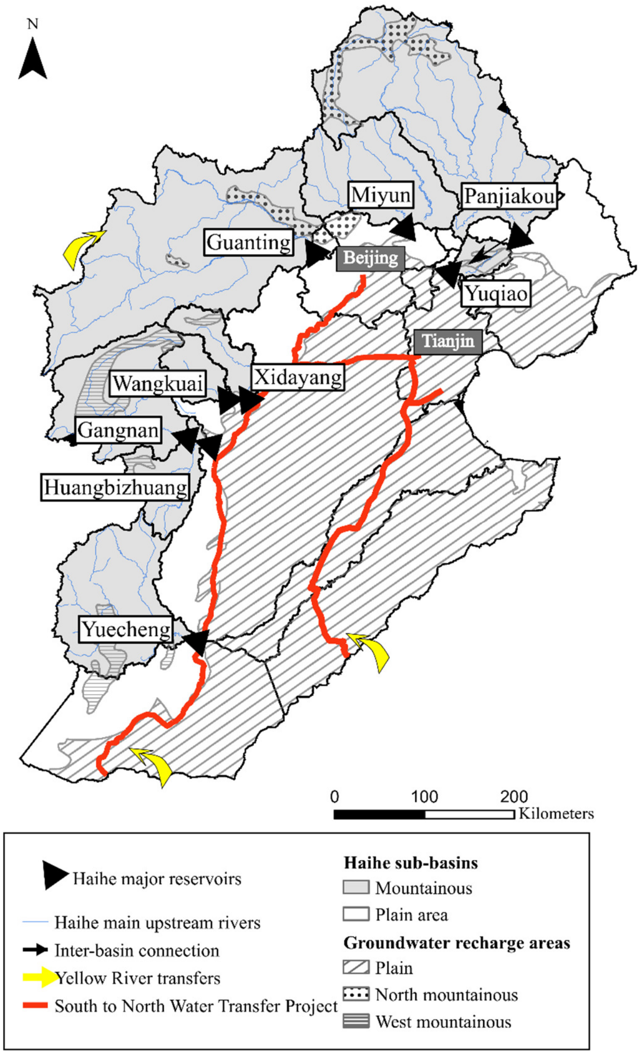

Figure 7. Conceptual illustration of the Haihe River basin, its main sub-basins, reservoirs, inter-basin transfers and groundwater recharge areas.

4.3 Collecting and merging hydrological and economic data

The core input datasets for the hydroeconomic model were water availability, water demands and economic data for valuing water allocations. The spatial and temporal overlaps between hydrological and economic data rarely match (Bauer-Gottwein et al. 2017), which was also the case in this study. **Table 2** gives a brief overview of the main data inputs and their relative spatial and temporal resolutions. The bottleneck for increasing the spatial resolution of the Haihe River basin conceptual model was not hydrological data but the spatial resolution of economic data and water demands. This section introduces some of the methods used to derive and merge the various types of datasets for the hydroeconomic optimization model.

Table 2. Overview of the main input datasets and their spatial and temporal resolution.

Description	Source	Spatial resolution	Temporal resolution	Paper
Precipitation and evapotranspiration	China Meteorological Agency (2017)	0.5º	Daily	I
In-situ runoff	Ministry of Water Resources (2011)	Hydrological stations of all major streams	Daily	I
In-stream surface water quality	IPA (2006)	All major streams	Daily to yearly	II
Domestic and industrial water fees	H2O China (2000)	Major cities	Daily	I
Water demand statistics	National Bureau of Statistics of China (2015a)	Province	Yearly	I
Agricultural water value	Gan et al. (2008)	Prefecture	-	I
Ecological water value	World Bank (2007)	Basin	-	I

Spatial and temporal resolution

4.3.1 Modelling of surface water runoff and agricultural water demands

Surface water runoff and agricultural water demands were determined from process-based modelling. Surface water runoff in the nine mountainous sub-basins was simulated from a Budyko rainfall-runoff model (Zhang 2008) calibrated for three minor upstream sub-basins, seemingly undisturbed by human abstractions. Details on the calibration process can be found in paper I. Agricultural water demands were estimated based on a method provided by Allen et al. (1998) and presented in the FAO Irrigation and Drainage Paper 56 (FAO 56). Meteorological forcing data on precipitation and evapotranspiration were accessed from the China Meteorological Agency (2017) at a spatial resolution of 0.5°. Paper I and Paper II used historical precipitation and evapotranspiration data from January 2007 to January 2015 to generate monthly runoff and agricultural water demand time series. An illustration of the process for deriving the hydrological dataset of the model can be seen in **Figure 8**.

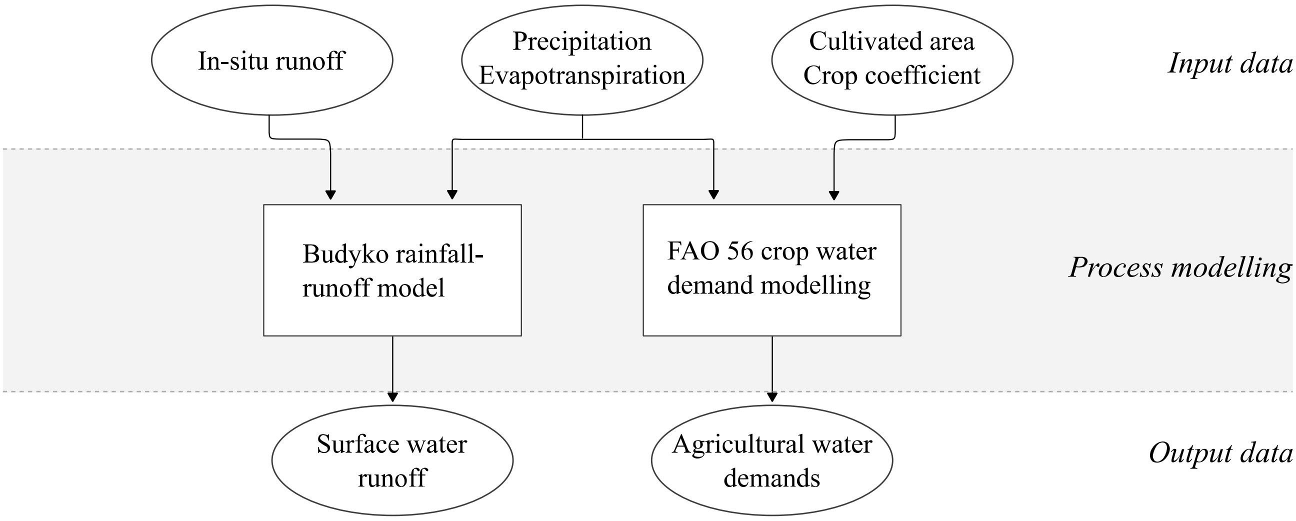

Figure 8. Process diagram of input data and modelling approaches for computing surface water runoff and agricultural water demands.

The crop water demand (Dem_c) in the FAO 56 method is determined based on the cultivated area (A_c), a crop- and season-specific crop coefficient (K_c) as well as the reference evapotranspiration (ET_0) and precipitation (P):

$$Dem_c = A_c \cdot (ET_0 \cdot K_c - P) \tag{1}$$

Identification of sub-basin-specific A_c and K_c values was based on several levels of data acquisition. Remote sensing products, observations and interviews on field trips (Appendix V), statistical data (National Bureau of Statistics of China 2015c) and the literature were used. The process is explained in detail in Appendix VII. The plain area basins were mostly located within Hebei province and were well-described by both statistical data and literature. Field trips were used to verify assumptions about cropping and irrigation practices in the mountainous regions, which were not covered by statistical information on Hebei province.

The main assumptions about agricultural water demands, based on field trip experiences, were:

- All rain-fed agriculture is assumed to be maize
- Double-cropping is not practiced in the mountainous regions
- All agricultural users are equipped with irrigation
- Vegetables were lumped into one single agricultural water user group with a fixed monthly water demand.

4.3.2 Scaling of non-agricultural water demands and groundwater recharge

The peripheral sub-basins in the mountainous regions were not well-described by either water demand statistics or groundwater recharge estimates. The low spatial and temporal resolution input data for non-agricultural water demands and groundwater recharge were therefore scaled to the sub-basin level, based on population and precipitation, respectively.

The population density dataset Landscan2016 (Bright et al. 2017) was used to scale ecological water demands as well as domestic and industrial per capita water use to the total population in each sub-basin. Water demands were calculated from statistics on yearly water use in sectors located in Hebei, Beijing and Tianjin provinces (National Bureau of Statistics of China 2015b). The mountainous sub-basins were assumed to share similar per capita water use with the population of Hebei province because of their vicinity and similar climate.

The plain area groundwater recharge was based on a numerical groundwater modelling study by Cao (2011) and scaled to the mountainous aquifers by a precipitation-scaling coefficient. The scaling method provided a coefficient between groundwater recharge in the plain area relative to the mountainous regions. Similar recharge processes were assumed to occur for the quaternary recharge areas in both the mountainous regions and the plain area, which were areas subject to the scaling approach. Their ranges were based on a USGS geological map provided by Steinshouer et al. (1997) and illustrated in **Figure 7**.

4.3.3 Economic data

The economic parameterization of the hydroeconomic optimization model was refined gradually during this study. In paper I, water-associated costs were determined from groundwater pumping and curtailment costs. The experience that came out of farmer interviews around the Haihe River basin was that irrigation water rarely had a price, except for pumping costs for groundwater irrigation (appendix V). Water user demands and the associated marginal benefits were assumed fixed, while curtailment costs were used to describe any lost benefit, i.e. costs, from not meeting users' full water demands. The cost of water deficits were determined by multiplying monthly water user deficits with the estimated curtailment costs, the latter of which were determined from economic datasets on three spatial levels: city, prefecture and basin. For domestic and industrial curtailment costs, city-level water fees charged to the consumer (H2O China 2000) were interpreted as point estimates of water users' willingness to pay. The residual imputation method, presented in section 2.1, was tried out as an estimate for agricultural curtailment costs. As also discussed in the World Bank (2007) report, production costs are not easily determined based on available Chinese statistics. The economic value of agricultural irrigation water was therefore based on a study of the benefit-sharing coefficient method by Gan et al. (2008) in seven prefectures of the Haihe River basin.

Ecological water was set as a demand in each sub-basin and associated with a curtailment cost (World Bank 2001), in contrast to minimum in-stream flow constraints. The reasoning behind doing so was the highly engineered water infrastructure of the Haihe River basin, where, in some places, channels are replacing natural river stretches, which are left to run dry. One such example is the Hutou River and the New Hutou River downstream of Huangbizhuang reservoir, as reported by Davidsen (2015).

Paper II added cleaning costs for water allocations, with water quality inferior to downstream water quality demands based on city-level water treatment fees (H2O China 2000). In paper III, the curtailments of the agricultural grain producers were modelled as yield responses to water allocations instead of monthly demand deficits. The benefits from agricultural yield can be determined as:

$$Benefit_{yield} = Y_{act} \cdot A_{crop} \cdot mp_{crop} - production\ costs \tag{2}$$

where the actual yield (Y_{act}) of the cropped area (A_{crop}) is multiplied with the market price for the crop (mp_{crop}) and subtracted the costs for agricultural production. As already discussed, production costs are not easily determined in a Chinese context. The benefit of agricultural yields were therefore back-calculated from the monthly curtailment costs, as explained in paper III. Directly back-calculating benefits of total yield from the estimated value of irrigation water will underestimate the sunken costs of production, such as labor, machinery, fertilizer, etc. The yield benefits will therefore represent an upper bound for the true agricultural benefits.

Figure 9 illustrates the spatial overlap between the hydrological units (the sub-basins) and the economic dataset. All Haihe sub-basins were populated with economic data by averaging inside sub-basins. For sub-basins not covered by data, extrapolation of data from nearby sub-basinwere used. The resulting economic dataset for all sub-basins can be found in **Table 3**.

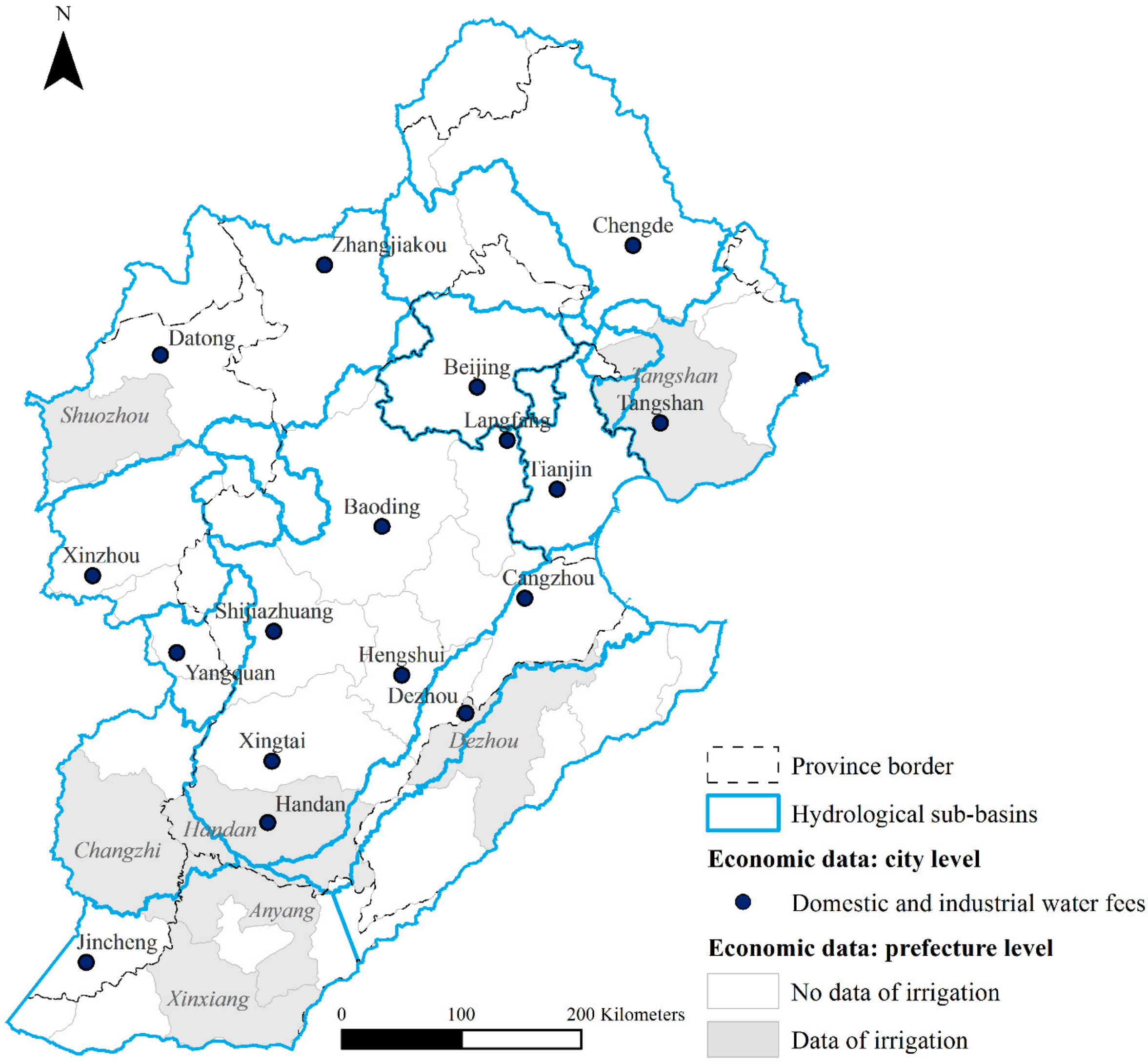

Figure 9. Spatial overlap of hydrological sub-basins, provinces and economic datasets.

Table 3. Economic dataset for curtailment costs, yield benefits and cleaning costs.

Sub-basin	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Curtailment costs (yuan/m^3)																
Industry	2.4	5.6	5.6	5.6	4.2	3.1	3.1	3.9	2.8	4.8	9.9	6.3	4.7	5.9	7.9	3.1
Domestic	2	2.7	2.7	2.7	2.6	2.3	2.3	2.5	2.1	2.6	5	4	3.2	3.5	4.9	2.3
Ecological	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Low-value irrigation	1.8	1	1.3	1.3	1.6	1.6	1.2	1.2	1.6	1.2	1	1.8	3.3	1.3	1	1.6
High-value irrigation	13.6	7.4	12.3	12.3	24.7	24.7	39.2	39.2	14.95	39.2	7.4	13.6	14.2	12.3	7.4	24.7
Yield benefit (million yuan)																
Summer maize (double-cropping)	5107	-	-	65	-	-	-	-	3547	-	77	2803	16838	950	433	-
Winter wheat (double-cropping)	2394	-	-	31	-	-	-	-	1889	-	49	1361	7906	430	213	-
Summer maize	2252	489	2234	109	4057	11	528	148	1750	690	379	2415	9107	1364	546	225
Spring wheat	-	90	410	-	384	18	232	159	-	495	-	-	-	-	-	91
Cleaning costs (yuan/m^3)	0.63	0.7	0.7	0.7	0.98	0.93	0.93	0.73	0.77	0.58	1.6	0.87	1	1.71	1.1	0.93

5 Optimization modelling applied to Haihe water challenges

The comprehensive water resources management problem of the Haihe River basin was formulated as one large linear optimization problem. In contrast to methods such as SDP and SDDP, briefly introduced in Section 2.2.3, this does not require a discretization and valuation of reservoir storage represented by the model. The linear model formulation enables the optimization model to work on numerous decision variables over a large number of time steps, with limited computational resources. The linearized model does not as such cope with stochastic properties of future climate and water availability. Solving all time steps in one single linear programming optimization problem, as in paper I and paper II, is only possible if an assumption of perfect foresight is adopted. Paper III quantifies and discusses the impact of the assumption of perfect foresight on model results. This section provides an overview of the methods used in the three papers, ending with their respective computational requirements.

