Ethical water allocations based on water footprint caps: a case study for the Yellow River Basin

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Preface

Hereby I present the master thesis on the topic of the ethical distribution of water within the Yellow River Basin. This report has been the final part of the Master thesis performed for the University of Twente as part of the track Integrated Water Management. The project has been performed internally at the University of Twente.

The creating of this master Thesis has been a continuous reiterating process. The ideas presented in the first iterative concept did not suffice for the current direction of the model and ideas and directions were changed constantly. The process was quite challenging in this regard and has been unlike any other project in the master. It would not have been possible without the supervision I received in the process. In particular I would like to thank Han for the daily supervision and ideas on how to complete the process and how step by step the model would start to take shape. Furthermore I would like to thank Maarten and Rick for their general perspective they gave during meetings to keep things within certain bounds and not to delve to much into the details.

Conlcuding this master thesis the time as a student in Enschede and Hengelo (later on) comes to an end. Starting in 2016 with a bachelor Civiele Techniek the journey has been quite long but all in all quite enjoyable. Besides studying quite some time was spent with the student association RSK Enschede which i have been very thankful to have been a part of. But above all I would like to thank God for his continuing support during my journey as a student.

Hopefully with this report I have shed some light on the process of incorporating ethics in water allocation and showing that it is not as straightforward as it would seem.

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Abstract

Water scarcity in basins is a recurring problem over the world. Determining the amount of water which can be used in a sustainable manner is paramount to guarantee future use of the resource. The amount of water which can be used in a basin is dependent on the availability of the water. The creation of caps for water usage in a basin prescribes a maximum amount of water that can be used in space and time, and can help allocate the water to places where more water is needed using the distribute effects of reservoirs. The strategy of re-distributing water over parts of the sub-catchments requires certain allocation principles. In previous studies the redistribution was based on historical demand, using what is available and aspects such as Gross Domestic Product and population density. However the choice of perspectives is limited and the question of using a multitude of perspectives and determining the consequences based on their implementation has not been taken into account. Furthermore, the operation of reservoirs and their ability for redistribution has been based on historical usage, and has not been adapted to become an integral part of the distribution component. This study aims to determine the underlying ethical philosophies for each allocation scenario, implement and evaluate them in a case study of the Yellow river basin. This case study simulates the period of the 2010 - 2014 and evaluates six allocation strategies and their underlying philosophies. These allocation scenarios regard area, population, Gross Domestic Product, inverse Gross Domestic Product, industrial water demand and irrigation water demand. Our results confirm previous findings of the distributive effects of reservoirs and allocation strategies, increasing overall water availability and probably reducing water scarcity. We find that each sub-catchment has a preferred allocation scenarios for implementation. Furthermore we find that sub-catchments with limited water availability, which often occurs in tributaries, significantly reduces the potential fairness in the basin as a whole independent on the ethical indicator selected. The results of this study creates an understanding of the implementation and impact of ethical philosophies for each allocation strategy and stresses the difficulty in achieving fairness in water allocation.

Keywords:
Water Management, Ethics, Allocation Strategies, Fairness

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Glossary

Notation	Description	Page List
ABW	Allocated Blue Water	14
Allocation strategy	Strategy which is used to distribute the water over a certain domain or area according to a specific set of criteria	iii, iv, 4, 7–10, 12–15, 17, 20–23, 26–29, 31–34, 40, 43
BWA	Blue Water Availability	iv, 14, 15, 21, 26
BWF-Caps	Blue Water Footprint Caps	10, 14, 15, 26
BWS	Blue Water Scarcity	14
EFR	Environmental Flow Requirement	8, 12–14, 34
GDP	Gross Domestic Product	6, 8–10, 12, 13, 15, 26
HDI	Human Development Index	6, 9, 12
IND	Industrial Water Demand	29
IRR	Irrigation water Demand	29
PRE	Presumptive Standard Approach	12
VMF	Variable Monthly Flow	12
YRB	Yellow River Basin	10–12, 14, 15, 32

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1 Introduction

Water scarcity is the lack of water availability, roughly 1.8 to 2.9 billion people experience water scarcity for 4 to 6 months a year Mekonnnen and Hoekstra [2016]. Water scarcity can consist of two components scarcity in the water available in the surface-water and groundwater flow (blue water) and water scarcity in soil moisture and subsequent evapotranspiration (green water). Blue water scarcity will likely increase due to increasing population and an increase in welfare across the globe WWAP [2019]. The impact of the of Blue Water scarcity is divided into four levels Hoekstra et al. [2012]. Each level with a greater increase of blue water consumption compared to the natural runoff with a severe water scarcity when the blue water consumption is larger than 40 % of the natural runoff. Severe water scarcity results in severe violations for flow reserved for conservation and preservation of the natural ecosystem within the specific river basin.

To determine the amount of water which can safely be used, without damaging ecosystems and harming posterior use, as a result of water scarcity, agreements are created between the stakeholders within a river basin. The agreements for water usage use a process which is water allocation. Water allocation is a process of distribution, designating a certain amount of water to an area which then can be used in the particular area. The process of designating water to certain users, or reserve water for users, is a practice with a long history of conflict and agreements Wolf [1999]. The main drivers for water conflict and subsequent agreements are who is allowed to use the water and in which quantities Wolf [1999]. To formalise the amounts of water usage agreements are signed which determines when and how water can be used, these agreements of allocation can help solve conflicts between riparian states.

Water allocation strategies
Water allocation strategies can help create water distributions between states. These distribution agreements state a certain amount of water which can be quantitative or as a percentage of the total amount of water within the basin which must reach a certain point or area. The creation of these water cooperation agreements is often based in water allocation, determining the amount of water which can be used by each state. The distribution of water between riparian states is often based in water need Wolf [1999], as in how much water is needed to fulfill their nation specific water need. In most cases this water need will always turn into a trade-off, for not all demands for water use can be met, due to water availability in time and space. However, allocation strategies can be used to lessen the water scarcity in certain areas by reserving water for areas / sub-catchments where the scarcity is most severe.

To determine the amount of water which can safely be extracted / used from the river without harming the environment or endangering future usage is the Blue Water Availability. The BWA is determined by taking the natural runoff of the river, the normal unimpeded and used flow of a river basin, and subtracting the water needed to satisfy the environmental component. The environmental component, the Environmental Flow Requirement, is a metric for how much water of the river is reserved to sustain the ecosystem within the river Richter et al. [2012]. Using the BWA a Cap can be determined for how much water can safely be used, the Blue Water Footprint Cap, describing the amount of consumptive water for all activities within the basin.

BWF-Caps
The BWF caps are used to determine what water can safely be used, without harming posterior use. These caps are often based on the available water within the basin Albers et al. [2021], and certain characteristics of the sub-catchments within the basin. The distribution of water over the sub-catchments in tandem with the characteristics is the allocation strategy for distribution. Metrics for distribution which can be made into an allocation strategy are population, total area within the basin van der Zaag et al. [2002]. These metrics are also used as basis in international agreements to determine distributions Wolf [1999]. Using specifics such as population allows for larger BWF-caps in locations with a larger population where locations with a lower population sacrifice water availability. This can specifically be helpful in basins where the water supply is mostly in the upstream parts of the basin and the consumption downstream. Other metrics for creating distributions can be Gross Domestic Product or efficient water use Cai et al. [2011]. By allocating certain amounts of water to a specific sub-catchment water is reserved for use in the sub-catchment.