5.1 Formalization of the water resources management problem

The water resources management problem of the Haihe River basin is formalized using flow path-based allocation variables, in contrast to node water balances. The flow path formulation is based on the principles of Cheng et al. (2009), and it is illustrated in **Figure 10**. This way of formulating water balances increases the number of model decision variables, but it also makes it possible to represent parallel channels and different water quality classes in the complex Haihe River basin water infrastructure. **Figure 10** also illustrates the use of flow paths to identify source water quality inferior to downstream water quality demands, a concept applied in paper II and III.

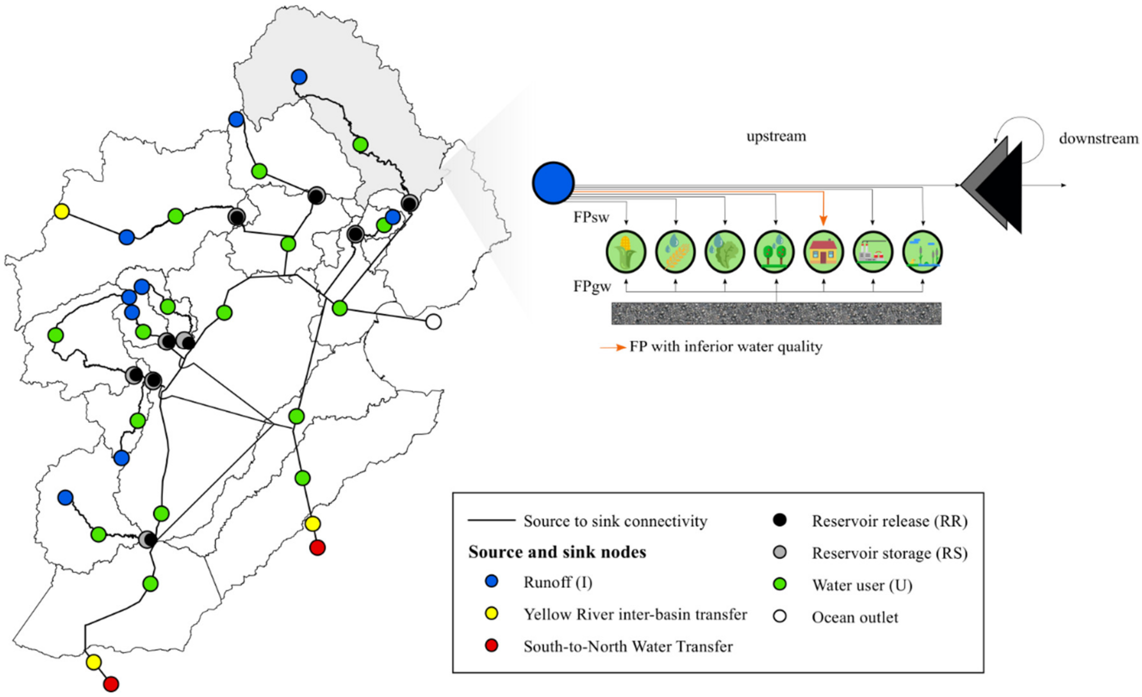

Figure 10. Source-to-sink network. Used to identify all possible flow paths in the formalization of the Haihe River basin optimization problem.

5.1.1 Decision variables

The model decision variables represent decisions such as water allocations to users, for specific time steps and from specific sources. **Table 4** gives an overview of the categories of model decision variables, and at what stage of the model framework (in which paper) they are introduced.

Table 4. Model decision variables and the paper in which they are introduced to the model framework.

Variable	Decision	Introduced in paper
FP_{sw}	Allocation from a surface water source to a downstream water user	I
FP_{gw}	Groundwater abstraction for connected users in sub-basins overlapping with the groundwater recharge areas	I
GRS	Groundwater reservoir storage in the groundwater mass balance	I, refined in II
Def	Water user demand deficit	I
S	Agricultural yield	III

The groundwater balances of the groundwater aquifer units are expressed by the groundwater reservoir storage decision variables, *GRS*. In paper I, the model represents the two mountainous and the plain area aquifer units. Papers

II and III split the plain area aquifer into a deep and a shallow aquifer unit with differentiated water qualities and pumping costs, resulting in an additional GRS decision variable. In paper III, the deficits of the agricultural grain producers are modelled as crop states, *S*, with yield response to water allocations instead of monthly deficit variables, *Def*. This sums up to 1490, 1722 and 1783 decision variables in every time step of the model setup for papers I, II and III, respectively.

5.1.2 Governing equations

The core optimization model for all three papers, namely I, II and III, allocates surface water and groundwater in the most cost-efficient way under a set of water infrastructure and environmental constraints. The model objective function minimizes total water-associated costs (see Equation (3)), which are found from the cost-vector of curtailment costs, cc, and groundwater pumping costs, c_{pump}, for all water users and time steps in the planning period, *T*. Surface water allocations are not associated with any costs in paper I. Curtailment costs and groundwater-pumping costs are exogenous model inputs, and these are explained in more detail in paper I.

$$Min(cc \cdot Def + c_{pump} \cdot FP_{gw}) \tag{3}$$

The optimization problem is constrained by a set of equality and inequality constraints defining both the water infrastructure of the river basin as well as water user demands and environmental constraints.

$$I_t = \sum_{i_{down}=1}^{I_{down}} FP_{sw,t,i_{down}} \tag{4}$$

$$GRS_t = GRS_{t-1} + Re_t - \sum_{gw_{down}=1}^{GW_{down}} FP_{gw,t,gw_{down}} \tag{5}$$

Equations (4) and (5) are water availability constraints for each source of runoff and groundwater allocations, respectively. I is surface water runoff, I_{down} is the downstream connected flow paths, *GRS* is the groundwater aquifer, *Re* is monthly groundwater recharge and GW_{down} is the connected flow paths for groundwater abstractions.

$$\sum_{rs=1}^{RS} FP_{sw,t,rs} \leq RS_{vol} \tag{6}$$

$$\sum_{rs=1}^{RS} FP_{sw,t,rs} = \sum_{rs=1}^{RS} FP_{sw,t-1,rs} - \sum_{rr=1}^{RR} FP_{sw,t,rr} \quad (7)$$

Equations (6) and (7) represent reservoir storage capacity and allocation constraints. *RS* is the upstream flow paths into the respective surface water reservoir, *RR* is the downstream flow paths leaving the reservoir, RS_{vol} is the total storage capacity.

$$Def_{t,u} = Dem_{t,u} - \sum_{u_{sw}=1}^{U_{sw}} FP_{sw,t,u_{sw}} - \sum_{u_{gw}=1}^{U_{gw}} FP_{gw,t,u_{gw}} \quad (8)$$

Equation (8) is the water demand constraint. *Dem* is water user demand and U_{sw} and U_{gw} are the flow paths of surface water and groundwater, respectively, to the user.

$$GRS_{end} \geq GRS_0 - \alpha \cdot GRS_{overdraft} \quad (9)$$

Equation (9) is the plain area groundwater sustainability constraint. $GRS_{overdraft}$ is the resulting overdraft with unconstrained groundwater abstraction for all users connected to the plain area groundwater aquifers, while GRS_0 is initial groundwater storage. By means of the constraining method, eleven groundwater scenarios were optimized by ranging α, an overdraft coefficient, from 0 to 1. The constraint was imposed on the groundwater aquifer storage in the last time step of the optimization period, to represent long-term sustainable groundwater abstractions.

5.2 Joint water quantity and quality management

The Chinese Water Law, introduced in section 3, defines water functioning zones as having to comply with a certain water quality standard based on water use in that specific area. In this way, water quality management is addressed by prevention instead of treatment (Liu & Speed 2009). Paper II adds water quality constraints to the water quantity optimization problem, which is done by considering the treatment costs of water sources inferior to downstream water user quality demands. Instead of simulating pollution and dilution from water user return flows into the river network, resulting in non-linearity (discussed in section 2.2.6), water source qualities are assumed fixed. The externalities of water pollution are internalized by adding cleaning costs if water user quality demands cannot be met. The optimization framework will not allocate and clean water to meet required in-stream quality standards, but instead it will quantify the economic effects of meeting downstream user requirements based on the water quality as it is now.

The objective function of Paper II is modified to include cleaning costs of treating inferior water qualities.

$$Min(cc \cdot Def + c_{pump} \cdot FP_{gw} + c_{clean} \cdot FP_{swq<demq} + c_{clean} \cdot FP_{gwq<demq}) \quad (10)$$

where c_{clean} is the cleaning cost for surface water and groundwater flow paths not meeting water user quality demands, $FP_{swq<demq}$ and $FP_{gwq<demq}$, respectively.

Figure 11 illustrates the routine used to add cleaning costs to the model framework. For groundwater allocations, shallow polluted groundwater is differentiated from deep clean groundwater by different quality classes and pumping costs. The method used to determine flow path water qualities is described in more detail in paper II.

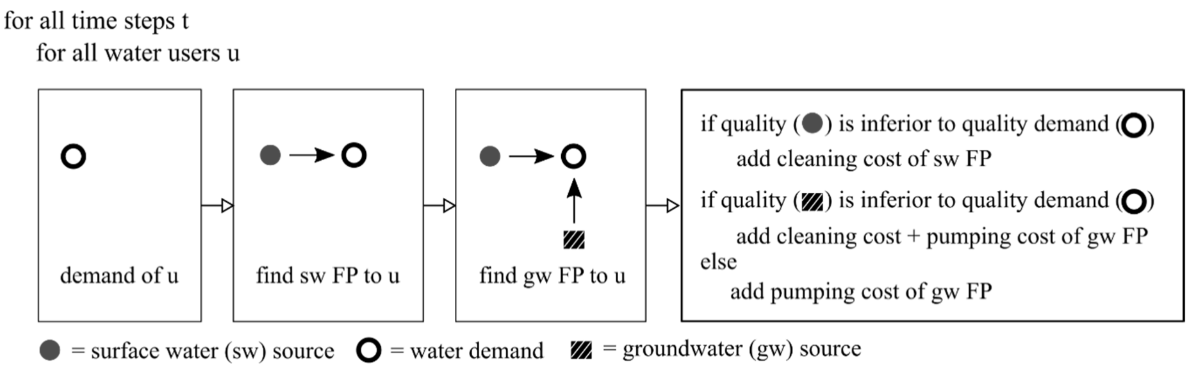

Figure 11. The routine used to assign cleaning costs to water allocations with a quality inferior to downstream user water quality demands. Modified from paper II.

5.3 Concept of delayed yield

At the same time as moving away from the assumption of perfect foresight in paper III, the concept of delayed yield was introduced to the model set-up. Delayed yield refers to the conceptual representation of agricultural yield as a function of all water allocations over the growing season, instead of isolated monthly yield losses. Modelling the impact on yields from all water allocations over the growing season was done by aligning the yield response method to water allocations. The method is described by Doorenbos and Kassam (1979) in the FAO 33 Irrigation and Drainage Paper. The effect of water stress as a relative reduction in actual crop yield (Y_{act}) compared to the maximum crop yield (Y_{max}) can be expressed by means of a yield response factor (K_y). The resulting crop water production function was originally formulated as:

$$\frac{Y_{act}}{Y_{max}} = 1 - K_y \cdot (1 - \frac{ET_{act}}{ET_{max}}) \tag{11}$$

Where ET_{act} and ET_{max} are the actual and maximum crop evapotranspiration, respectively. Estimating ET_{act} precisely is difficult and requires daily water balance calculations (Steduto et al. 2012). Ghahraman and Sepaskhah (2004) demonstrated a re-formulation of Equation (11) to a function of crop water allocation (w_{all}) and demand (w_{dem}). This only represents an approximation of the actual water stress experienced by the crop, but is sufficient for the model framework applied in this study. A crop state variable (S), ranging from 0 to 1, was added to the set of decision variables to represent the relative crop yield reduction. In each initial time step of a new growing season, the crop would have the potential for a maximum yield, reflected by initiating S with a value of 1. The yield response to water allocation was fomulated as:

$$S = 1 - K_y \cdot (1 - \frac{w_{all}}{w_{dem}}) \tag{12}$$

where w_{all} is the sum of all upstream flow paths to the crop plus the precipitation. w_{dem} is set equal to ET_c, which is calculated from the FAO 56 method (see Section 4.3.1).

Only the grain producers, i.e. those growing wheat and maize, were represented by the concept of delayed yield. The agricultural water demands for vegetables were kept as fixed monthly demands with deficit curtailment costs as in paper I and paper II, because of the wide variety of crops covered by this user demand category. The yield from orchards is highly infleuenced by carry-over effects between growing seasons (Steduto et al. 2012), and it was also not modelled with the delayed yield concept.

Equation (12) was implemented in the model framework by the minimum approach (Allen 1994). Moreover, the final crop state was not a function of the previous month's crop state but was constrained by it. The governing equations for the agricultural crop states can be seen below:

$$S_{u,t} \leq 1 - K_y \cdot (1 - \frac{\sum FP_{sw,u,t} + \sum FP_{gw,u,t} + A_{c,u} \cdot P_t}{A_{c,u} \cdot ET_{c,u,t}}) \tag{13}$$

$$S_{u,t} \begin{cases} = S_{u,t-1}, & if\ A_{c,u} \cdot ET_{c,u,t} = 0 \\ \leq S_{u,t-1}, & otherwise \end{cases} \tag{14}$$

$$0 \leq S_t \leq 1 \tag{15}$$

$$S_0 = 1 \tag{16}$$

The constraint in Equation (14) represents the constraining effect between the time steps of the growing season. In this way, the largest reduction of S during the growing season determined overall yield reduction. The concept is illustrated in **Figure 12**.

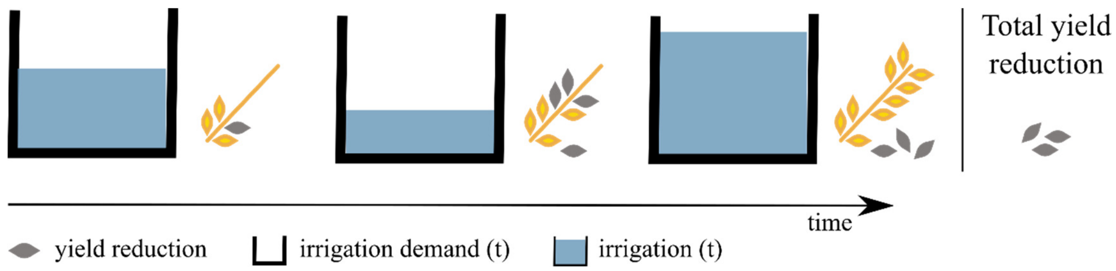

Figure 12. Conceptual illustration of delayed yield using the minimum approach.

The model objective function was modified to consider only the benefits from agricultural grain producers' yields in the last time step of the growing season. This was done by identifying yield lost from the last crop state of the growing season (S_{end}) and evaluating the loss compared to the benefit of a maximum yield ($Benefit_{yield}$). This was done for all growing seasons (s_{growth}) over the course of the planning period, T, for all grain producers (u_{grain}):

$$\min(\sum_{t=1}^{T}\sum_{u=1}^{U}(Def_{u,t}\cdot cu_u + FP_{sw<demq_{u,t}}\cdot c_{clean,u} + FP_{gw<demq_{u,t}}\cdot c_{clean,u} + \sum_{aq=1}^{GRS_{tot}} FP_{gw_{u,t,aq}}\cdot c_{pump,aq}) + \sum_{s_{growth}=1}^{S_{growth}}\sum_{u_{grain}=1}^{U_{grain}}(1 - S_{end_{s_{growth},u_{grain}}})\cdot Benefit_{yield_{u_{grain}}}) \tag{17}$$

5.4 Quantifying future uncertainty

Under an assumption of perfect foresight, there are no unforeseen hydrological events. This will likely result in different reservoir operations and agricultural water allocations compared to a system where present decisions cannot anticipate full information on how the future will play out. This issue was addressed in Paper III by adding the delayed yield concept to the model set-up, thus accounting for the effect of unforeseen droughts on agricultural yields. To simulate unforeseen future hydrological events, the model framework was wrapped by a continuous re-optimization routine inspired by the control strategy MPC. As introduced briefly in section 2.2.3, MPC was developed to adapt system performance to continuous unforeseen disturbances, a conceptual illustration of which is seen in **Figure 13**. The initial state of the system, in this case reservoir and groundwater storage as well as crop states, is passed to the controller for time step t. Based on model predictions of future water availability and demands, control actions that will satisfy the model's objective and constraints are found from an internal optimizer. These control actions are implemented as decisions for time step t. Based on the actual water availability and -demands of time step t, which will later be referred to as the "truth", the resulting updated state of the system in the beginning of time step t+1 is passed to the controller, continuing the same re-optimization as for time step t.