Incorporating ethics in water allocation agreements results in more equitable allocations Lautze and Giordano [2006]. Combined with the statement of more equitable allocations resulting in a more equitable society Peña [2011] makes for a case for incorporating ethics in water allocation. The consideration of ethics in previous studies has been missing, although focusing on fairness in distribution van der Zaag et al. [2002] Cai et al. [2011] Albers et al. [2021] to some extent, the underlying ethical philosophy has not been explained. The focus on social equity by focusing on the underprivileged Babel et al. [2005] seems to be step towards equity a further explanation on how and why this focus is implemented is bare-bones. This in stark contrast to climate related literature, which continually stresses equity as an underlying operation principle in creation of allocation strategies Metz [2000] Méjean et al. [2015].

However, the amount of water which can be used is based on the BWA of that specific area / sub-catchment and on that specific moment. Due to the seasonality of rivers the amount of Available Blue Water is highly fluctuating based on the time of the year and often will not align with the demand for water Hoekstra et al. [2012]. Reservoirs increase water availability by redistributing the water which is available over the year. Increasing the options in water distribution using the allocation strategies. The inclusion of reservoir operation in allocation strategies based on population and demand has not been conducted Albers et al. [2021]. Even-though the impact of reservoirs on water availability and mitigate capacity for water scarcity is large Zhuo et al. [2019].

Reservoirs

The impact of reservoirs on water distributions is significant, over half the large river systems are regulated by humans and reservoirs hold back one seventh of the global natural runoff Zhuo et al. [2019]. These reservoirs can have several purposes, while reservoirs located in river basins in which water is abundant are mainly for electricity generation. Reservoirs in water scarce basins redistribute the water from wet periods to dry periods to ensure water availability Mekonnnen and Hoekstra [2012]. Ensuring water availability comes at a cost, reservoirs themselves are water consumers due to the water cost in construction and operation due to evaporation Hogeboom et al. [2018]. Reservoirs reduce water scarcity in dry periods but consequently increase water scarcity in wet periods in combination with the evaporation from reservoirs results in an overall lower water availability compared to a situation without reservoirs Zhuo et al. [2019]. The creation of BWF-caps helps create an understanding of this consumptive behaviour and is necessary to understand the runoff and distribution Zhuo et al. [2019].

The Blue Water consumption of reservoirs is mainly dependent on the location, in wet areas the consumptive amount is a small factor in the hydrograph Biemans et al. [2011], whereas in dry areas this component can become much larger. The location has a large impact on its water use, as well as the purpose it serves such as hydropower or irrigation or general water availability. Previous studies have modelled the amount of water which can be designated using reservoir operations Haddeland et al. [2006]Hanasaki et al. [2006]Biemans et al. [2011]. These studies have all focused on a monthly target for release based on historical usage of the water. The methods developed in their models describe a target for release which should be met at the end of the year to have the preferred amount of water in the reservoir. And each selects a different amount of water reserved to satisfy the EFR or a derivative of the EFR. This creates a different distribution in each case, Hanasaki et al. [2006] adepts the reservoir operation based on the demand upstream and downstream of the reservoir. Biemans et al. [2011] further elaborates on this by only considering irrigation water need, creating an allocation strategy based on agricultural usage and demand.

Ethics and use

The incorporation of ethics is important, although the extent to which ethics should be incorporated is unknown. Due to the limitations of water distribution in river systems, limiting to geography and water flows from upstream to downstream, excluding water transfer projects. This may result in a distribution which can be considered ethical but uses only a small amount of available water in the system. Although this may be considered ethical in principle, not using the water which is available for use can be considered strange. To what extent does an ethical distribution overrule actual water usage, or does total water use take precedent.

This study will mainly be a continuation of the work of Albers et al. [2021] which created several allocation strategies for the Yellow River Basin. Adapting on their work to create an ethical understanding of the choices made in the model will help create distributions grounded in ethical principles, which should be considered fair. Due to the historical usage of reservoirs in the methods proposed by Albers et al. [2021] adaptations have to be made to the model to account for these operations. Furthermore the top down approach of allocation implemented in the model, will have to be adapted to accommodate for certain allocation strategies, to allow for greater ranges of freedom in allocation.

Research Questions

Incorporation of reservoir operation in the water allocation strategies, calls for a combination of strategies. To achieve this goal a model will be created which can reflect the ethical principles in water allocation strategies. The goal of this model is to be able to reflect on the implementation of the ethical principles.

- How can the ethical principles be translated into allocation strategies?
- What are the differences between the resulting allocated water volumes in time?
- What are the differences between the resulting allocated water volumes in space?
- How well can the model implement fairness principles?
- What is the impact of the allocation strategies on the reservoir management?
- To what extent do the blue water footprint caps increase fairness?

To be able to implement and answer the research questions the Yellow River Basin is proposed as a case study. The Yellow River Basin is an interesting case due to its size, geographical characteristics and importance to the Chinese economy. The YRB consist of a relatively wet parts where most of the precipitation originates and some dry parts where the major population centres are located. This creates an interesting case for distributions which will skew different for each allocation strategy. furthermore the basin has also been used by Albers et al. [2021] and this being a continuation of their work, allows for comparison and continuity in the research. Thus the same period of research will be used from 2010-2014 which contains a wet year and a relatively dry year Fleurbaey et al. [2014]. This is further compounded by the availability of spatial data of the river and tributaries for this period and area Zhuo et al. [2016] Albers et al. [2021]. The allocation strategy require data of the basin itself, water usage industrial and municipal and this is also available for this period Kummu et al. [2018] Zhou et al. [2020].

The Chapters will have the following layout, the first chapter is the introduction, the second chapter is the explanation of the Theory and the translation into allocation strategy. The third chapter is the method on how the model is created the assumptions in creation and how the model will be evaluated.

2 Theory

The creation of equity based allocation strategies is based on the claim that the principle of Equity is key to water allocation Wolf [1999]. This is also in line with the inclusion of Equity in climate change literature Metz [2000]. Although both share some overlap the focus is a bit different between global responsibilities and basin specific / local responsibilities. Equity in climate change literature is about equally sharing the burden of climate responsibilities Fleurbaey et al. [2014]. Thus, who is allowed to do what who is responsible or can be held responsible for the current situation, or can there be any responsibility at all? In this literature the most common arguments are the following:

- Equality / Egalitarian principle
- Capability / Capacity
- Sovereignty
- Utilitarianism
- Rawlsian Justice
- Rose et al. [1998] Metz [2000] Fleurbaey et al. [2014]

These philosophical arguments are used in the discussion of climate change literature and the creation of agreements on climate change. These arguments have been grounded in climate change literature for some time now and are all focused on the creation of a fair system of tackling climate change. The translation of Equity principles to the field of water has been done in the past, especially regarding the underlying ethics of water distribution agreements Wolf [1999] van der Zaag et al. [2002]. Although a direct translation of one of an equity principle to a distribution has prove to be difficult for the general terms in international cooperation agreements leaves much room for interpretation van der Zaag et al. [2002]. To further incorporate equity within water management the Integrated Water Resource Management has been operationalised. The goal of the IWRM is to promote coordinated development of land and water resources to create economic and social benefits in an equitable and sustainable manner GWP/TAC [2000]. The question remains in this framework what can be considered Equitable? When is the access to water, or which distribution can be considered equitable in which framework Peña [2011].

The interpretation of Equity allows for much room within agreements and although it can be used to effectively come to an agreement between parties, no equity principle or interpretation can be considered better or more fair than another principle Rose et al. [1998]. The choice of Equity principle is not only dependent on its interpretation where there can be a multitude of differing, but also the correct implementation. Furthermore, Equity may be sought in a multitude of ways in an allocation based, process based or outcome based Metz [2000]. The focus of this study will an equitable allocation of the water over the sub-catchments. Another factor which may greatly impact the water distribution within the basin is the division of the sub-catchments, the boundaries which are chosen may be based on geographical, historical or administrative boundaries. The effect of choosing different boundaries will be outside the scope of this project, and the geographical boundaries will be used.

Allocation strategies distributing the amount of water over the different sub-catchments within a basin have been multitude, the following strategies have been used. The designation of the Allocation strategy to a philosophical equity principle will be expanded upon in the following Sections 2.1 - 2.5. The most common distributions are land or area based distributions and distributions based on population Wolf [1999] van der Zaag et al. [2002], or are derived from a need which is dependent on area and population.

2.1 Equality / Egalitarian principle

The role of equality within equity is a debate much discussed Rawls [1971] Peña [2011] Méjean et al. [2015], especially the interpretation of equality if it is about the same options or the same outcome. A general consensus within international law is that everyone has the same equal moral worth and thus the same equal rights Fleurbaey et al. [2014] Méjean et al. [2015]. Extending this definition that everyone has the same rights to the same amount it could be argued that an equal distribution of the available resources over each equally worth human being could be considered within the equity domain Metz [2000] van der Zaag et al. [2002].

The interpretation that everyone has equal rights and worth can lead to a distribution wherein everyone should be equal and should be able to equally pollute / use the earths resources Agarwal and Narain [1991].

The basis for the common use of the earths resources in contemporary philosophy as described by Starkey [2011] seems to reject this basis of common use or Per capita distribution. This argues against the use of common resource use of the sky as an emission sink for the emitted greenhouse gases. The usage of the sky suggest a common ownership of the sky, or the earth, as its inhabitants Cooper [1968] Locke [(1689], although the question of such a common ownership existing can be questioned in itself Starkey [2011]. Although these questions cannot translate directly to water and its ownership there is some common ground. The main argument proposed by Starkey [2011] which carries over is in how far does the common ownership hold if the needs for the usage is different, this question can be translated directly to water distribution. How fair is an equal distribution per capita if the need is different for each person, from adult to child, or rural compared to urban life. This comparison borders on the arguments put forward by Rawls [1993] which proposes a different equality measure outlined in 2.5.

Concluding Starkey [2011] proposes although a per capita allocation may not be the fairest distribution in theory it is a distribution which could work in practice. The question of ownership does hold for the usage of water resources, who owns them and how have they been distributed. In case water can be deemed a common good the equal usage of this common good does fall within the domain of an egalitarian worldview Méjean et al. [2015]. Concluding, the usage of population / a per capita distribution can be considered within the egalitarian worldview, although it does still raise some questions about ownership and precedent over this, especially looking at equal opportunities versus equal outcome Peña [2011].

Population based scenarios for water allocation have been proposed by van der Zaag et al. [2002] and has been used by Albers et al. [2021] for creating BWF caps. The usage of population in the distribution holds some precedent especially looking at water treaties where population sizes have been used as arguments for water distributions in the Nile river basin Wolf [1999]. In case the basin spans multiple nations all riparian states have access to the amount of water which is their share based on the area of the basin which it occupies van der Zaag et al. [2002]. This distribution holds closely to an explanation of the sovereignty principle as in everyone has equal right to pollute or not pollute within the system Rose et al. [1998]. Extending this to water usage to use the water or not the use the water in the system, equal rights mean equal access to the water proportional to the land.

- Equality allocation 1: Area
- Equality allocation 2: Population

Critique

A critique of the equality distribution principle is that the distribution does not take into account that current distributions are unequal or in some cases extremely unequal which may lead to skewed distributions which are not feasible Méjean et al. [2015]. This critique is made in context of greenhouse gas emissions, although it can also be applied to water usage. The main driver behind this critique is the feasibility of the drastic redistribution's which have to be make this distribution a reality. Furthermore the natural distribution of water is uneven and amending this requires extensive resources such as inter basin water transfers. Although this also raises the question if the unevenness of nature can be deemed unfair in the same manner as carbon distributions. Human consumption is a small factor in the total water consumption in the YRB Zhou et al. [2020], and larger consumers e.g. agriculture, pastoral and industrial use may be inconsiderately penalized. Although this critique can be made in every distribution scenarios, it can be extremely prevalent when applying the equality principle without compromise.

Critiquing both scenarios, the population and area based scenario falls back on the same arguments. Both do not take into account geographical and climate differences, one more gregarious than the other. The dependency of the sub-catchment on the water may be way larger than the initial population values seem to indicate, arid areas may need a larger share of the water to be able to sustain their population than humid areas. Continuing some locations may be entirely unsuitable for water use and distributing water to a location consisting of large arid areas may lead to over-allocation of the water. Especially in context of the widely different climates within the YRB, Section 3.1.

2.2 Capability

The inherent inequalities in the world, the unequal distribution of wealth and capabilities, would make an equal distribution of resources to be allocated to climate related actions unfair Rawls [1971]. It can be argued that the strongest shoulders should carry the heavier burdens if it improves the situation for all Méjean et al. [2015]. Thus describing this principle as the party with the largest pool of resources should contribute most to make the changes Shue [1999]. This idea of Capacity, Capability or ability to pay are different denominations used in literature for the same phenomenon Metz [2000] Peña [2011] Fleurbaey et al. [2014].

The capacity to contribute to the common goal of climate related actions can result in creating an abatement cost / contribution Metz [2000] Méjean et al. [2015]. This contribution to pay for the abatement should be distributed along the different parties according to its capacity to pay for this abatement Méjean et al. [2015]. The question remains how to determine the abatement cost for this particular issue, scholars argue for the usage of Gross Domestic Product (GDP) as abatement cost Smith [1993]. This can mean that the cost is scaled along the axis of a larger GDP the larger the burden one should bare Metz [2000], but could also be discussed as an inverse of the GDP Smith [1993]. The amount of abatement should be proportional to the capacity but not lead to unacceptable loss of welfare Baer [2013], creating a trade-off between acceptable amounts of abatement costs and total distribution in capacity.

The capacity for climate related actions scaled to the GDP of a country is not the only measure which can be used. Although GDP does reflect many aspects of a country the capacity should also reflect the technological abilities Fleurbaey et al. [2014]. Reflecting the technological capacity of a country to adept to climate change is a different metric which should not fit itself and should be more of a combination. A combination of factors to determine the capacity has been proposed with a basis in GDP and Human Development Index Baer [2013]. Thus, another measure which can be used to determine the abatement cost is the usage of the Human development Index Méjean et al. [2015]. Although the Human Development Index (HDI) could be used as an indicator for the capacity of a country for it does in term reflect the technical capabilities of a country often GDP is considered the better indicator Baer [2013].

Using GDP and the HDI for determining a certain abatement cost for each country can work on a global scale, although the agreement to use these metrics in specific resolution is lacking Baer [2013]. Translating the principle of the strongest shoulders should carry the heaviest burdens does not translate directly to the water field. In case of climate related strategies it is clearly about targets for reduction in usage or contribution to adaptation, while on a basin scale these targets may not be the focus. Although it could be argued that using less water so more water can be left to the environment can be considered as a good does it stipulate the fairness principle expounded in the previous paragraph.

The translation cannot be made directly when looking at the philosophical principle behind the concept of Capacity. For the capacity is a large concept which encompasses a wide range of scenarios, see previous paragraphs. one of these scenarios is the mitigating use potential Fleurbaey et al. [2014]. This potential states that the larger the reduction which can be made in usage the larger the capacity for change becomes. This circles back to the fact that countries with a larger GDP and HDI have an overall larger potential for reduction Baer [2013]. Thus, the usage for GDP and HDI as indicators for capacity could be used. Applying this to the YRB, the areas with the largest GDP / HDI will have to lessen their consumption or apply water saving techniques so water can be used elsewhere to achieve an equality of outcome Rawls [1971].