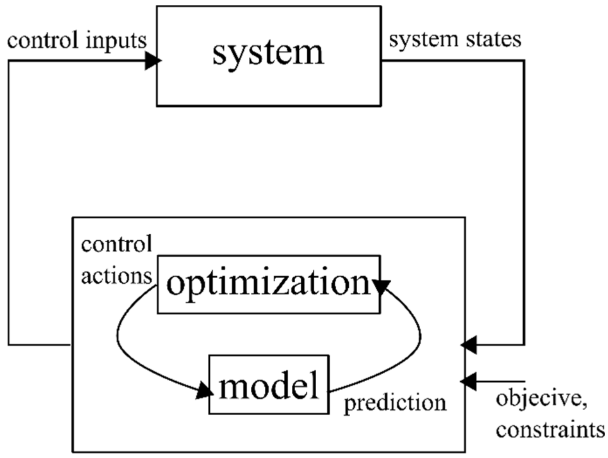

Figure 13. Conceptual illustration of Model Predictive Control (MPC). Modified from M Arnold et al. (2009).

In paper III, system disturbances are represented by unforeseen hydrological events, such as drought. A single synthetic time series of future hydrological events is generated to present the "truth" over the planning horizon (H). Using the "truth" as a perfect foresight benchmark can subsequently be used to evaluate the impact of managing a system with decreasing levels of foresight of future events. Time series of runoff, precipitation and evapotranspiration were simulated with a parameterized first-order periodic autoregressive Thomas-Fiering model (Harms & Campbell 1967). The Thomas-Fiering model was used to simulate both the "true" runoff availability, as well as predictions of future hydrology. Predictions of future hydrology were based on f months foresight of the "truth" followed by an ensemble of synthetic future hydrological time series, all equally likely to occur. Different degrees of future foresight could be represented by changing the length of the forecast resembling the "truth", i.e. f. A conceptual illustration of the resulting runoff time series with foresight (f) of one and six time steps, compared to the "true" runoff over the same period, can be seen in **Figure 14**. With every future synthetic series of precipitation and evapotranspiration, corresponding future agricultural water demands were also determined, based on the FAO 56 method (Allen et al. 1998).

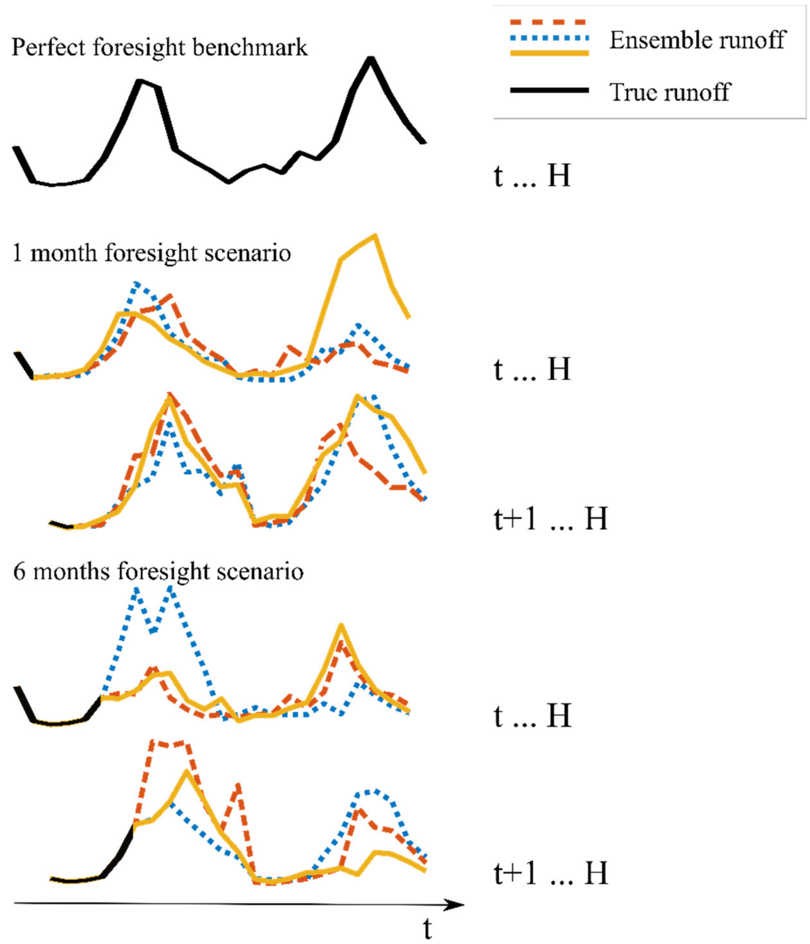

Figure 14. Conceptual illustration of Thomas-Fiering model simulations of "true" hydrological runoff compared to time series with foresight of one and six time steps.

The dynamics of the MPC framework continuously re-optimize a series of decisions over a planning horizon, representing adaptation to unforeseen events. A model framework combining the LP model setup from paper II with the MPC routine was run with various levels of foresight for the same truth. The LP-MPC framework applied in paper III is illustrated in **Figure 15**.

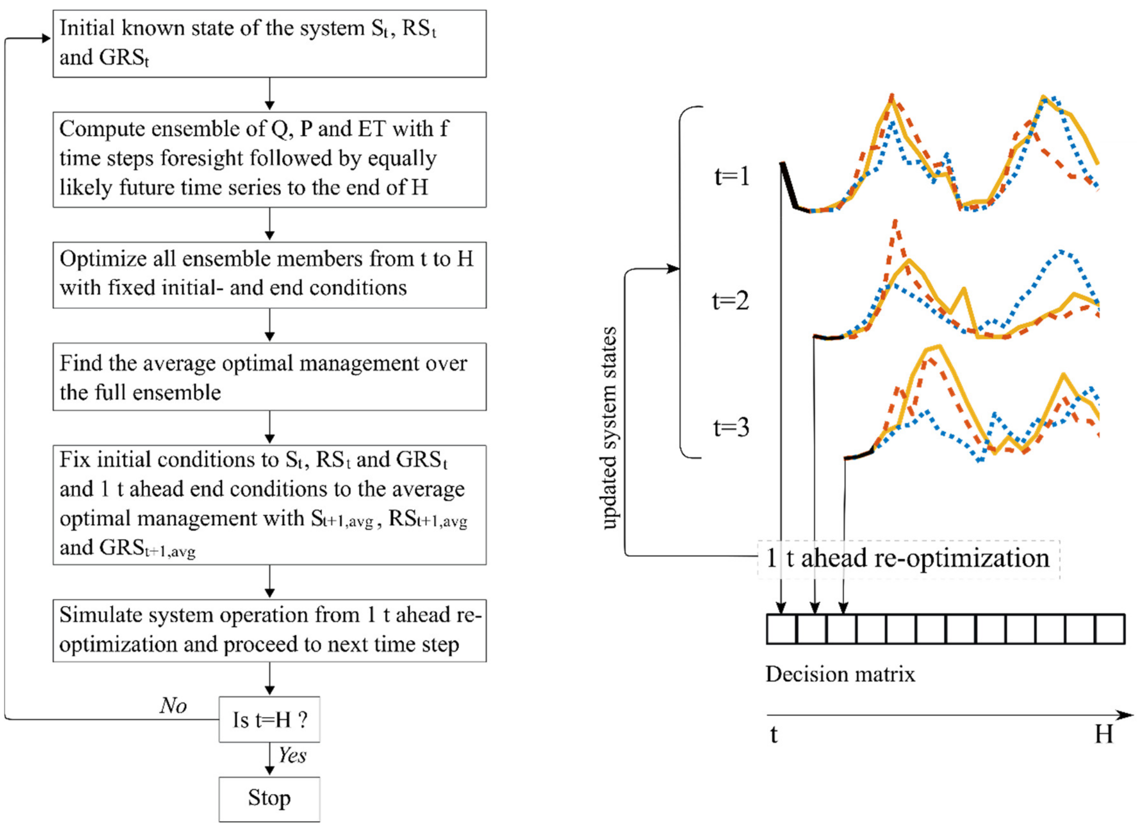

Figure 15. Flowchart and illustration of the LP-MPC routine applied in paper III. The figure modified from paper III.

The impacts of managing a system with decreasing levels of foresight will be reflected by increased costs. The LP-MPC framework was utilized in paper III to evaluate the impact of foresight, not only on costs, but also on benefits from water infrastrcuture projects.

5.5 Computational resources

An advantage of the linear model formulation is that fast and efficient LP solvers are available, which can be found in many programming toolboxes (Nocedal & Wright 2006). This study used the built-in linprog solver for Linear Programming in MATLAB R2018a (MathWorks 2018). The problem was optimized with the dual-simplex optimization algorithm, a variant of the simplex algorithm (Dantzig 1963).

With pre-prepared constraint matrices and simulated hydrological runoff, precipitation and evapotranspiration time series, the computational requirements for solving the optimization problems of the three papers shown in **Figure 16**. Paper I and paper II were solved on a 2 Intel Core i5-7200U processor with 8 GB RAM. The model in paper III was parallelized using the MATLAB parfor command and solved using the DTU's High-Performance Computer (HPC), using 12-core Intel Xeon E5-2650 v4 processers with 256 GB memory.

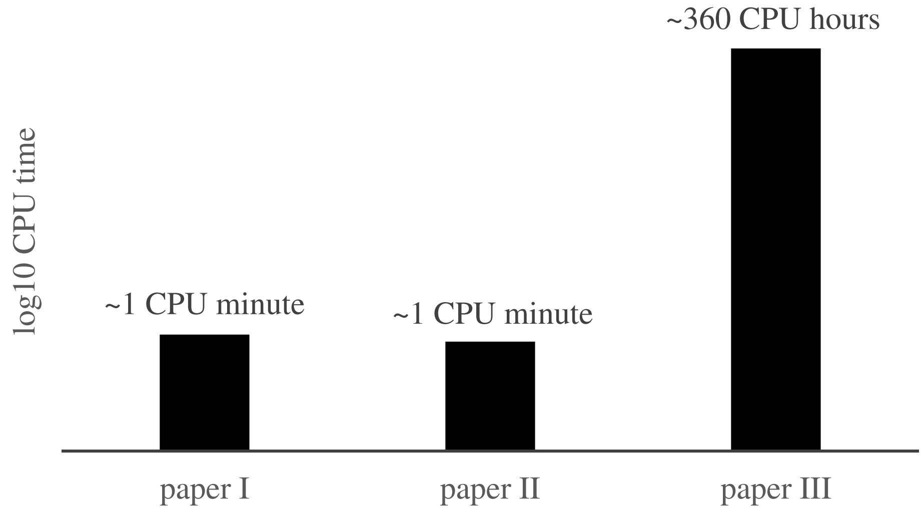

Figure 16. Computational requirements for the optimization problems in papers I, II and III.

Required computational resources increase significantly for the continuous re-optimization in the MPC model framework of paper III. With parallelization of the code in MATLAB and available resources at the HPC, the turnaround time for the whole optimization problem was limited to fewer than seven hours.

6 Overview of the main results

All of the results in this study can be found in papers I, II and III. This section aims at providing an overview and comparison of the findings in the three papers. A comparison of the results shows the impact of model refinement and the decision support that the model provides. Results from paper III are still preliminary.

6.1 Total costs and trade-offs from limiting groundwater overdraft

Pareto optimal solutions for all groundwater scenarios show the minimum water-associated costs, under optimal management. From the slopes of the Pareto fronts, in **Figure 17**, the economic trade-off from limiting groundwater overdraft is identified. The different magnitudes of costs of the Pareto fronts between the three papers illustrate the sensitivity of the total cost estimates to the model's system representation. The relatively higher total cost of paper I compared to paper II can be attributed to the simpler representation of the groundwater aquifer system. The single plain area aquifer unit results in a less flexible decision space for groundwater pumping costs, compared to the shallow and deep layer represented by the models in paper II and paper III, and thereby higher total costs.

Results reported in paper I do not vary much in terms of economic trade-offs from one groundwater scenario to the other, and the economic trade-off is reflected mostly by an increased curtailment of low-valued grain producers during constrained groundwater abstractions. As the model is refined, the decision space becomes more complex. Considering the uncertainty of future hydrological events in paper III reveals costs that cannot be represented by a model setup assuming perfect foresight. With limited foresight come increased yield losses for agricultural grain producers, especially when groundwater allocations are constrained. The optimal allocation scheme also changes in line with increasing curtailments among the higher valued users, such as industries, and ecological demands, as groundwater allocations are constrained.

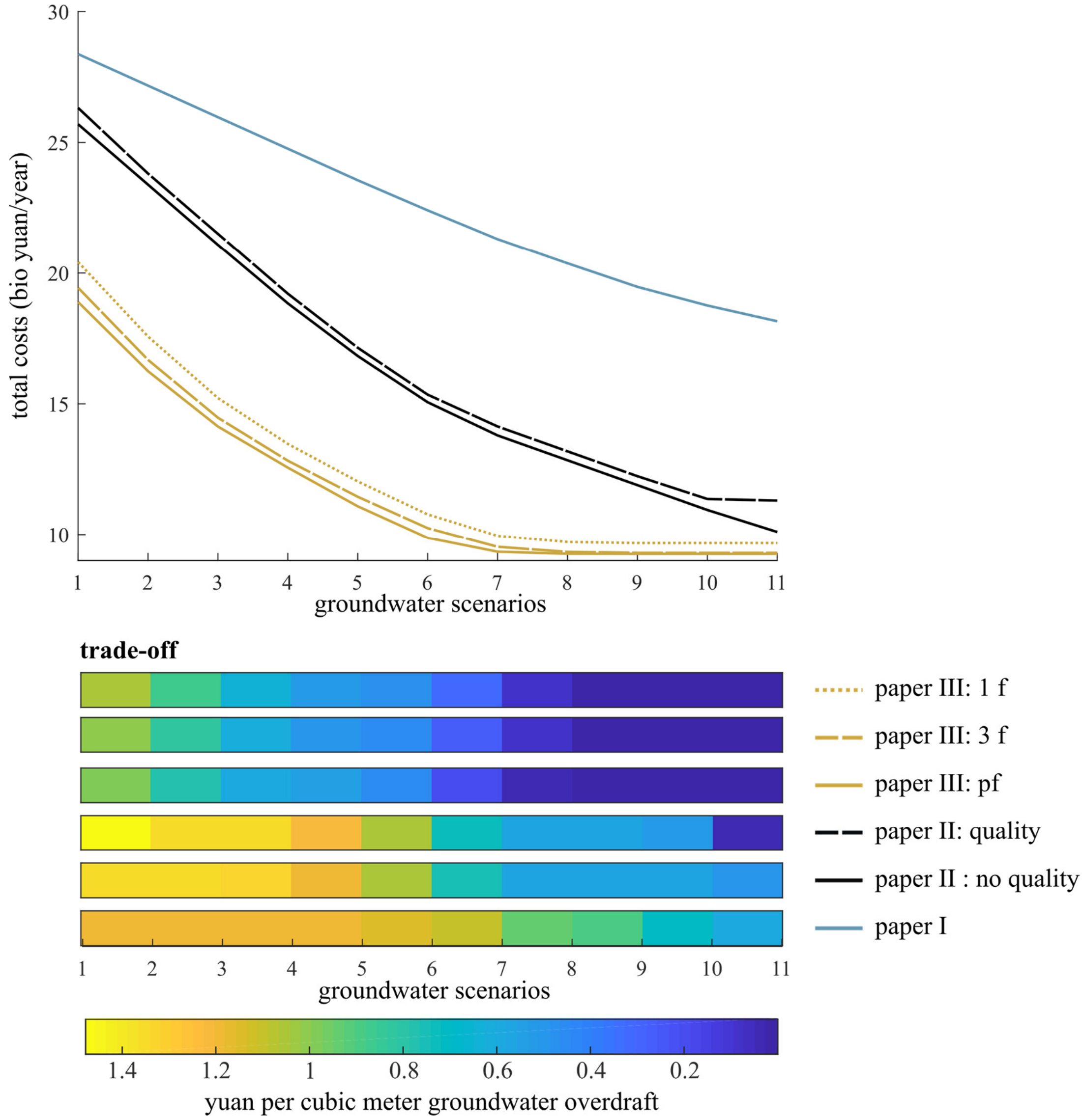

Figure 17. Pareto optimal fronts and the economic trade-offs from limiting groundwater overdraft in all three papers, namely I, II and III.

6.2 Shadow prices of water availability

The shadow prices of the various water sources reflect the resulting reduction in water-associated costs from an additional unit of water availability. **Figure 18** maps out spatial differences in average shadow prices for the runoff of all sub-basins as well as inter-basin transfers and plain area groundwater recharge in the Haihe River basin. The figure shows shadow prices for the model framework, with and without water quality. Adding water quality to the model set-up in paper II did not change the total costs significantly (see **Figure 17**), since the major curtailments are for the low-valued agricultural users, i.e. those who do not have strict water quality demands. A significant impact from implementing water quality in the model framework was found mainly in the water availability shadow prices. This added insight to the spatial distribution of costs from meeting downstream water quality demands. Spatial variability in runoff shadow prices reflected upstream quality versus downstream water quality demands.