- Capability allocation 1: inverse GDP
- Capability allocation 2: inverse HDI

Critique
The notion of Capacity is heavily rooted in Ethics, the strongest shoulders should carry the largest burdens. The problem arises in the consumption of water and the impact of GDP as an economic indicator, agriculture being the largest user of water within the YRB Zhou et al. [2020]. The usage of this water does not yield the largest contributions to the GDP, while it could be argued that water savings in areas with a large GDP would be beneficial for all. The largest Capacity for reduction in usage does correlate with the largest users of water (add source). Compounding this idea, to which extent can the proposed reduction in areas with a large GDP / HDI be feasible, in case the Basin has large differences in GDP and HDI over the basin, that municipal water usage becomes endangered especially within basin with water scarcity.

2.3 Sovereignty

The concept of Sovereignty can be explained in a multitude of ways. In climate related literature the explanation the explanation is that current emissions are the only degree on which to discuss equity and no other metric can be used Metz [2000]. Another explanation for this principle is that every country is allowed to pollute or be protected from pollution Rose et al. [1998]. Using the first definition of Sovereignty, there is no specification in reduction of current emissions it only specifies it should be the primary point. This creates a point of ambiguity for does one use current usage for distribution, and how does this reflect the right to develop Fleurbaey et al. [2014] and the stark differences of emissions between wealthy and less wealthy countries Agarwal and Narain

[1991] Metz [2000]. Further problems arise for the usage of the Null / reference point, which period or point in time is considered as reference for allocation for the choice of this point may lead to widely changing results.

Equal right to pollute or not pollute Rose et al. [1998] is an interesting notion, for it implies that every country has their own responsibility for their actions. In regards to climate action this specific action often refers to a general overall cutback in a proportional manner over all nations. In regards to water distribution it has been argued in section 2.2 that allocation of general decreases cannot be directly transformed into a water Allocation strategy. Another interpretation is the grandfathering-principle as in that historic use of a resource adds rights to the continued usage of this resource. Although this is popular in scarce resource distribution agreement Méjean et al. [2015] and in water treaties Wolf [1999] it does not hold any ethical basis Grubb [1995]. The claim to use a resource based on historic use often holds closely together with the need of the usage of that specific resource.

In water literature and water treaties the principle of sovereignty has been used in context of absolute sovereignty versus absolute river integrity Wolf [1999]. Although these principles have been used in discussion they never have been enforced and have often watered down to reflect the needs of a country than a right. van der Zaag et al. [2002] proposed a distribution wherein each sovereign state would be allocated an amount of water based on the overall Blue Water Availability and equally distribute this water from upstream to downstream, this method has also been applied by Albers et al. [2021]. The distributions created using this method cannot be entirely attributed to aforementioned Sovereignty domain when looking at it through a climate related lens. It does become more feasible when looking at it from the explanation of absolute sovereignty over the water within the basin, although the precise application of this principle is not sufficient.

The application of the sovereignty principle to water allocation creates two different strategies. The first strategy describing absolute sovereignty of a state or area over the usage of the river, in line with everyone can use the resources as they deem necessary Rose et al. [1998], would result in a distribution which favour an allocation purely on the amount of water which only uses local precipitation. A second scenario is the historic / current usage, the usage and usefulness of this scenario is up for debate for it strongly depends on the choice of reference year. The third interpretation that the normal flow of the river should not be impeded at all and absolute river integrity is achieved holds closely to the "natural" scenario proposed by Albers et al. [2021]. For this scenario seems to simulate a flow regime without human influences this scenario is deemed not very suitable in the comparison.

- Sovereignty allocation 1: Precipitation
- Sovereignty allocation 2: Historic usage
- Sovereignty allocation 3: Need based

Critique
The main critique in applying this principle is the usefulness in general application. As Wolf [1999] mentioned the actual use of absolute sovereignty versus river integrity has not been observed in water treaties between riparian states. For the argument of total river integrity of the river stream, would result in a distribution where no consumptive water use can be present in the basin. Having any consumptive water use, even in downstream riparian state would invalidate the argument of demanding absolute river integrity. The argument for absolute sovereignty over the river within an area infringes heavily on historic usage and thus right of use.

2.4 Utilitarianism

The philosophical notion of utilitarianism is that an action is good when it produces a good which is maximised for the largest amount of people Carter [2002] Mill [1871]. The idea is that the world should be made as good as we can and this can be accomplished by making the lives of the people as good as we can Bykvist [2009]. The classical understanding of this idea is that every person has a utility function for their satisfaction and the maximisation of this individual utility function should be the most fair distribution Peña [2011]. Wherein every distribution which does not maximise the amount of individual utility can be considered unequal and are thus unjustified.

The argument of utilitarianism is often argued from a economic point of view, the distribution of largest economic benefit is a just distribution. Although the theory of utilitarianism has been criticized by ethicists Fleurbaey et al. [2014] Peña [2011] Rawls [1993]. The argument for the usage of the utilitarian principle is that it is an ethically minimal theory Budolfson et al. [2021]. For it determines each persons interest equally and should be applied equally to all. Furthermore the concept can be applied without taking into account historical precedents and should only be able to be placed in the present, this in contrast to the sovereignty principle where the application time is ambiguous.

Criticism of the utilitarian principle is the focus on a cost-benefit framework without taking into account key ethical principles such as human rights and moral imperatives Fleurbaey et al. [2014]. This critique of focusing of the total amount of benefits and not the distribution of the benefits Peña [2011], holds close with this criticism. This criticism often applies to the direct application of the utilitarian perspective, even though the utilitarian perspective can encompass some moral perspective Bykvist [2009]. Using the utilitarian perspective for emissions standard as proposed by Budolfson et al. [2021] shows an interpretation of utilitarianism which promotes an equal cost for emissions for everyone. The equal cost is determined based on the value of each monetary unit spend on emissions, so a poor person will spend less than a rich person for a poor person will sacrifice more when spending the same amount of money.

The translation to an allocation scenario can lead to different interpretations. Cai et al. [2011] proposes a distribution of the water within the YRB wherein the maximisation of the GDP was the most important factor, this takes the utilitarian perspective in its classic form. The result of this distribution was a maximisation of the GDP, but would result in the allocation of all the water to effectuate this allocation, for this utilitarian perspective designates all water which does not allow for maximisation of the common good as unjust. This led to a distribution where the environmental flow could not be sustained. It could be argued from the utilitarian perspective that the action which produces the greatest amount of happiness as a whole is the best choice Mill [1871] Bykvist [2009]. Neglecting the Environmental Flow Requirements could have disastrous impact on the environment leading to an environment which in time would not result in happiness, thus refuting the strategy of maximising GDP at the cost of the Environmental Flow Requirement (EFR).

The focus on the greatest economic benefit, within reason, could be justifiable when applying the utilitarian principle. For an economic analysis is the dominant policy analyses methodology in governmental practice Budolfson et al. [2021]. Thus an economic analysis can be constructed, for the utilitarian theorem strives to create the largest amount of good several interpretations can be determined:

- Utilitarian allocation 1: GDP
- Utilitarian allocation 2: Industrial gross value added per m^3 of water
- Utilitarian allocation 3: Agricultural water usage

These allocations have been selected for the following reasons: The first Allocation strategy relates closely to a free market taking into account an adaptation on the classical utilitarian approach. The second application seeks to maximise the economic benefit per m^3 of water for the greater the economic benefit the larger good. The third Allocation strategy is created on the notion that the largest benefit for creation of good can also be determined in the maximisation of the Crop Yield, thus creating a distribution which maximises the agricultural yields form a certain area. this is of extra interest because of the specific basin characteristics, Section 3.1.