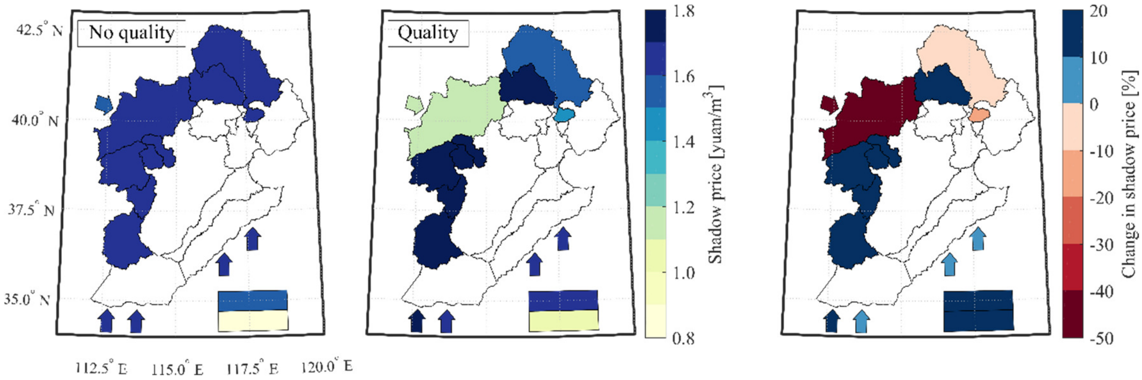

Figure 18. Water availability shadow prices from paper II, without and with water quality added to the model framework. Last map shows the percentage change from considering water quality.

Adding water quality to the model framework showed that the reduction in water availability shadow prices could not be linked directly to the relative water quality classes. It was driven by a more complex interaction between upstream water qualities, downstream water quality demands, water infrastructure and water availability. A few sub-basin water sources showed a large decrease in shadow prices from implementing water quality in the model framework. Targeted water quality improvements at these water sources could alleviate water-associated costs in the Haihe River basin. The water sources that showed increased shadow prices reflected the possibility of limiting overall costs by supply augmentation with the present water quality status.

6.3 Project evaluation

Basin-scale decision support models can help decision-makers quantify the benefits of water infrastructure investments. In a classical cost-benefit approach, costs and benefits with and without a project are compared as a part of the decision process determining whether or not to invest in the project. Hydroeconomic optimization models can identify basin-wide water-associated costs for various system representations, thereby revealing the possibility of optimizing water resources management with a proposed infrastructure project. Several projects to alleviate the water challenges of the Haihe River basin have been evaluated in paper II and paper III of this study. Paper

II evaluated the economic benefits from improving the SNWTP's eastern line's water supply quality (scn 1), as well as the benefits of managed groundwater recharge of surplus water from the Gangnan and Huangbizhuang reservoirs (scn 2). Paper II found that the shadow prices of the water sources in the north-western sub-basin upstream of the Guanting reservoir were comparatively low in, as seen in **Figure 18**, hence indicating the possibility of more valuable use. Paper III addressed a proposed water infrastructure project allowing Yellow River water, from the "Yellow-into-Jin" inter-basin transfer project, to be transported via the Guanting reservoir to the thirsty plain area, also improving the water quality of Guanting reservoir water resources. The project's benefits, resulting from a comparison of basin-wide water-associated costs with and without the projects, can be seen in **Figure 19**. The project in paper III will result in the highest basin-wide cost reduction compared to the projects evaluated in paper II. Paper III used the coupled LP-MPC framework to evaluate project benefits with limited future foresight of only the present time step in each time step (1f), as well as an additional two months' foresight (3f) compared to a perfect foresight benchmark (pf). From the comparison it was noted that assuming perfect foresight of future hydrological events would underestimate the evaluated project benefits. The paper III's results imply that the actual benefits of the projects evaluated in paper II might be higher. The actual feasibility of the projects would require a further comparison between the costs of implementing each project and the estimated benefits in a cost-benefit analysis.

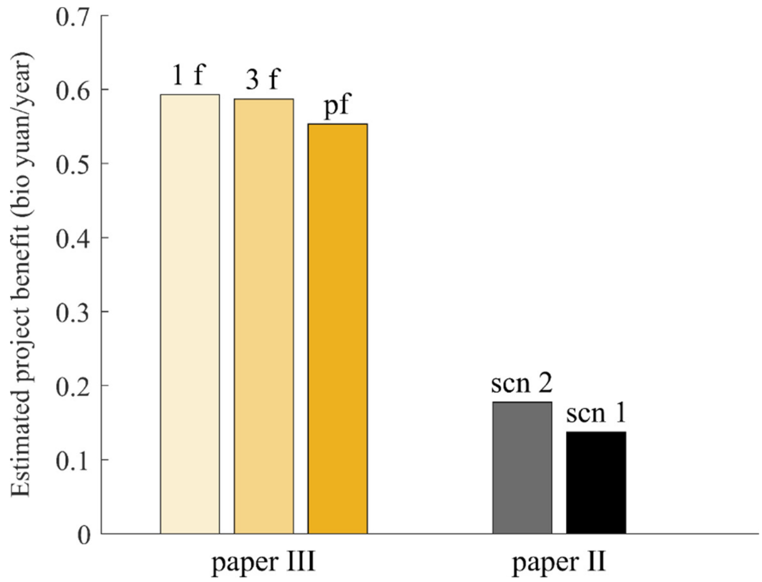

Figure 19. Project benefits evaluated with "present" time step foresight (1f), two additional months foresight (3f) and perfect foresight (pf) in paper III. The two projects in paper II (scn1 and scn2) are evaluated with pf.

7 Conclusions

The purpose of this study was to develop a flexible, linear hydroeconomic optimization model to address the water challenges facing the water-scarce and polluted Haihe River basin. The model set-up was refined gradually to capture economic trade-offs from groundwater overdraft, externalities of water-polluting activities on downstream water user quality demands and the impact of assuming perfect foresight in water resources optimization modelling. These three aspects are valuable in large-scale river basin decision-making when the economic impacts of projects and policies must be evaluated.

Some of the main conclusions of this study are:

- A flexible model framework with limited computational costs could represent Pareto optimal solutions addressing both groundwater overdraft as well as water quality management in a single linear model set-up.
- Limiting groundwater overdraft will have substantial socio-economic consequences for the Haihe River basin.
- The severe water pollution issue of the Haihe River basin's water sources is revealed in water availability shadow prices, which reflect the externalities of water pollution from the downstream water user perspective.
- Reflecting water pollution in water availability shadow prices can provide a spatially resolved indicator for the economic consequences of upstream polluting activities.
- Several water infrastructure projects can help alleviate the economic consequences of reducing groundwater overdraft in the Haihe River basin.
- The benefits of these infrastructure projects might be underestimated under the assumption of perfect foresight. LP-MPC frameworks can be used as an initial screening method to address the inaccuracy of project benefits evaluated under an assumption of perfect foresight.
- Moving away from the assumption of perfect foresight makes it important to represent economic losses for agricultural users in irrigation-dominated river basins. Linking yield to water allocations will reflect higher economic losses from less foresight, and a more realistic representation of project benefits.

There exists a wide range of model frameworks to address large-scale river basin hydroeconomic analysis. The starting point of this study was a simplistic approach in the form of a linear model formulation with an assumption of perfect foresight. This set-up is valuable in “where do we go from now” decision support. A subsequent critical analysis of the use of such model frameworks for estimating infrastructure benefits is addressed in the LP-MPC framework, which demonstrates the impact of assuming perfect foresight in hydroeconomic analyses of infrastructure projects that might lead to inaccurate conclusions in a cost-benefit context. The use of deterministic hydroeconomic optimization models is valuable for providing an overview of the links between the hydrological and economic systems. Their simplistic representation of future uncertainties, though, must be evaluated critically when applied in decision-making.

8 Limitations and future research

The hydroeconomic optimization model was formulated with a holistic approach, meaning that hydrological and economic responses were optimized in one integrated optimization model. This is in contrast to a modular approach, where sub-modules, representing the economic and hydrological system, are solved independently with varying degrees and means of interaction (Brouwer & Hofkes 2008). The holistic framework must be accommodated by a simpler representation of the two systems compared to what is possible in a modular approach. The economic responses to water allocations and scarcity in this PhD study were exogenous model inputs and did not reflect changes in willingness to pay in water user demand curves or head-dependent pumping costs as an economic incentive to switch to surface water use. A compromise between the holistic and modular approach could be to integrate a hydrological response curve into an economic model, or vice-versa, as discussed in a study by MacEwan et al. (2017). Such an approach would require a substantial amount of data to calibrate response curves. Paper II refined the representation of groundwater pumping costs by separating the shallow and deep plain area aquifer layers, each with its own water quality and groundwater pumping cost, but this still did not capture the effect of decreasing groundwater head in each separate layer. Paper III refined further the representation of the economic value of irrigation water demands. A risk of losing a full growing season yield would result in increased irrigation value. The link between drought-sensitive yield benefits and water allocations was driven by unforeseen water scarcity, and thus it was only effective in the dynamic LP-MPC framework.

The spatial resolution of the model was limited by data availability; however, data from well-described areas could be extrapolated to areas with insufficient data coverage by means of population density scaling. A further increase in the model's spatial resolution would pose the risk of faulty conclusions, if special industries, cropping patterns, etc. dominated specific regions not represented by the available datasets. As amentioned above, the groundwater compartment of the model was especially coarse, and the groundwater aquifer units were modelled as lumped storage under the assumption that pumping was distributed uniformly over the entire area. This does not take into account the fact that many big cities struggle with severe cones of depression (Feng et al. 2013; Chen et al. 2016). Distributed groundwater aquifer units have been integrated into river basin optimization models by means of surrogate models (e.g. Wu et al. 2015), response matrices (e.g. Yang et al. 2001) or the embedding method (e.g. Pulido-Velazquez et al. 2008). A numerical groundwater modelling study of the plain area aquifer could have provided the basis for a stricter constraining of the model's groundwater pumping, thereby corresponding to the actual hydrogeology.

The LP-MPC framework used in paper III, to evaluate the impact of assuming perfect foresight on model results, simulated operations with monthly time steps. In actual management, forecasting products vary in their ability to provide estimates of future water availability, and some are limited to timescales of days to weeks. In a study by Palmer et al. (2011), the MPC concept is used to optimize hydropower revenue on a single reservoir with weekly time steps. Depending on the foresight of forecasting products used for actual management, weekly time steps might provide a more realistic framework for reflecting actual levels of foresight in reservoir operation. On the other hand, it would increase model complexity in a large-scale river basin model, since aspects of routing delays (e.g. Schwanenberg, Breukelen, and Hummel 2011; Xu, van Overloop, and van de Giesen 2013), soil water balances, etc. would have to be considered.

The results of this study were presented to decision-makers at Haihe River basin water management institutions on several occasions. The response was often: "Why don't you look at a smaller spatial scale?" The present decision-making in Chinese water resources management is not done from a river basin perspective. In a complex river basin, like Haihe, integrated river basin management is essential to solve the water challenges of water scarcity and pollution. The groundwater overdraft in the plain area is linked to available surface water resources from the upstream sub-basins. This is seen, for example, in paper I from an increased allocation of upstream runoff to Beijing when plain area groundwater abstractions are constrained to a sustainable level. Likewise, the preference for groundwater and inter-basin transfers in the plain area can be related to water quality deterioration by upstream polluting activities. Both groundwater and inter-basin transfers had increasing shadow prices in paper II as a result of adding water quality to the model framework. Limited data access makes research on a large river basin scale challenging. Better access to data could have sharpened the analyses and conclusions of this study. Improving access to data comes through strengthening collaboration with authorities. Continuous development of hydroeconomic optimization models in an attempt to be more recognizable and supportive for decision-making will hopefully bridge the present gap between research and application.

In a dynamic world facing dramatic climate change, population growth and increased pressure on natural resources, water managers are part of a complex and multifaceted web. Political targets on greenhouse gas emissions, the ecological status of rivers and economic growth are set by many countries as well as in trans-boundary political arenas, and large-scale planning models will probably become increasingly important in guiding and informing decision-makers. Strengthening the links between the hydrological cycle and food security, energy production as well as ecology will be valuable in hydroeconomic optimization. For the case of China, many dams have approached or exceeded their designed lifespan (Liu et al. 2013), and a re-evaluation of their value will be necessary. With increasing awareness of renewable energy resources, such as biofuels, nuclear power and other options, water-energy-food links are important, and adding the ecological status of water bodies to the picture will be equally important, since several renewable energy resources also rely on water supplies of a certain quality. Within these challenges, the adaptive capabilities inherent in methods such as MPC might prove valuable. More attention given to narrowing down the most influential interactions between the hydrological cycle and the economic system could also help in strengthening hydroeconomic optimization modelling.

9 References

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10 Papers and appendices

I Martinsen, G., Liu, S., Mo, X., Bauer-Gottwein, P, 2019. Optimizing water resources allocation in the Haihe River basin under groundwater sustainability constraints. Journal of Geographical Sciences. In press.

II Martinsen, G., Liu, S., Mo, X., Bauer-Gottwein, P, 2019. Joint optimization of water allocation and water quality management in Haihe River basin. Science of the Total Environment. 654:72-84. DOI:10.1016/j.scitotenv.2018.11.036

III Martinsen, G., Liu, S., Mo, X., Davidsen, C., Payet-burin, R., Bauer-Gottwein, P., 2019. Assessing water resources projects with and without perfect foresight: A framework combining linear programming and model predictive control. Manuscript.

IV Appendix: Summary of meetings with water resources management institutions in Haihe River basin
V Appendix: Field report
VI Appendix: Haihe River basin water infrastructure connectivity
VII Appendix: Supporting documentation for agricultural water demand estimates

In this online version of the thesis, **paper I-III** are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from.

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IV

Summary of meetings with water resources management institutions in Haihe River basin

Grith Martinsen

Institutions

Haihe River Water Conservancy Commission (HRWCC)

Beifang Investigation, Design and Research (BIDR), Tianjin

Institute of Water Resources and Hydropower Research (IWHR)

1 Memo of meeting with Hai River Water Conservancy Commission

Date: 19th of November 2015

Location: HRWCC headquarter in Tianjin

Participants from CAS and DTU:

Claus Davidsen, Postdoc, DTU

Grith Martinsen, PhD student, DTU

Liu Suxia, Professor, CAS

Mo Xingguo, Professor, CAS

Lin Zhonghui, Assoc. Professor, CAS

Wang Yueling, Assoc. Professor, CAS

The meeting was held as an informal QA session, where HRWCC employees explained their main challenges and interests followed by questions and presentation of current research projects by the DTU and CAS guests. The following summarizes some of important insights from the meeting.

1.1 Key Challenges

- Hai River basin is facing the most serious basin water problems among the largest river basins in China.
- The two major water challenges recognized by HRWCC are within flood protection and hydrological modelling.

1.2 Areas and responsibilities of HRWCC's administration

- River Commissions are only responsible for the largest reservoirs with more than one downstream province. In Haihe River basin this limits the number of reservoirs to three: Panjiakou, Yuecheng and Daheiting Reservoir.
- They are only managing surface water and not groundwater.

- Water quality is a task of the Ministry of Environmental Protection.
- They primarily focus on flood protection and not much on allocation. Allocations are mainly the responsibility of provincial managers and allocations are based on permits.
- Water resources shared between provinces are allocated by river water commissions.
- The policies from HRWCC are not legally binding and therefore only a guidance. Local governments are responsible for the final decisions.

1.3 Models used by HRWCC

- They experience erroneous model results because they do not have data for water abstractions and cannot consider these in their hydrological models.
- HRWCC has previously used a model for water allocation which had very poor representation of groundwater pumping and did not include groundwater overdraft.
- They do not have anything similar to the multi-objective optimization model they use in Yangtze River Commission.
- None of their models consider GW-SW interactions.
- Their hydrological models are lumped and not distributed.

1.4 Water allocations

- Provinces annually apply for next year's water allocations to the Ministry of Water Resources.
- Provinces allocates the water resources among users.
- Most surface water is allocated to urban use. Farmers are dependent on groundwater. A ratio between water use sectors is enforced – if domestic demand increases, the agriculture is cut.
- There are government restrictions on groundwater pumping, but farmers do not comply with these.
- Every year a general allocation plan of SNWTP water is carried out. Provinces can apply for water and the MWR will decide who shall get how much water. The provincial government decides where to extract the water from the SNWTP. They diversion points along the canal are paid and operated by the province.

- Annual water use is reported to the provincial statistics. More detailed data will not be publicly available.

2 Memo of meeting with BIDR, Tianjin

Date: 7th of December 2016

Location: BIDR institute in Tianjin

Participants from CAS and DTU:

Peter Bauer-Gottwein, Professor, DTU

Grith Martinsen, PhD student, DTU

Liu Suxia, Professor, CAS

Mo Xingguo, Professor, CAS

A morning meeting with presentations and discussions were followed by an excursion to the Beidagang reservoir at the coast of Tianjin.