2.5 Rawlsian Justice

"Rawlsian justice or the Maximin principle states that the underprivileged should benefit from the division of costs or benefits" Metz [2000]. This theorem of justice states that true equality can be forgone if it benefits the underprivileged Méjean et al. [2015]. The creation of this theorem is a critique on the utilitarian principle is the maximisation of the benefits and condoning unfair and unequal distributions of well-being Rawls [1971]. The translation of the Rawlsian justice principle to climate literate is direct, maximise the welfare of the worst-off nations Rose et al. [1998]. Because this holds closely to the capability / capacity of a nation to perform changes there will be overlap in justice principles.

The difference from the capability stems from the fact that some inequalities may be acceptable to society Rawls [1993], as long as they contribute to the improvement of the weaker sector. Thus society should hold people to an unequal standard as long as the basic needs are met Peña [2011]. Where basic needs are defined as : "The basic needs are the needs which should be met is a person to take advantage of the rights liberties and opportunities of society" Rawls [1993]. The selection of the basic needs of humans within society should be done with care, for designating these basic needs as human rights results in them needing to be fulfilled Peña [2011]. The application of basic needs to the Climate discussion proves difficult, for the indication is indirect counting the emissions for the provision of food and housing and not the direct emissions Peña [2011].

The indirect usage of water in industry and food production can be used to apply the Rawlsian Justice principle.

By benefiting the underprivileged the current system of distribution and allocation has to be changed. Although this may lead to a more fair distribution in time the system should be able to accommodate these changes Budolfson et al. [2021]. These changing in allocation may be easier to achieve when distributing emission rights for they can be traded between parties. The role of water trading between countries and areas can prove difficult Cai et al. [2011], especially considering the physical limitations of a basin. These limitations become more prevalent when applying water use, water cannot be located from a downstream area to an upstream area.

Creating the allocation strategies the following strategies can be created, some have a direct overlap with the Capability allocation but they should also be evaluated using the principle of Rawlsian Justice. The last two allocation strategies are the inverse of the Utilitarian principles listed in Section 2.4. The last principle is the minimum basic human need for water based on the Human right to water UN [2002]

- Rawls allocation 1: inverse GDP (*Capability*)
- Rawls allocation 2: inverse HDI (*Capability*)
- Rawls allocation 3: inverse Industrial gross value added per m^3 of water
- Rawls allocation 4: inverse Agricultural water use
- Rawls allocation 5: Basic human need

2.6 Evaluation scenarios

Each scenario will be evaluated based on a set of criteria. The most important criteria is to measure the extend of generated equity within the principle, or what does the equity principle look like. The indicator to measure the implementation of equity in the Allocation strategy is expanded upon in Section 3.5.

- To which extent does the distribution result in its represented equity?
- Representation of the BWF Cap for the allocated Blue Water.
- Is the Allocation strategy reflected in the allocated water?

The representation of the BWF Cap for the allocate Blue water determines how well does the cap represent the allocation. In case there are large yearly fluctuations for the BWA the BWF cap may be set very low. Thus, measuring the representation of the cap for the Allocation strategy itself.

Historic Use
The fulfillment of the Actual Blue Water use within the basin is an interesting comparison. The allocation scenarios may propose a scenario which is considered equitable but does not fulfill the historic usage the actual BWF of the water. Although it should be a metric of comparison to determine the amount of unfulfillment and the resulting Blue Water Scarcity, it is not a metric of comparison how the Allocation strategy is used. The actual BWF for the period can be used to determine the distance between the proposed BWF cap and the actual thus determining a metric of feasibility of implementation of the Allocation strategy.

The main understanding of the creation of feasibility of implementation is the incorporation of actual BWF of the reservoir. The historic use has not been used in the optimisation process, and because the historic use does not strictly follow the natural flow patterns of water availability water scarcity could easily occur.

3 Method

The alternative Allocation strategy discussed in Chapter 2, are to be compared and implemented into a model to determine the equity. The implementation of these principles, just like the translation made before, is not perfect, mainly due to physical constraints, to get as close as possible to fairness within the system an optimization algorithm is created. This algorithm will determine the optimal distribution of fairness for this particular Allocation strategy. To determine the effectiveness of this optimization an indicator of fairness is created, this indicator is measures the maximum achievable fairness with the fairness created using the optimization procedure, see section 3.5. The indicator can than be used to determine the strengths and weakness of the optimisation procedure.

To create an optimised distribution of fairness each Allocation strategy is optimised in a model. The indicators of measuring fairness in Chapter 2, such as the GDP, population and area are applied to each distribution scenario as an Allocation strategy. The optimisation procedure will then find the optimal solution for each Allocation strategy. The optimisation procedure is conducted in a manner which diverges from the method used by Albers et al. [2021]. The method used by Albers et al. [2021] uses a distribution approach which requires perfect knowledge of all components of the system, such as historic use and reservoir operation. When using historic reservoir operations this would be adequate, but in this case the reservoir operation is dependent on the Allocation strategy. Creating an interdependence which can be solved using an optimization algorithm. Furthermore the historic usage of water within the reservoir is used to determine the leftover water within the allocation which can get redistributed to downstream sub-catchments. Although this measure can be used to great effect of optimal water usage van der Zaag et al. [2002] Albers et al. [2021], implementing this method would result in skewed results when comparing the indicator of fairness. For fairness as being applied to its best ability will be influenced by historic use, being an external factor, and will thus not be implemented in an optimised manner.

The impact of the allocation strategies on the reservoirs is measured using the historical usage and the reservoir usage for each Allocation strategy. Each Allocation strategy will have their respective water use compared to the reservoirs. And to determine the manner in which the reservoir is used. Does a different Allocation strategy warrant a completely different reservoir operation procedure. The measure of difference will be deviation of the historic usage compared to the usage observed with the Allocation strategy. The Blue Water Footprint Caps (BWF-Caps) will be formed based on the blue water availability. Because the study period encompasses multiple years, with a relatively dry and wet period the amount of variation within is large and quite representable for the basin. BWF-Caps can be constructed based on the amount of water available in the system by taking a 25 percentile of the of the five year period. These BWF-Caps can then again be evaluated using the fairness indicator to determine the applied fairness of the chosen method. Furthermore, the BWF-Caps can be compared with each other to determine Blue water scarcity and measure of fulfillment and under-fulfilment compared to historic use.

3.1 Case study description: The Yellow River Basin

The Yellow River Basin (YRB) is the second largest river basin in China, with a drainage area of 795.000 km^2, and a length of 5464 km. The river has been divided into three different reaches, the upper- middle- and lower reach. The long-term average annual runoff is $58 * 10^9 m^3$ or 77 mm per year basin wide Yazdandoost and Attari [2014]. The basins supplies water to 105 million people, feeding 9 % of the national population and supplying 13 % of the national grain production while only providing 2 % of the natural water resources Zhuo et al. [2019]. The northwest region within the basin is arid and semi-arid, while the southeast region is semi-humid Xie et al. [2020], combined with the monsoonal climate the river basin suffers from moderate to severe blue water scarcity 7 months a year Zhuo et al. [2016] Hoekstra et al. [2012]. Reservoirs redistribute the water over the year which can reduce the blue water scarcity over the year, the YRB has 29 large and 174 small reservoirs Zhuo et al. [2019], accounting for in total 1.2 times the total average annual runoff Ran and Lu [2012].

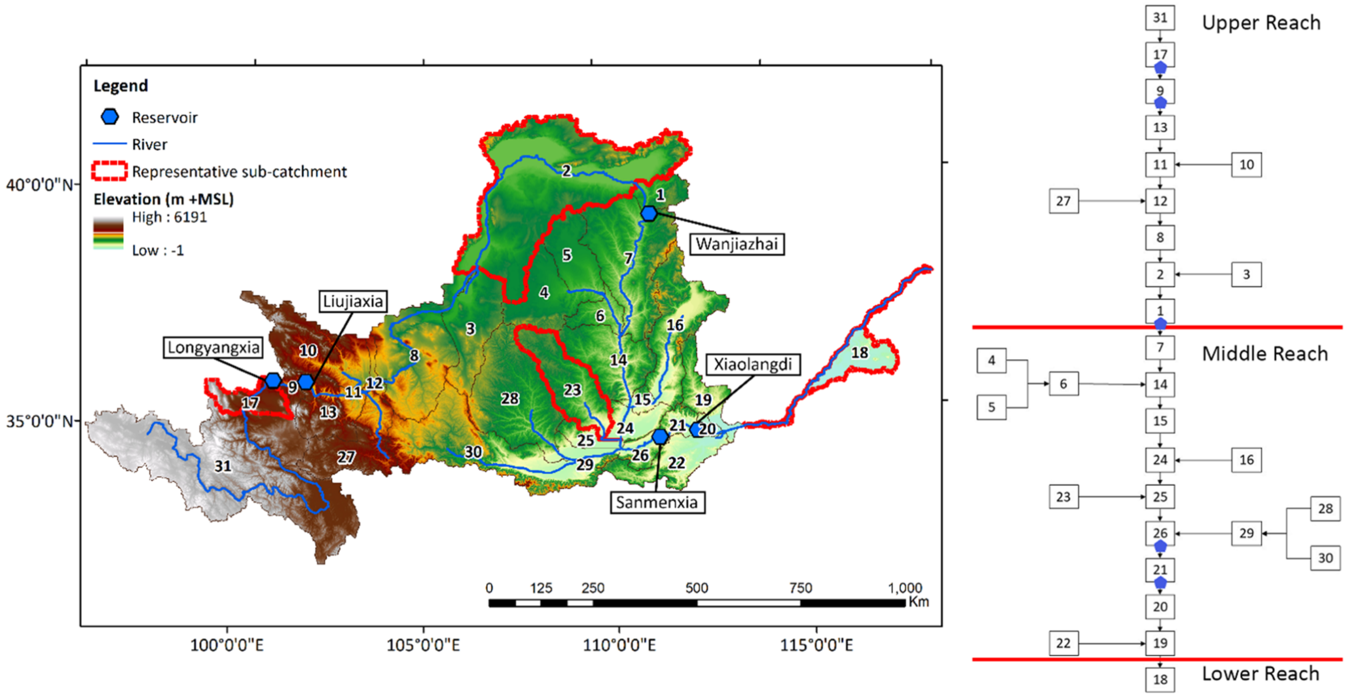


Figure 1: Schematization of the Yellow river basin Albers et al. [2021]

The reservoirs considered in this study from the 29 major reservoirs along the YRB are the 5 major reservoirs shown in Table 2. The reservoirs Longyanxia, Liujiaxia, Wanjiazhai, Sanmenxia and Xiaolangdi are selected because they account for 78 % of the storage capacity of the YRB Zhuo et al. [2019] and have been used in previous study of Albers et al. [2021]. The preferred storage seen in Table 2 is based on the historical storage levels YRCC [2010], of note is the Sanmenxia reservoir. In the central part of the river the river cuts trough a large loess plateau with an area of 580.000 km^2 where 75 % is subject to severe soil erosion leading to severe sedimentation in certain parts of the river Yazdandoost and Attari [2014]. This area of large erosion leads to the Sanmenxia reservoir having the largest annual sediment load of all the worlds rivers at $1.9 * 10^9$ ton Yazdandoost and Attari [2014]. To prevent floods upstream from the reservoir due to large soil deposition in the area upstream from the reservoir the reservoir has been modified to allow for flushing the sediment along the river, practically nullifying the storage capacity of the reservoir.

5 Main reservoirs in the Yellow river					
Index	Longyanxia	Liujiaxia	Wanjiazhai	Sanmenxia	Xiaolangdi
Storage capacity ($10^9 m^3$)	27.6	5.7	0.9	9.6	12.7
Preferred storage %	70.3	59.1	33.4	4.8	37.8
Longitude	100°54'57"	101°48'26"	111°25'42"	111°20'41"	112°21'37"
Latitude	36°7'15"	36°7'3"	39°34'45"	34°49'47"	34°55'26"

Table 2: Reservoirs

3.2 Data

The data set used by Albers et al. [2021] contains daily precipitation data on a sub-catchment scale for the years of 2010 until 2014. The data contains daily runoffs which have been validated for two meteorological stations in the upper reach of the Yellow river basin Albers et al. [2021]. The daily runoff used by Albers et al. [2021] have been delineated from Xie et al. [2020] which calibrated monthly runoffs for the entire basin. The choice has been made to use the data from Albers et al. [2021] so a more direct comparison can be made between the different methods. The Yellow river has been subdivided into 31 sub-catchments each with their own runoff and characteristics. The subdivision of the sub-catchments has been executed using the SWAT model based on the natural elevation data, resulting in division of areas which does not directly overlap with a regular administrative division of the country.

The runoff generated form the SWAT model does not translate directly to the Blue Water Availability which can be used to allocate the water according to its usable characteristics. The natural runoff consist of a Blue water component and a component reserved for the Environmental Flow, otherwise known as the EFR. Satisfying the EFR can be done in a multitude of ways, the most common are the Presumptive Standard Approach (PRE) Richter et al. [2012] and the Variable Monthly Flow (VMF) Pastor et al. [2014]. Both methods have been applied in research for the YRB Zhuo et al. [2019] Xie et al. [2020] which used the PRE method and Albers et al. [2021] which used both methods. The PRE method reserves 80 % of all the natural flow for the environmental flow, while the VMF method divides the into flow regimes which allocates between 30 %, 45 % or 60 % of the natural flow. To get a better representation in rivers with a large seasonality the VMF method is preferred Pastor et al. [2014], this has also been the main point for comparison in the study conducted by Albers et al. [2021].

Zhou et al. [2020] provides spatial GIS data for the water use trends from 1965 to 2013. This data set contains the amount of water used in agriculture, municipal, industrial and the added economic benefit of the water use. Combining the map of the sub-catchments and the prefecture based water use map creates a data set which can be used for the allocation strategies. The data set provided by Zhou et al. [2020] does not include the year 2014 and the results for this year have been extrapolated. The respective GDP and HDI are available in a 5 arc-min resolution Kummu et al. [2018], which provides grid spatial data for the entire world where the specific application for the YRB has been extracted. To determine the impact of each Allocation strategy on the Blue Water Allocation each strategy has been quantified according to a metric which closely represents the ethical principle. The quantification of each principle has been selected in the purest form, thus excluding any basic needs which logical would have to be applied. The foremost needs which has to be fulfilled is the basic human water need as described by UN [2002].

3.3 Blue water Allocation

The usage of the approach by Albers et al. [2021] was not possible due to different constraints and trade-offs with optimisations. Thus, the allocation process of the blue water is presented using a Genetic Algorithm, specifically the DEAP package Fortin et al. [2012]. A Genetic Algorithm is an algorithm which simulates the genetic transfer from one generation to the next generation. This is an iterative process, where generations of solutions are tested for their performance and recombined into new a new generation. The genetic information is simulated by having a sequence of values which get changed over time, for this study these values represent the allocated water to each sub-catchment. The transfer of genetic information from generation to generation includes the combination of data from parents to offspring and any possible mutation occurring in the process. Aforementioned concept is the core of a genetic algorithm, where each population is combined mutated and recombined until a certain amount of time has passed. For a more detailed description see Section 6.1. The objective function of the Genetic Algorithm is the distribution of the available Blue Water according to the principles of each Allocation strategy, the allocation strategies are described in Section 2.