2.1 Main tasks of BIDR

BIDR is an offspring from Ministry of Water Resources (MWR). Its main tasks are:

- Water resources planning
- Design of hydraulic infrastructure
- International hydraulic infrastructure projects

2.2 Models used by BIDR

- Hydroeconomic models addressing the water-energy nexus of hydropower generation and water transfers.
- Hydroeconomic assessments of most beneficial water use based on input-output models have been applied.
- Multi-objective decision support with different scenarios/schemes based on simulation models.

2.3 Reservoir operation

- Daily maintenance and operation of reservoirs and water infrastructure are mainly the responsibility of local water authorities.
- Function and purpose of all reservoirs are specified “from above”.

- Local water authorities can ask for help and assistance from BDIR on reservoir release policies and operation.

2.4 Tianjin water supply

- Beidagang reservoir was intended for storing water from Yellow River transfers.
- Transfer from Yellow River is through old channel systems and underground pipe systems.
- From it was constructed in 1980 there has only been 12 events of Yellow River transfers to the reservoir.
- The water quality of Beidagang is not of suitable quality for urban water supply.
- Main water supply for Tianjin is the South-to-North-Water Transfer Project (SNWTP).
- Panjiakou reservoir is also feeding Tianjin water supply but is mostly too polluted to be used for drinking water.
- Luanhe River water (from Panjiakou reservoir) is used in periods of water shortage along with Haihe River water (very polluted) and desalinated water.

3 Memo of meeting with IWHR

Date: 11th of December 2017

Location: IWHR in Beijing

Participants from DTU:

Grith Martinsen, PhD student, DTU

IWHR is a research institution under the Ministry of Water Resources. The meeting was an informal Q&A session facilitated after a conference held at the IWHR by the Danish Embassy in Beijing.

3.1 Water allocations

- There are yearly allocation plans, as well as monthly allocation plans.
- 10-day plans also exists.
- Water suppliers apply for permits, which should clarify the use and demand of their water deliveries.
- It is necessary to apply for permits to set up a groundwater well – also for farmers.
- In Haihe River basin the supply side is determining the demand side
- There is a priority list of who to allocate water under scarcity
    1. Domestic
    2. Ecosystems
    3. Industrial
    4. Farming

3.2 Water resources management

- The Three Red Lines are the main incentives for water resources management.
- Cascade water pricing is used for demand control.
- IWHR mainly use computational general equilibrium models (CGEM) to estimate the economic value of water.
- There are official technical guidelines for water resources management. The applied methods and processes vary for different basins and cases.

V

Field report

Participants

Grith Martinsen, PhD student

Victor, driver and translator

17th to 21st of October 2016

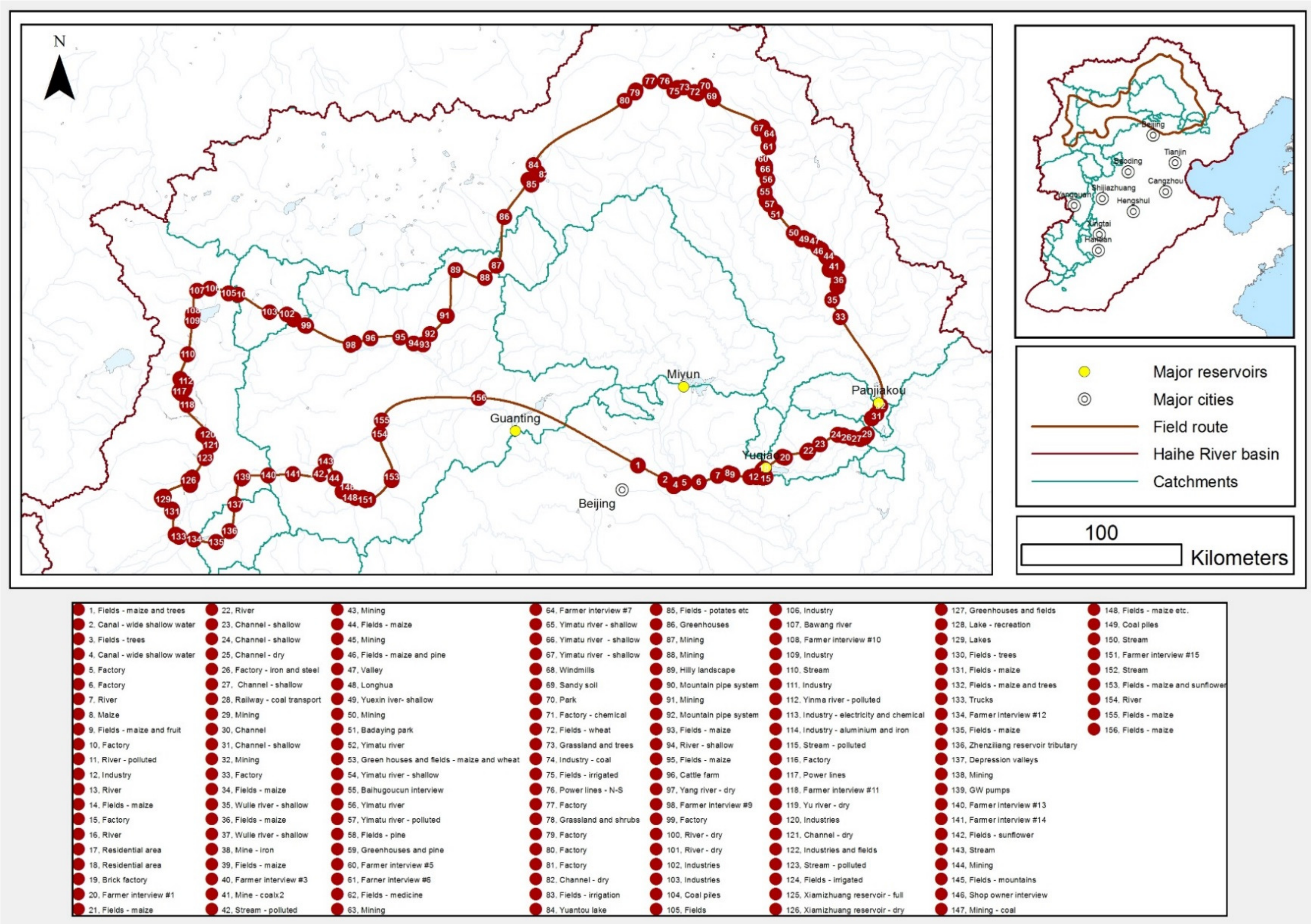


Figure 1. Fieldtrip itinerary of the northern Haihe River sub-basins. Red dots indicate field observations described in the legend

1 Field trip summary

The field trip was intended to support the conceptual understanding of the catchments upstream the three reservoirs Yuqiao (玉桥), Panjiakou (潘家口) and Guanting (官厅). The focus was to identify major water users and water distribution infrastructures in each of the reservoir catchments. The field trip itinerary departed from Beijing going to Yuqiao reservoir, through the upstream catchment of Yuqiao to Panjiakou reservoir. From here, the route continued up along Luanhe (滦河) River, upstream Panjiakou reservoir crossing into Inner Mongolia. The sub-basin upstream Guanting reservoir was entered from the city of Zhangjiakou (张家口). The trip continued northwest crossing through Datong, down to Zhenziliang reservoir (榛子两水库), to Cetian reservoir (侧田水库), passing through Guanting reservoir before returning to Beijing. As expected, an underground pipe system connected the two reservoirs Yuqiao and Panjiakou. The catchment upstream Panjiakou reservoir was dominated in the eastern part by mountainous terrain, small scale farming of mainly maize with little irrigation, mostly fed from groundwater, and mining activities. The western part of Luanhe river basin was characterized by hilly to flat terrain with shrubs and grassland. Large part of the catchment was dominated by farming of maize and potatoes, the latter fed by groundwater irrigation. The presence of heavy industries was also observed. The most western part of the basin hydrology was dominated by big natural lakes, not well connected to the eastern part of the basin. These lakes served ecosystem demands, some also used for water supply. Water levels of rivers and reservoirs was noticed to be generally shallow throughout the region, despite 2016 being a wet year with more precipitation than usual. The upstream catchments of Guanting reservoirs with the main river Yongding (永定河) generally showed signs of polluting activities judging from observed air- and water qualities. Heavy industries were observed in Zhangjiakou city and upstream of Datong (大同) city, with limited flow and poor quality of the water sources. Datong's water supply system was connected to the Yellow River (黄河) through an underground channel system. People generally described the area as having water shortage. Water shortage seemed most pronounced in the areas with many heavy industries. The areas west of Datong and in the mountains to the south were influenced by mining activities. Southern and westerns Guanting catchments was dominated by maize farming, rain fed but supplemented by groundwater irrigation. The need for irrigation seemed correlated with precipitation patterns as well as soil quality. Few farmers reported to be using reservoir water for irrigation. Only farmers convenient located downstream reservoir outlets and not being able to abstract groundwater would depend on surface water. Luanhe River basin did not seem to have any charges for water except the associated electricity cost of groundwater abstractions. The same applied to the catchment upstream Guanting, but here several farmers used reservoir water with a fixed costs. No farmers seemed to be cultivating winter crops except the ones found in green-houses. A market price of maize around 1.2-1.8 yuan/kg was reported all along the route of the field trip.

2 Field observations and interviews

The data collected in the field is presented in chronological order of the field trip itinerary. They are aggregated into sections describing a specific area or observation. Numbers specified in both interviews and figures refer back to the location of field observations shown in the

Figure 1 legend. Farmers report the area of their fields in the Chinese unit mu, which is 666 2/3 m^2. All interviews have been anonymized.

2.1 Plain area from Beijing to Yuqiao

The route from Beijing to Yuqiao was densely populated with villages and bigger cities. Both agriculture and industries were seen on the way. Fields observed along the way were mainly maize and orchards of various sorts.

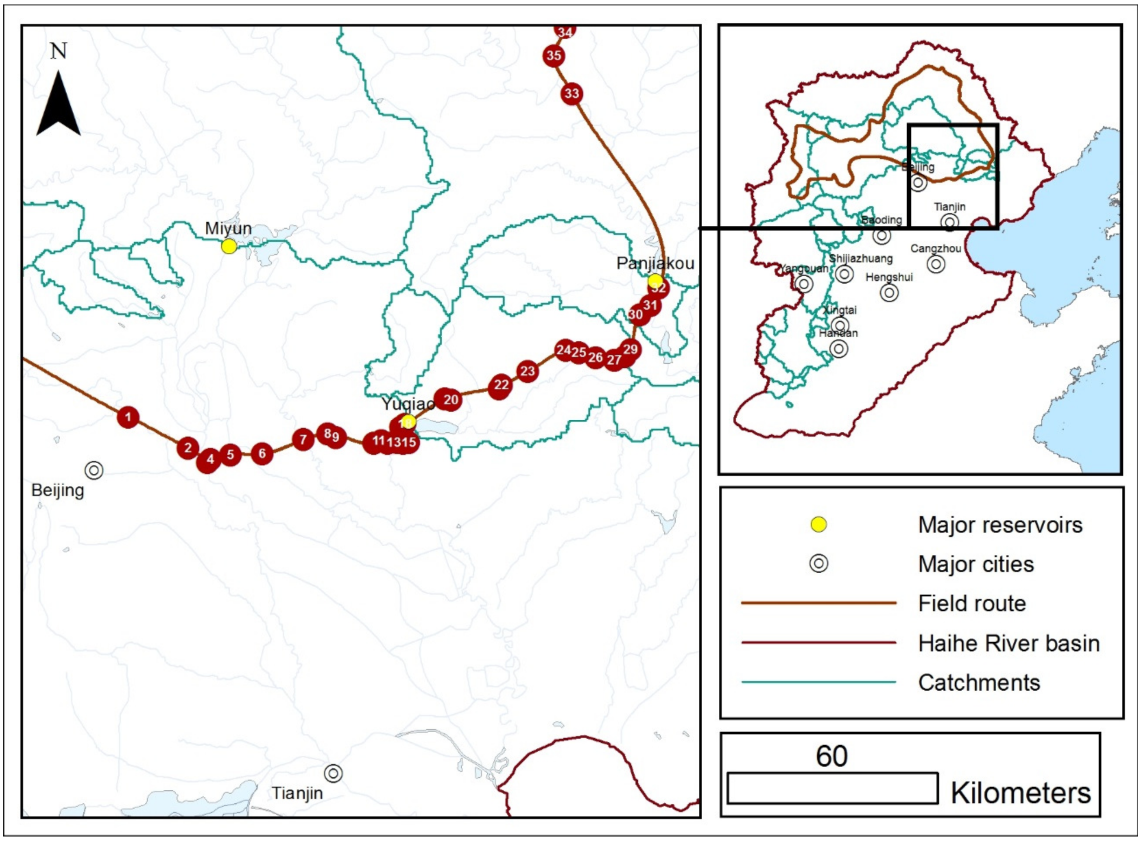


Figure 2. Field route from Beijing to the two reservoirs Yuqiao and Panjiakou.

Further east on the plain area the city Tangshan (唐山市) is known to be home for several of the bigger industries that have been reallocated from Beijing, as 首都刚切公司. It also has a big port for importing CNG to Northeast China.

2.1.1 Farmer interview no. 1

Location: 10 km upstream Yuqiao reservoir **(20)**

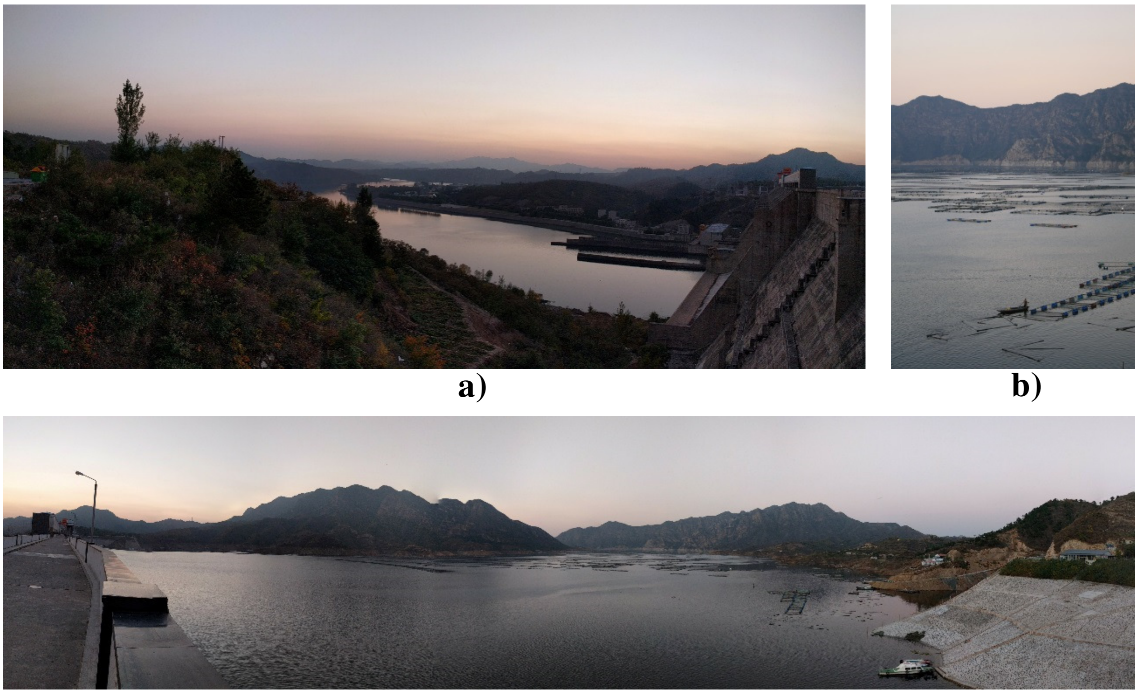
Crop: Blueberry

Field: 400 mu greenhouse

Water use: Irrigation using government installed GW well. 300 m deep well. Water level 10-20 m below terrain. Not possible to buy surface water because of government restriction. Only cost of irrigation is electricity costs for pumping. Use 40 m^3 irrigation water per month.

2.2 Yuqiao and Panjiakou reservoirs

Yuqiao reservoir is connected to the downstream plain area and Tianjin city. According to one of the engineers working in the reservoir administration bureau, the surface water (SW) of Yuqiao is no longer used for irrigation. Yuqiao reservoir is connected by an underground pipe to Panjiakou reservoir. Engineers at neither Yuqiao nor Panjiakou could confirm the capacity of this connection. Panjiakou reservoir, just upstream the Daheiting reservoir, supported hydropower production, fishing and aquaculture, see **Figure 3**. From next year, fishing will be banned from the reservoir to limit water pollution, according to the reservoir engineers.



a) b) c)

Figure 3. Panjiakou reservoir. A) downstream, b) fishing in the reservoir and c) upstream.