The amount of Blue Water allocated to the sub-catchments is determined using a minimisation function, which compares the total amount of available water to a distribution parameter based on the allocation scenario. The goal of the minimisation function is to create a water allocation which is as fair as possible.

$$\sum_i ((\frac{X_{i,m}}{\sum_i X_{i,m}} - \frac{\text{Dist}_{param,i,y}}{\sum_i \text{Dist}_{param,i,y}})^2) \tag{1}$$

Where $X_{i,m}$ is the monthly amount of water which is allocated to each sub-catchment. The amount of Blue Water is the monthly total for that specific month. The monthly amount of water which is allocated is the factor which is optimised using the Genetic Algorithm. The fairness of the water allocated to each basin is evaluated based on the fairness indicator. $\sum X_{i,m}$ is the sum of all the available Blue Water within the basin. The same applies to the subtraction part of Equation 1 these values use the same monthly time-step, although they change only yearly. The change of the distribution parameter is yearly due to data availability constraints, but this does come with the assumption that the temporal pattern in water use is static. The $\text{Dist}_{param,y}$, the distribution parameter is the quantification of the Allocation strategy this can entail the population within-, area- or GDP of the sub-catchment.

The objective function described in Equation 1 distributes the available water (not all the available water) over the sub-catchments, which can be used to assess the fairness. Not all water allocation patterns are physically feasible as water flows from upstream to downstream and water availability is limited and interannually variable. Thus, several constraints are added to the process to ensure the amount of allocatable water is within the physically possible limits. Secondly the reservoirs should be taken into account.

The constraints help guide the algorithm to create physically feasible solutions. The main constraint within the model is the available water in the system, limiting the amount of water which is allocated to each sub-catchment and reservoir to the maximum amount which is present. The main function of the constraints is adding the travel-time of the water to the model, the travel-time from sub-catchment to sub-catchment and any travel-time from the reservoirs. The objective function is a minimization function which minimises the strategy with the actual distribution. This results in an allocation which can be deemed fair and inline with the allocation scenario. However this could lead to a distribution which is optimal according to the distribution scenario but omits the usage of the main part of the water, which can be amended by creation of a second objective function. Because of the large differences in population, agriculture, GDP, etc. throughout the basin large inequalities in distribution can occur. These inequalities in distribution have to be solved by the algorithm, within the physically feasible realm. This phenomenon is exasperated in several side-streams, where water availability is low and water usage is high Zhou et al. [2020].

To account for the complications of these side-streams a second objective function is implemented. The second objective function allocates all water which is not part of the EFR to the sub-catchments. Creating a second objective function (Equation 2) helps create a better understanding of the model, due to the conflicting nature of both objective functions a clear trade-off between the two objective functions can be observed creating a better understanding of the model. The main benefit is that all water will be allocated to the sub-catchments, so a fair comparison can be made between the allocating strategies. To clarify this phenomenon an equitable solution according to the algorithm may be that roughly 10 % of all the available blue water is allocated, due to water availability issues in the side-streams. For a distribution is considered equal when the sub-catchment with the lowest water availability has its equal share, thus dictating the amount of water which can be distributed in total. Because this may not occur when applying all allocation strategies, this results in an unfair comparison. Although this has a major drawback in the integrity of the allocation, for altering the distribution one can argue that the intended fairness is infringed and no longer applicable. By allocating in-allocated water to the sub-catchments the distribution proposed by the Allocation strategy is in a trade off position between using as much water as possible and an equitable distribution.

$$\text{UnusedWater} = \max(AW) - \sum_i X_{i,m} - \sum_i Y_{i,m} + \sum_i Z_{i,m} \tag{2}$$

Equation 2 is a minimisation function, thus the smaller the Unused Water component the better the result. The AW component is a measurement for the available water in the system, the available water in the system is a constraint for Equation 1. The $X_{i,m}$ describes the sum of all the allocated water to each sub-catchment. Where $Y_{i,m}$ describes the reservoir inflow component, water leaving the system to enter the reservoir and $X_{i,m}$ describing the reservoir outflow, which allows for water to be reallocated.

The following core assumptions have been made in the creation of the Blue water availability:

- The water designated for the Environmental Flow Requirement will always flow through the river basin
- The reservoir can be used to its full extent
- There is no minimum amount of water to be stored in a reservoir
- The reservoirs have no flow rate cap
- evaporation losses are not considered, will be seen as historical these historical water losses are based on surface area Zhuo et al. [2019].

Reservoir operation losses although significant in their blue water consumption Hogeboom et al. [2018] Zhuo et al. [2019]. Are not considered and use the historical fluxes. The largest evaporative component is the reservoir, and dependent on the amount of water within the reservoir. Because the reservoir storage targets are close to the historical operation, the evaporative component is partially incorporated in the water balance. The Core assumptions mentioned above limits the complexity of the model. Allowing the freedom in the reservoir operation each Allocation strategy has a larger degree of freedom when allocating. So the reservoir operation will have a minimal influence on the Allocation strategy. Although a comparison between the reservoirs, to compare the influence of the Allocation strategy on the reservoir operation will be conducted.

3.4 BWF caps

The blue water footprint cap is the total natural runoff minus the Environmental Flow Requirement Hoekstra et al. [2012]. This creates a fluctuating pattern of caps over the year with larger caps in the wet season and lower caps in the dry season. Reservoirs located within the YRB raise the BWF-Caps in the dry months and lower the BWF caps in the wet months Zhuo et al. [2019]. The operation of the reservoirs should also alleviate water stress in a dry year, allowing for regular operating procedures within a dry year. The BWF-Cap which is created should be able to be fulfilled within a dry year as well as a wet year, thus a 25 percentile is used of the five year average.

To measure the effectiveness of the BWF-Caps the Blue Water Scarcity (BWS) is determined based on historical usage and compared to determine the feasibility of the cap. The BWF-cap can be used as a guide for reducing the blue water consumption, and thus reducing the BWS. BWS takes place when the water footprint is larger than 20 % of the total runoff Hoekstra et al. [2012] which can become severe water scarcity when using more than 40 % of the total runoff. The BWF-Caps is combined with the water reserved to satisfy the EFR to compare the water scarcity for historic use (the Blue Water Footprint) in Equation 3.

$$BWS_{i,m} = 1 - \frac{EFR_{i,m} + BWF_{cap,i,m} - BWF_{hist,i,m}}{EFR_{i,m} + BWF_{cap,i,m}} \tag{3}$$

The blue water scarcity in Equation 3 shows the amount of water is used compared to the total amount of water in the sub-catchment. The resulting blue water scarcity per basin per month can be evaluated to determine the feasibility of the equity principle. The feasibility of implementation is a metric of the required change to be able to bring this equity principle in its current form to fruition. A large BWS would indicate the water consumption in the sub-catchment is large compared to other sub-catchments in regards to what should be used. A low water scarcity should indicate the water usage in the particular sub-catchment could be increased based on the BWF-Caps in the sub-catchment. Thus, blue water scarcity can be used as a metric for determining the amount of adjustments which have to be made.