2.3 Eastern Luanhe River basin

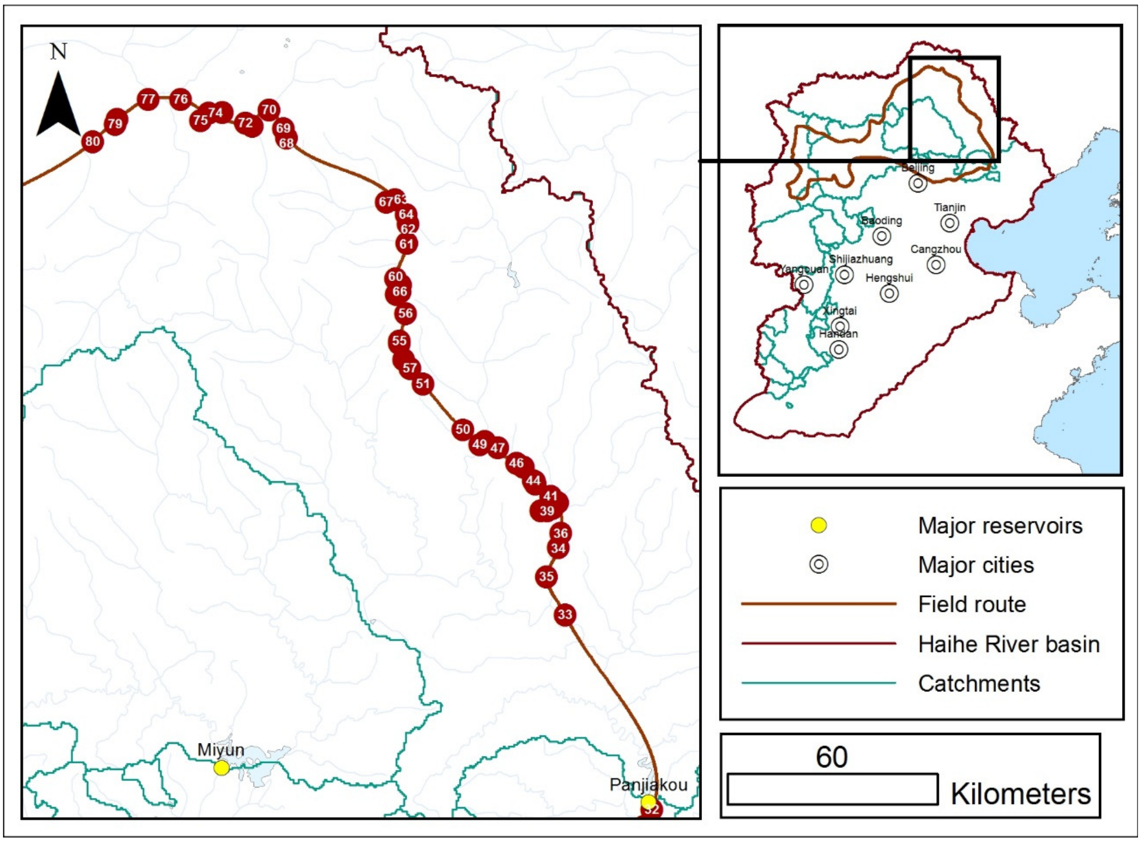


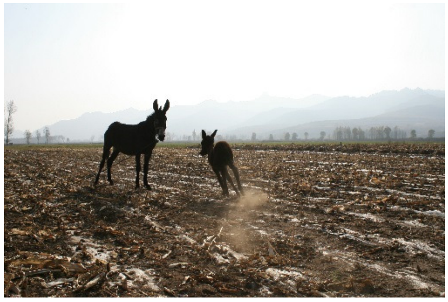
Figure 4. Field route up through the eastern Luanhe River basin.

Observation 33 to 67, see

Figure 1 and **Figure 4**, have been classified as "Eastern Luanhe River basin". Several farmer interviews were carried out to get an impression of the water use in this area. The mountainous terrain was dominated by small scale farming, supporting single families or serving as additional income for labour workers. The farmers generally reported that they did not pay for water except the pumping costs of groundwater (GW) wells. Generally farmers found it difficult to support their families solely from farming. Mining was also frequently observed along the route. Field observation no. 38 in **Figure 4** shows a visit to an iron mine, which can be seen in Figure 5.

Figure 5. Mine north of Chengde.

2.3.1 Farmer interview no. 2



Location: Village just upstream Chengde city **(34)**

Crop: Maize

Field: Few mu. The government has bought the field, as well as most of the other villagers' fields. The village is being demolished to clear the area for a reservoir for a big government run agricultural area.

Water use: Use nearby Wulie River water for irrigation. Supplement with private GW well if necessary. Each family has its own well. Only cost of water is the electricity for pumping.

2.3.2 Farmer interview no. 3

Location: Village north of Chengde **(40)**

Crop: Maize and wheat

Field: Each family has around 2 mu. Majority of fields are maize. No winter crops. Spare time farming of labour workers (mines etc.). Only sell if there is surplus yield.

Water use: Maize is rain fed. Wheat uses irrigation water diverted from nearby Wulie River. Irrigated 20 times per year by flooding the field with approximately 10 cm. No cost of irrigation.

2.3.3 Villager interview

Location: Village Baihugoucun (白虎沟村) **(55)**

Crop: Maize

Field: Lady working in a restaurant, with family owned maize field. They use maize for animals in the village and sells the surplus. Market price of maize is only 1.2 yuan/kg, so many farmers must go to Beijing for labour work. Some come back for autumn harvest. Nearby coalmine has been closed down.

Water use: GW pumps, if necessary.

2.3.4 Farmer interview no. 4

Location: Village Baihugoucun (白虎沟村) **(55)**

Crop: Maize

Field: Couple of mu

Water use: The villagers tipped in to get a public well. Most houses have piped water supply from the well. Villagers donate labour work for well maintenance. Otherwise the water is free of charge.

2.3.5 Farmer interview no. 5

Location: Village in eastern Luanhe River basin **(60)**

Crop: Chinese medicine huangqi (黄芪) and pine

Field: 20 mu for Chinese medicine. Pine trees are for wind protection, which are seen in many of the fields in the nearby area. Local government has 800 mu agricultural land. A plot of land will be given for free, if you wish to cultivate it.

Water use: Use GW for irrigation. Only cost is the 0.8 yuan/electricity degree.

2.3.6 Farmer interview no. 6

Location: Village Xiahuofangcun (下伙房村) **(61)**

Crop: Maize and Chinese medicine huangqi (黄芪)

Field: Couple of mu

Water use: Mainly rain fed. In dry years, the Chinese medicine will be irrigated using the village GW well. To avoid using the electricity, villagers tipped in for a generator to cover pumping costs. Only irrigation cost is generator fuel. GW well depth is 20-30 meters.

2.3.7 Farmer interview no. 7

Location: Fields in north-eastern Luanhe River basin **(64)**

Crop: Potatoes and cauliflower

Field: 800 mu. 500 mu potatoes, 300 mu cauliflower.

Water use: Uses three different irrigation systems: Drip-, sprinkler- and surface irrigation. GW is used for irrigation since the upstream surface water is very polluted. Only cost of irrigation is electricity for pumping. The electricity costs vary in this area: 0.3 yuan/electricity degree for agriculture and 0.8 yuan/electricity degree for industries. **Potatoes:** Yearly irrigation of 300 m^3 distributed over two months. 1000 yuan/month for electricity. **Cauliflower:** Yearly irrigation of 150 m^3.

2.4 Western Luanhe River basin

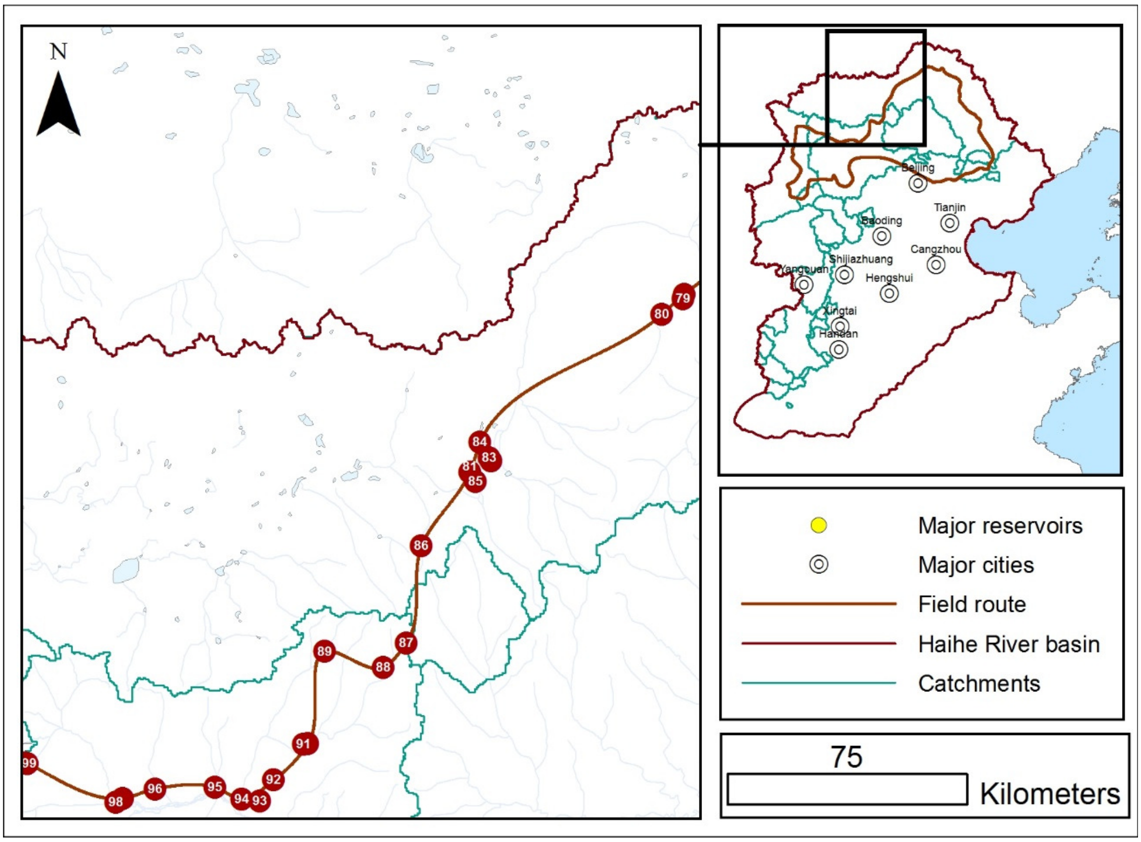


Figure 6. Field route through the western Luanhe River basin.

Observation 68 to 86, see

Figure 1, have been classified as "Western Luanhe River basin". The field trip did not proceed further west into the Luanhe River basin. This was mainly based on an assumption that the SW in this area was poorly connected to the downstream. Around the city Guyuan (沽源市) several lakes seemed endorheic or with very little connection to the downstream Luanhe catchment. This was confirmed by a visit to Guyuan's local water administration bureau. Lakes were either not connected or connected by very small natural streams.

The lakes in the area seemed to serve ecosystem demands, and wildlife. Especially birdlife was observed and the water quality seemed generally good. Near Guyuan the Shandianhe reservoir (闪电河水库) seemed the furthest upstream water source of Luanhe River. Downstream the reservoir there was a natural wetland with birdlife. See **Figure 7a**.

a)

b)

Figure 7. Surface water bodies near Guyuan city. A) Guyuan lake and b) Shandian reservoir.

Generally the environment of the western Luanhe River basin changed from vegetated mountainous to hilly grassland. It was a drier landscape and fields with sprinkler irrigation, such as the centre-pivot, was frequently observed, see **Figure 8**. Main crops were maize and potatoes, the latter often irrigated. GW seemed to be the source of irrigation. Huge factory grounds and heavy industries were observed, but not as densely as later on the field route.

Figure 8. Centre-pivot irrigation system near Guyuan.

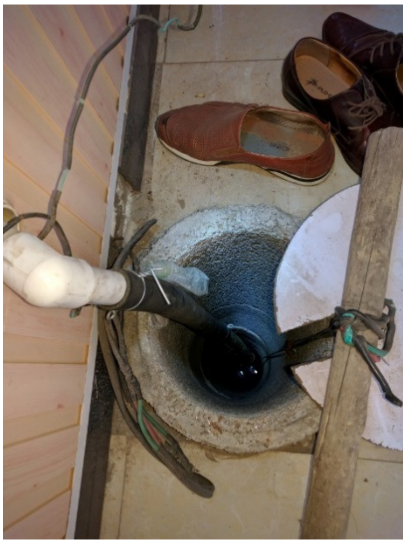
2.4.1 Hostel owner interview (no. 8)

Location: Village south of Guyuan near **(83)**

Crop: Maize and potatoes

Field: Couple of mu

Water use: Private well seen from picture is 30 m deep with a water level around 5 m below terrain. Maize is rain fed and potatoes are irrigated using a 100 m deep groundwater well. Only cost of water use is from pumping. The family tells that the groundwater level in the region was higher 30 years ago.



Proceeding toward Zhangjiakou, the terrain again got more mountainous, mining activities were observed, and many irrigation systems, as drip irrigation, were observed in the fields, see **Figure 9**.

Figure 9. Village with farming and a small-scale factory **(89)**.

2.5 Zhangjiakou to Datong

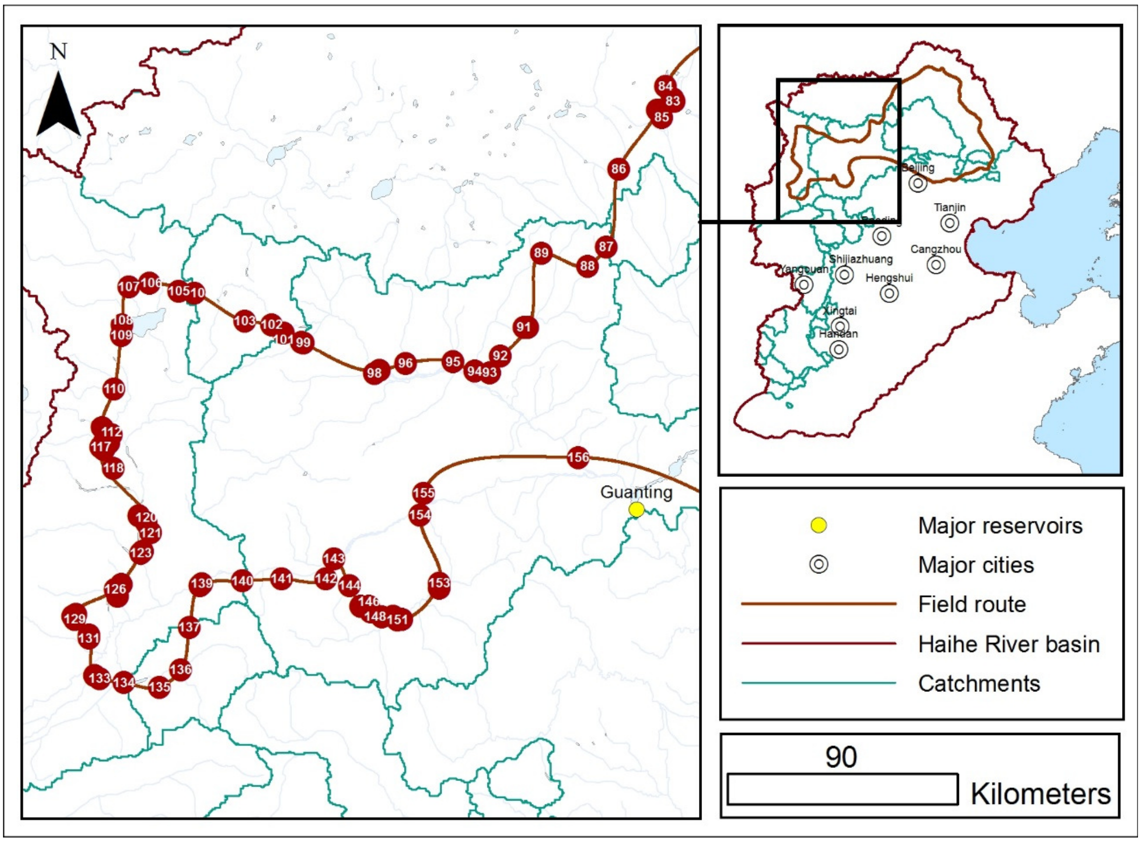


Figure 10. Field route through the sub-basin upstream Guanting reservoir.

Zhangjiakou is located on the southern rim of the mountains bordering Guanting and Panjiakou basins. The air quality was significantly worsened south of the mountain passage and the area around Zhangjiakou was dominated by heavy industries and mining (iron, steel, coal power plants). Proceeding towards west, the environment changed into a flatter terrain with farming dominated by maize fields and pump houses in the majority of the fields. Coal freights by railway and trucks were frequently seen in eastbound direction. Westward the landscape again turned hilly and often with natural "sand valley depressions".

2.5.1 Farmer interview no. 9

Location: Village upstream Huai'an (怀安) **(98)**

Crop: Maize

Field: 7 mu

Water use: No winter crops. Use GW for irrigation. Buys irrigation water from a nearby private well. 2.5 hrs to irrigate 1.5 mu. 1 mu irrigation typically costs 35 yuan in pumping costs. Upstream reservoir SW costs 70 yuan/mu. Usually only irrigates one time in March. She tells that crops of farmers located far from GW wells and reservoirs will dry out in drought years. In the area there is greenhouse owners with private wells for irrigation, otherwise the farmers in the area are similar to her. The dealer gave a too low price for their maize, why they are stocking it until he gives a higher price.

2.5.2 Farmer interview no. 10

Location: Fields south of Ulanqab (乌兰察布市) and Huangqihai (黄旗海) near **(108)**

Crop: Maize, cabbage and sugar beet

Field: 800 mu

Water use: Has private GW well for irrigation. Do not use SW of the Huangqihai lake. The water level used to be higher several years ago. Well depth for irrigation is 80 m. Water found 40-60 m below terrain. Only irrigates if rain is not sufficient. Typically 3 times per year for maize and 3 to 4 times per year for cabbage and beets. Cost for pumping is 0.3 yuan/electricity degree. 1 mu needs two hours pumping, which will cost approximately 12 yuan/hour.

Fengzhen city (丰镇市) north of Datong was dominated by many heavy industries as mineral, chemical and electrical. The air quality was very poor and downstream waterways polluted and shallow or dry. A general perception among the residents of the city was that the region was "water scarce". Residents also told that the electricity plant, see **Figure 11c**, got its water from the "third layer groundwater". Proceeding south towards Datong city, the upstream Yuhe River (御河) seemed dried out. Within Datong city the Wenyinghu reservoir (文瀛湖水库) contained water from the Yellow River, serving the city's water demands. It used to be a "natural" lake that dried up in the past years, until the Yellow River link was established.

a) b)

c)

Figure 11. Fengzhen city. A) Smog over the residential areas, b) shallow water levels of the river downstream of the city, and c) outskirt of industrial area with a huge electricity plant.

2.6 Datong to Guanting reservoir

West of the Datong region was dominated by a vast number of mines. In recent years many private coalmines have been closed down. Southward the area was flat, dominated by small-scale farming of maize. Maize fields were mostly rain fed but in dry years irrigated with groundwater.

2.6.1 Farmer interview no. 11

Location:	Village south of Datong **(118)**
Crop:	Maize, wheat and yam
Field:	1 mu

Water use: Has private 20 m deep GW well for irrigation and household (seen in the picture). Water is brownish. All crops are adapted to drought conditions, and rain is sufficient. In dry years, spring irrigation is crucial (April-May). Cost of water is the pumping cost of 0.5 yuan/electricity degree.

The big Xiamizhuang reservoir (下米庄水库) south of Datong was partly dried up and very eutrophic in the northern end, still having water in the southern end. The northern part of the reservoir can be seen in the background of the photo in farmer interview 12. Several big commercial farms were observed in this area, also having greenhouses.

2.6.2 Farmer interview no. 12

Location: North part of Xiamizhuang reservoir near **(126)**

Crop: Maize, cabbage, chili and eggplants

Field: Labour worker at farm with 40 mu

Water use: His boss irrigates with GW from private well. The Xiamizhuang reservoir water level has been declining for many years. This year it is higher than usual. Several commercial farms exists in this area.

2.6.3 Farmer interview no. 13

Location: Zhenziliang reservoir **(134)**

Crop: Maize, wheat, potatoes and sorghum

Field: Couple of mu.

Water use: Farmer in one of the 48 villages around Zhenziliang reservoir. The reservoir was

build for irrigation of the surrounding fields. "Powerful" local people sets reservoir SW prices and sell it to the villagers. Farmers supplement irrigation demand with groundwater pumping, as can also be seen from the many pump houses in the fields. GW level is around 17 m below terrain near the reservoir. His own well is 100 m deep and water is reached in 70-80 m depth. Westwards the GW quality is poor and "bitter" and the SW cannot reach there, so the crops die during droughts. There is no winter crops in the area. Wheat is not irrigated but the other three crops are 3 to 4 times per year in April, July/August and end August. Pumping of GW costs around 0.4 yuan/electricity degree. 1 mu needs 2 hrs of pumping for irrigation. Reservoir water is usually sold for 180 yuan/mu irrigation. The water level in Zhenziliang reservoir is low.

2.6.4 Cetian resident interview

Location: Cetian reservoir near **(140)**

Crop: No farming. Few greenhouses.

Field: 500 mu

Water use: Uses 38 m deep private GW well for greenhouse irrigation and domestic use. Tells that Cetian has a local board from the government deciding on water allocations. At least 20 m water level in the reservoir before sending water downstream to Guanting and Beijing. Cetian reservoir irrigation price is 20 yuan/hour.

Cetian reservoir was located in a region dominated by villages and small scale farming. Villages were poor, many of them almost depopulated and in a worn down state. No farmers reported to use SW for irrigation. Some places, with bad soil, there was a fair amount of irrigation, other places the crops were mainly rain fed. Most frequently observed crops were maize, fruit trees and sunflowers.

2.6.5 Farmer interview no. 14

Location: Village near Cetian reservoir **(140)**

Crop: Maize and wheat

Field: 520 mu

Water use: Does not use irrigation, only in drought years. During drought years, she generally irrigates 2 to 3 times per year during April/May and June/July. Cost of GW is the pumping cost, which is 22-24 yuan/hour pumping. GW well is 240 m deep, and water level is reached around 200 m below terrain (the terrain is very hilly and sandy). Cetian reservoir water is not used because there are no channels to their fields.

2.6.6 Farmer interview no. 15

Location: Village near Cetian reservoir **(141)**

Crop: Maize

Field: 20 mu

Water use: Irrigates 3 to 4 times every year from March to August. Soil is "bad", so irrigation is necessary. Village has a 50 m deep public GW well. For domestic water supply, the price is 2 yuan/month/person. For irrigation, they pay 90 yuan/hour pumping. 1.5 hours pumping will provide irrigation for 1 mu. Approximately 100 yuan per mu. Uses totally 2000 yuan for irrigation.

In the mountains on the way to Guanting reservoir there were several mines. Many of these had resulted in re-allocation of whole villages and pollution of local water resources.

2.6.7 Shop owner interview

Location: Village near Yuxian town (蔚县) **(146)**

Profession: Re-allocated from his land

Water use: Coalmines re-allocated him and the rest of his village. Mines use GW. Because of the mining activities, the GW in the area is polluted and the inhabitants buy water from near-by villages. Generally, there is no irrigation in the mountain area.

2.6.8 Farmer interview no. 16

Location: Fields near Yuxian town (蔚县) **(151)**

Crop: Maize and sunflower

Field: 6-7 mu

Water use: Shifted from cultivating wheat to maize and

sunflower, because these crops do not require irrigation. The nearby Huliu (壶流) reservoir is only used for irrigating wheat fields in the area.

VI

Haihe River basin water infrastructure connectivity

Grith Martinsen

1 Hai River basin water infrastructure connectivity

The representation of the water infrastructure connectivity in Haihe River basin model was gathered from several sources. Official maps and descriptions of each sub-basin from the Ministry of Water Resources and Haihe River Water Conservancy Commission was supplemented with details from the Chinese search engine Baidu as well as Google Earth and field trip observations. **Table 1** gives an overview of the supporting documentation for model water infrastructure connectivity.

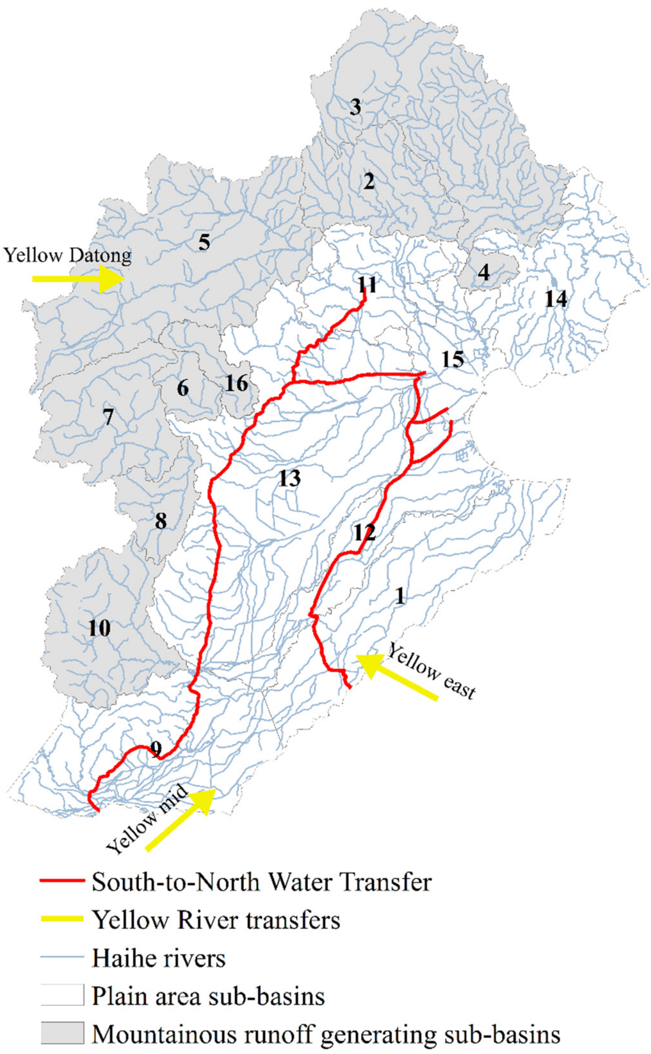


Figure 1. Sub-basins and inter-basin transfers of Haihe River basin.

Table 1. Connectivity of the surface water sources and sub-basins in Haihe River basin.

Sub-basin		Surface water source	Reference
1	**Tumahe**	Yellow east	(Chen et al. 2004)
		SNWTP east	(NSBD 2001a)
2	**Miyun**	Miyun	
3	**Panjiakou**	Panjiakou	
4	**Yuqiao**	Yuqiao	
		Panjiakou	(Baike 2018b), Appendix V
5	**Guanting**	Guanting	
		Yellow Datong	(Baike 2017b; Wikipedia 2017) Appendix V
6	**Wangkuai**	Wangkuai	
7	**Gangnan**	Gangnan	
8	**Huangbizhuang**	Huangbizhuang	
9	**Zhangweihe**	Yellow mid	(Baike 2016)
		SNWTP mid	(NSBD 2001b)
10	**Yuecheng**	Yuecheng	
11	**Beijing**	SNWTP mid	(NSBD 2001b)
		Huangbizhuang	(China Daily 2004)
		Gangnan	(China Daily 2004)
		Wangkuai	
		Xidayang	(China Daily 2004; Baike 2018d)
		Guanting	(Haihe River Water Conservancy Commission 2003c)
		Miyun	(Haihe River Water Conservancy Commission 2003b)
12	**Heilonggangyundong**	Yellow east	(Baike 2018a; Chen et al. 2004)
		SNWTP east	(NSBD 2001a)
		Gangnan	(Baike 2017c; Ministry of Water Resources 2011)
		Huangbizhuang	(Baike 2017c; Ministry of Water Resources 2011)
		Yuecheng	(Haihe River Water Conservancy Commission 2003d)
13	**Plain mid**	SNWTP mid	(NSBD 2001b)
		Yuecheng	(Davidsen 2015)
		Huangbizhuang	(Ministry of Water Resources 2011)
		Gangnan	(Ministry of Water Resources 2011)
		Wangkuai	(Haihe River Water Conservancy Commission 2003a)
		Xidayang	(Haihe River Water Conservancy Commission 2003a)

14	**Plain north**	Panjiakou	
15	**Tianjin**	Yellow east	(Chen et al. 2004; Baike 2016), Appendix IV
		SNWTP east	(NSBD 2001a)
		SNWTP mid	(NSBD 2001b)
		Yuecheng	(Haihe River Water Conservancy Commission 2003d)
		Huangbizhuang	(Ministry of Water Resources 2011)
		Gangnan	Ministry of Water Resources 2011)
		Wangkuai	(Haihe River Water Conservancy Commission 2003a)
		Xidayang	(Haihe River Water Conservancy Commission 2003a)
		Guanting	(Haihe River Water Conservancy Commission 2003c; Baike 2017a)
		Miyun	(Haihe River Water Conservancy Commission 2003b; Baike 2018c)
		Yuqiao	(Haihe River Water Conservancy Commission 2003b)
		Panjiakou	(Haihe River Water Conservancy Commission 2003b; Baike 2018b)
16	**Xidayang**	Xidayang	

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VII

Supporting documentation for agricultural water demand estimates

Grith Martinsen

The estimates of cultivated areas and water demands are motivated by a lack of high spatial resolution data of irrigation and cropping patterns in the mountainous regions of the model. **Figure 1** illustrates the process from inputs to intermediate results to the final water demand estimates.

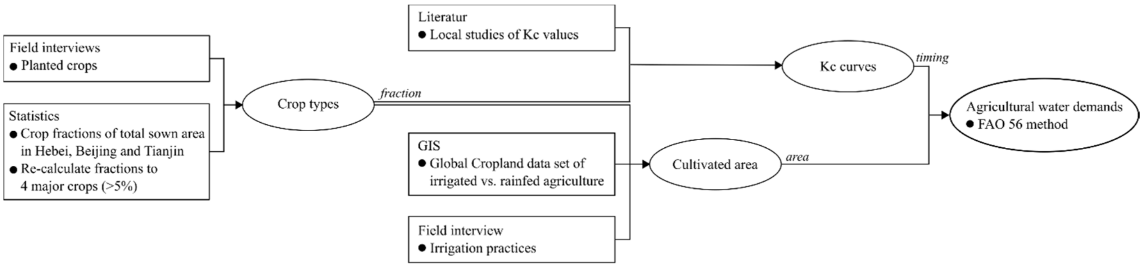


Figure 1. Input data (boxes) and outputs (circles) for estimating agricultural water demands.

1 Agricultural water demands

The agricultural water demands were determined for wheat, maize and orchards based on the method proposed by Allen et al. (1998) in the FAO 56 Irrigation and Drainage Paper. The crop water demand (Dem_c) is determined based on the cultivated area (A_c), a crop- and season specific crop coefficient (K_c) as well as the reference evapotranspiration (ET_0) and precipitation (P):

$$Dem_c = A_c \cdot (ET_0 \cdot K_c - P)$$

Vegetables consisted of a heterogeneous group of crops, with an insufficient data set to map cultivated areas and determine water demands for each group. Vegetables were therefore lumped into one group of agricultural water users. Averages of field interviews of irrigation water demands for farmers growing vegetables were used to estimate this group of crop's water demand, shown in **Figure 2**, including standard deviation error bars.

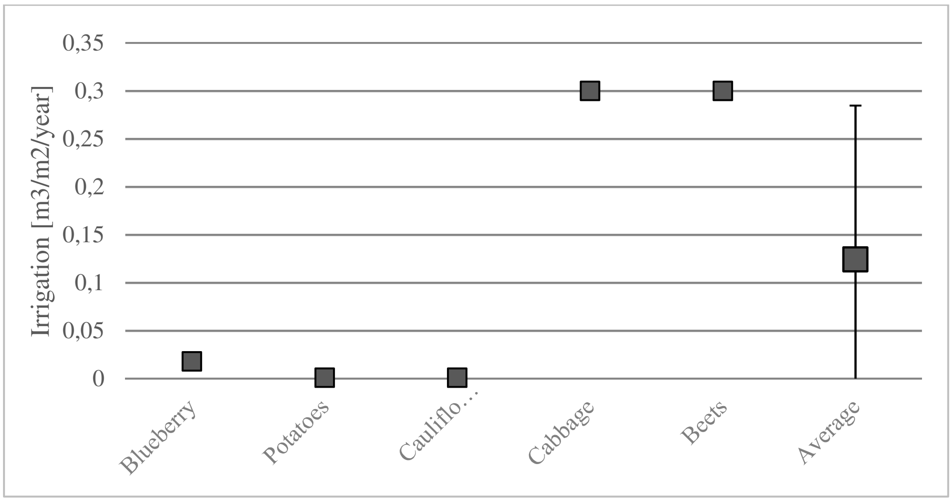


Figure 2. Reported irrigation demands for groups of vegetables.

1.1 Crop fractions

The fraction of sown crops on the cultivated areas were based on available statistical information from the Statistical Yearbook of China (National Bureau of Statistics of China 2015). The percentage of crop types in Hebei province can be seen in **Figure 3**. Only the four biggest groups were represented in the model, i.e. wheat, maize, vegetables and orchards.

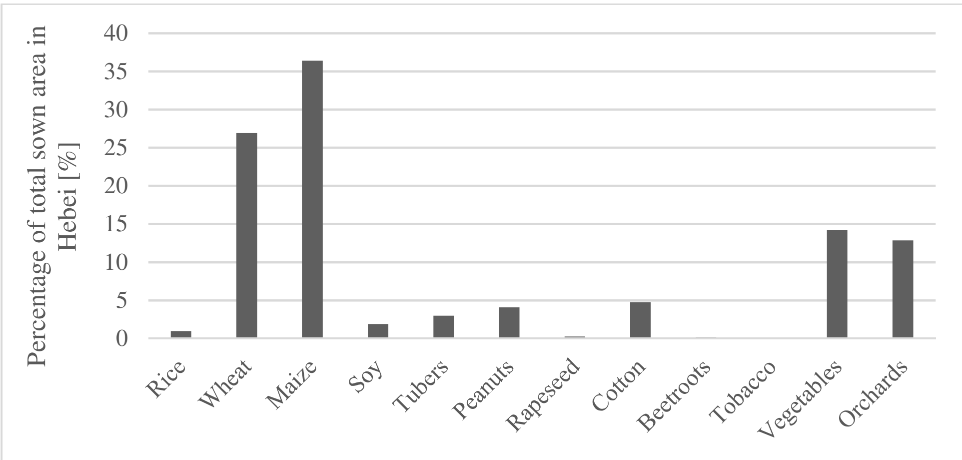


Figure 3. Percentage of crop types of the total sown area in Hebei province.

Based on field interviews (Appendix V) it was reported that the maize fields were primarily rain fed and not irrigated, in contrast to the other crops. The sown areas of irrigated versus non-irrigated farmland was categorized according to **Table 1**. The cropping practices were distinguished between the plain area, with an intensive cultivation of the double cropping winter wheat and summer maize system, compared to the mountainous regions, that did not have double cropping systems, also confirmed by farmer interviews (Appendix V).

Table 1. Categorization of cropping and irrigation practices in the plain and mountainous sub-basins.

	Plain	Mountainous
Irrigated	Double cropping (wheat+maize), vegetables, orchards	Spring wheat, vegetables, orchards
Rain fed	Maize	Maize

The fraction of sown areas for the four major crops were re-calculated from the reported fractions in the Statistical Yearbook of China, assuming these four major crops constituted the whole sown area. The resulting fractions can be seen in **Table 2**.

Table 2. Re-calculated crop fractions of total sown area.

			CROP FRACTION OF SOWN AREA			
	Province	**Total sown area [1000 hectares]**	**Wheat**	**Maize**	**Vegetables**	**Orchards**
	Assuming total area equal to wheat, maize, vegetables and orchards					
Plain area	Beijing	227.2	0.12	0.32	0.28	0.28
	Tianjin	436.6	0.34	0.28	0.28	0.10
	Hebei	7870.1	0.42	0.15	0.22	0.20
	Assuming total area equal to wheat, vegetables and orchards					
Mountainous areas	Hebei	4699.2	0.50		0.26	0.24

1.2 Crop area

Since maize was reported to be primarily rain fed by the farmers in the mountainous regions (Appendix V), it was assumed to make up the whole area of rain fed agriculture. In the plain areas, the rain fed area was assumed to be maize as well, but maize was also calculated as a fraction of the total irrigated sown area. The sown areas in Haihe River basin consisted of irrigated (A_{irr}), rain fed (A_{rain}) and mixed (A_{mix}) agriculture. These areas were determined from the remote sensing product Global Agriculture Monitoring (GLAM) (Pittman et al. 2010) masked in ArcGIS by the higher spatial resolution Global Cropland product (Thenkabail et al. 2012) distinguishing agricultural and non-agricultural land use and can be seen in **Figure 4**.

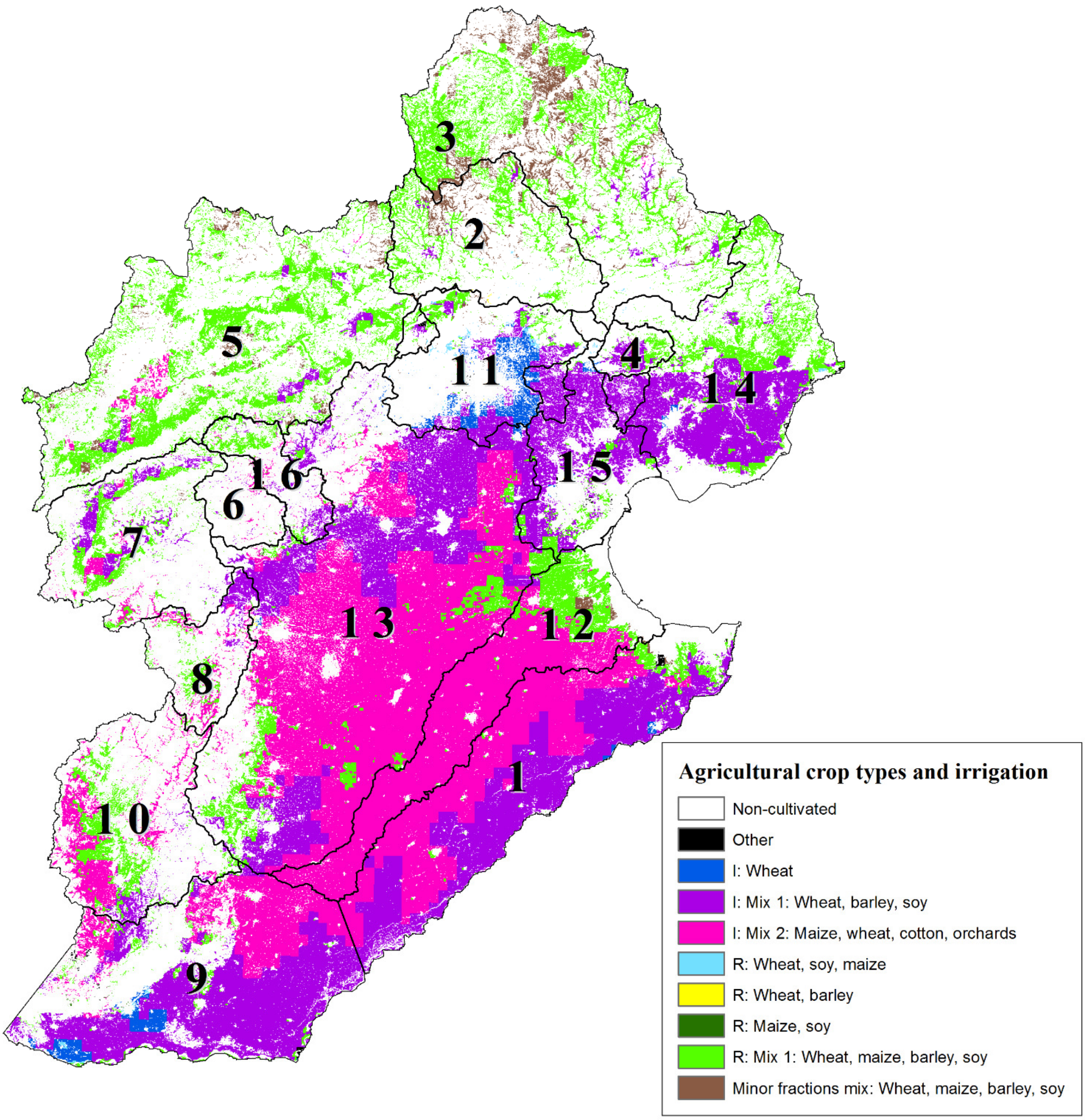


Figure 4. Crop specific cultivated areas of haihe River basin sub-basins. Based on the GLAM (Pittman et al. 2010) and Global Cropland (Thenkabail et al. 2012) data sets.

The sown area of maize and the other three major crop types were calculated for sub basins (i) in the plain and mountainous (mnt) regions respectively, in the following way:

$$A_{maize,plain_i} = A_{rain,plain_i} + (A_{irr,plain_i} + A_{mix,plain_i}) \cdot f_{maize,plain}$$

$$A_{crop,plain_i} = (A_{irr,plain_i} + A_{mix,plain_i}) \cdot f_{crop,plain}$$

$$A_{maize,mnt_i} = A_{rain,mnt_i}$$

$$A_{crop,mnt_i} = (A_{irr,mnt_i} + A_{mix,mnt_i}) \cdot f_{crop,mnt}$$

Table 3 shows the resulting areas for each crop type in all 16 model sub-basins.

Table 3. Cropped areas in each model sub-basin.

Crop area [km^2]/ Sub-basin ID	Double crop system	Maize	Spring wheat	Orchards	Vegetables
1	10702	4725	-	5112	5653
2	-	2332	446	213	236
3	-	7698	1472	703	777
4	222	391	-	106	117
5	-	9848	965	461	510
6	-	34	62	30	33
7	-	1888	864	413	457
8	-	506	568	271	300
9	8602	3889	0	4109	4544
10	-	2114	1593	761	842
11	336	1602	-	818	818
12	5785	4908	-	2763	3056
13	19754	10638	-	9435	10435
14	3328	5069	-	1589	1758
15	1725	2246	-	514	1404
16	-	584	245	117	130

1.3 Crop coefficients for water demands

Crop coefficient curves for the crops modeled by the FAO 56 method can be seen in **Figure 5**.

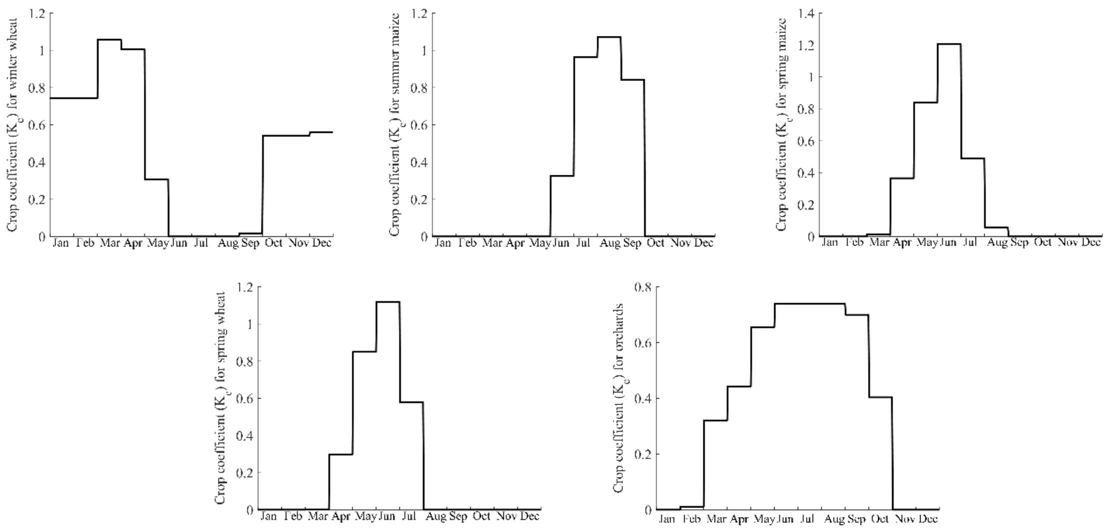
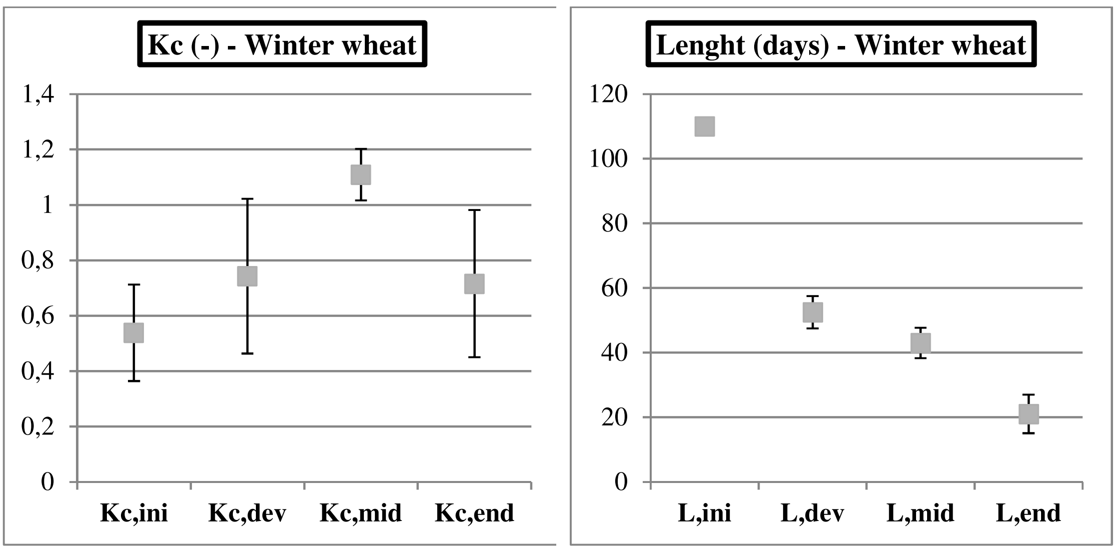


Figure 5. Crop coefficient curves of winter wheat, summer maize, spring maize, spring wheat and orchards.

Figure 6 shows the mean values and standard deviation of selected local literature values of crop coefficient (K_c) for each crop state as well as the length of each state (L) for the double cropping system of winter wheat and summer maize as well as spring maize (single cropping). The Kc and L parameters for spring wheat and orchards were selected from local studies by WANG et al. (2006) and Sun et al. (2012), respectively.



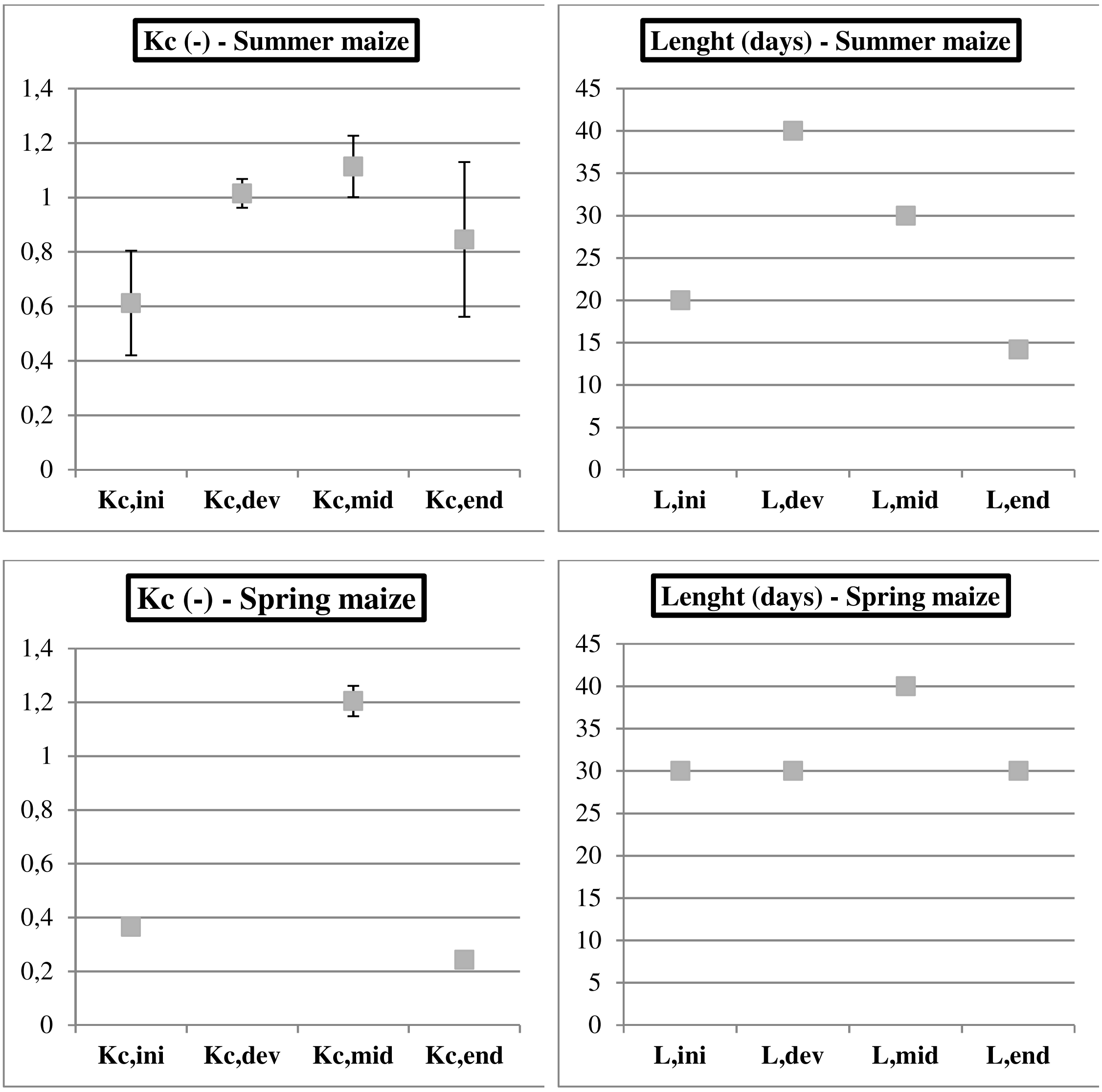


Figure 6. K_c values and lengths of crop stages from literature.

Winter wheat K_c and L values are based on studies by Liu and Luo (2010), Sun et al. (2012), Zhang et al. (2011), Cai (2009) and Gao et al. (2009). Summer maize K_c and L values are based on studies by Liu and Luo (2010), Sun et al. (2012) and Cai (2009). Spring maize K_c and L values are based on the study by Zhang et al. (2011).

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The Department of Environmental Engineering (DTU Environment) conducts science based engineering research within five sections: Air, Land & Water Resources, Urban Water Systems, Water Technology, Residual Resource Engineering, Environmental Fate and Effect of Chemicals. The department dates back to 1865, when August Colding gave the first lecture on sanitary engineering

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