3.5 Indicator of Equity

The indicator of fairness is the main indicator to determine the implementation of the ethical principle in the model. This will be achieved by evaluating the optimisation performed by the objective function in Equation 1. To determine the effectiveness of the allocation the distribution parameter is evaluated with the Allocated Blue Water (ABW) (Equation 4) and the BWF-Caps (Equation 5). Wherein a performance indicator is created for every month in the five year simulation period. To determine for each month and each strategy the implementation of equity. The unit of measurement is different between the allocated blue water and the distribution parameter so both are divided with their total see Equation 4.

$$FairnessABW_{i,m} = \frac{Dist_{param,i,y} / \sum_i Dist_{param,j,y}}{ABW_{i,m} / \sum_i ABW_{j,m}} \tag{4}$$

The $Dist_{param,i,y}$ is the distribution parameter for the specific Allocation strategy. It signifies the amount which should be allocated to the specific sub-catchment for the month in the year, in contrast to the total which is allocated signified in $\sum Dist_{param,j,m}$ which is the sum over all sub-catchment in the specific month. This also applies to the BWA where the allocation specific to the sub-catchment for a certain month is compared to the allocation to all the sub-catchments for the same month. Thus Equation 4 and 5 results in a fairness value for each sub-catchment and month, creating an overview both in time and space.

$$FairnessBWFcap_{i,m} = \frac{Dist_{param,i,y} / \sum_i Dist_{param,j,y}}{BWFcap_{i,m} / \sum_i BWFcap_{j,m}} \tag{5}$$

The measure of fairness determines the implementation of the strategy. Each Allocation strategy is evaluated based on the the fairness of implementation. This will result in global statistics of each Allocation strategy, these can be used to evaluate the allocation strategies and to identify potential weaknesses in the model. The value of the fairness ranges from zero to infinity with an ideal value of one. A fairness value below one indicates that the particular sub-catchment receives too much water compared to the need.

4 Results

In Chapter 2 several allocation scenarios are put forward which can be applied to simulate the BWA in the distribution. BWF-Caps are created based on the blue water availability. Due to limiting factors in the modelling process and direct data availability not all of these principles have been implemented. The following allocation strategies have been implemented in the model: Area, Population, GDP, inverse GDP, Irrigation water Need, Industrial demand. These were implemented in the model in a manner which reflects the intended equity. Historic usage is not used as an Allocation strategy, but used as a comparison to measure the adaptability of the system to adapt to an Allocation strategy.

The methodology has a large part on the results, therefore some highlights from the methodology chapter. The implementation approach of the allocation principle in the model is one dimensional, it does not change over time or with time, even when allocated water volumes do. The only changes which are made are the differences between the sub-catchments and their characteristics. For certain allocation strategies which reflect GDP and population this is of no concern for the changes over the years are relatively small. This changes for the irrigation water need and the derivative, because of the seasonality of the water usage the fluctuations can be significant within the year. By using the total consumptive irrigation water need for each sub-catchment a distribution can be made, which should reflect its consumption but will not reflect the seasonality.

4.1 Allocation of water in time

To determine the impact of the allocation strategies on the water distribution in several sub-catchment along the basin is visualised in Figures 2 - 5. These figures show the changes over time for each sub-catchment, visualising the different allocations of blue water in the YRB in wet and dry years. The allocation scenarios will first be analysed in a temporal manner and than in a spatial manner, Section 4.2. The sub-catchments which are analysed in a temporal manner are selected for they encompass most features of the YRB. For comparative purposes these sub-catchments are the same which Albers et al. [2021] used, creating continuity in comparison, Table 3. The exact location of these sub-catchments can be observed in Figure 1. The amount of water allocated to each sub-catchment is low compared to natural flow, for the blue water availability is the natural flow without the water reserved for the environmental footprint. Water reserved for the environmental footprint fluctuates throughout the year and has a reduction between 40 - 60 % compared to the normal distribution. The choice to compare with the natural flow and not the available flow is to get a better understanding of the system at large.

5 Main reservoirs in the Yellow river				
Sub-catchment	17	2	23	18
Location	upper reach	upper reach	middle reach	lower reach
Population	small	medium	medium	large
Blue water demand	low	high	medium	high
Additional	reservoir	-	tributary	-

Table 3: Sub-catchment characteristics

Sub-catchment 17

Sub-catchment 17, the sub-catchment where a reservoir is located directly upstream from the sub-catchment shows a wide range of distributions. The actual historical water usage in this sub-catchment is low, compared to the natural flow through the sub-catchment. Thus, according to all allocation strategies this particular sub-catchment should be allowed to use more water than it is historically using. The second observation which can be made are the large peaks in specific months for some allocation scenarios which are not in line with the natural flow (The seasonal pattern which can be observed) or even exceed the natural flow. This phenomenon can be explained by the presence of a reservoir directly upstream from the sub-catchment allowing for a distribution which does not have to follow natural flow patterns as closely, Figure 14a. What is of note is the capriciousness of most allocation scenarios, the most egregious example for this sub-catchment is the irrigation allocation scenario. The need for irrigation coincides with the period just in front of the rain season, see the historical use bar graph for irrigation is the largest component. However this cannot be observed in the model, and a highly varying amount of water is distributed over the years, especially in the fifth year where the water availability is medium.

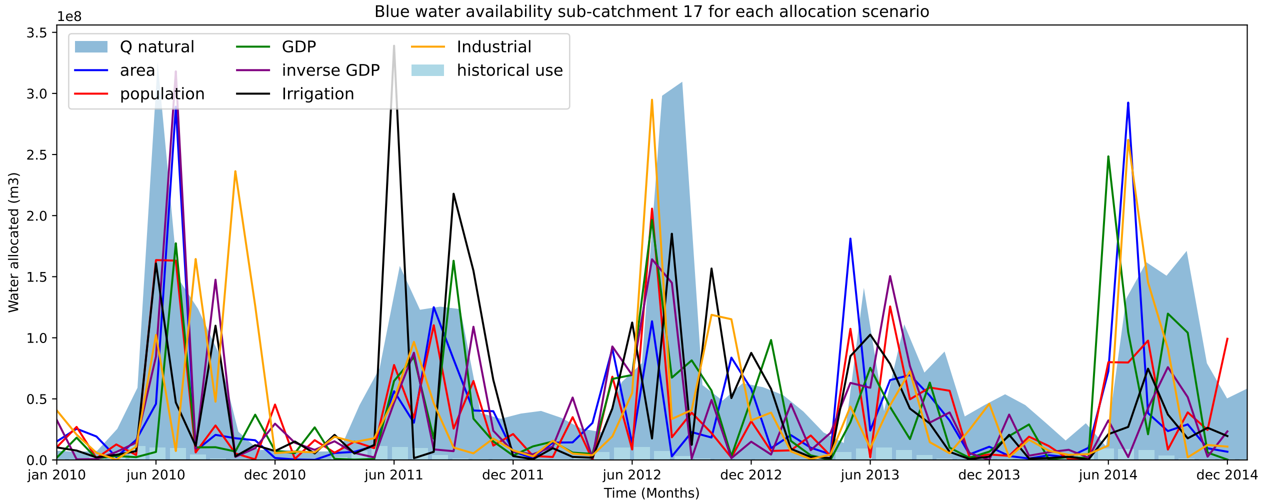


Figure 2: The blue water availability in sub-catchment 17 for each allocation scenario indicated by the lines, the light blue histogram indicates historic use, the dark blue shaded graph indicates historic natural flow, Albers et al. [2021].

Sub-catchment 2

The observations made for sub-catchment 2 is the large historical use of the water. This sub-catchments which is located in the lower end of the upper reach is a large water user. It contains vast amounts of irrigated areas as well as a medium population resulting in large water requirements. The main comparison between sub-catchment 2 and sub-catchment 17 is the water need, and the amount of water flowing through the river at this point. A direct comparison cannot be made because of differences in scale between the two sub-catchments, where sub-catchment 2 is using a factor 100 more water than sub-catchment 17. The amount of water which is allocated to sub-catchment 2 is larger than that of sub-catchment 17 so a distinction between sub-catchments seems to be working. Even though the differences between the allocation strategies leaves shows some distinction between the allocation strategies the overall trend is capricious.

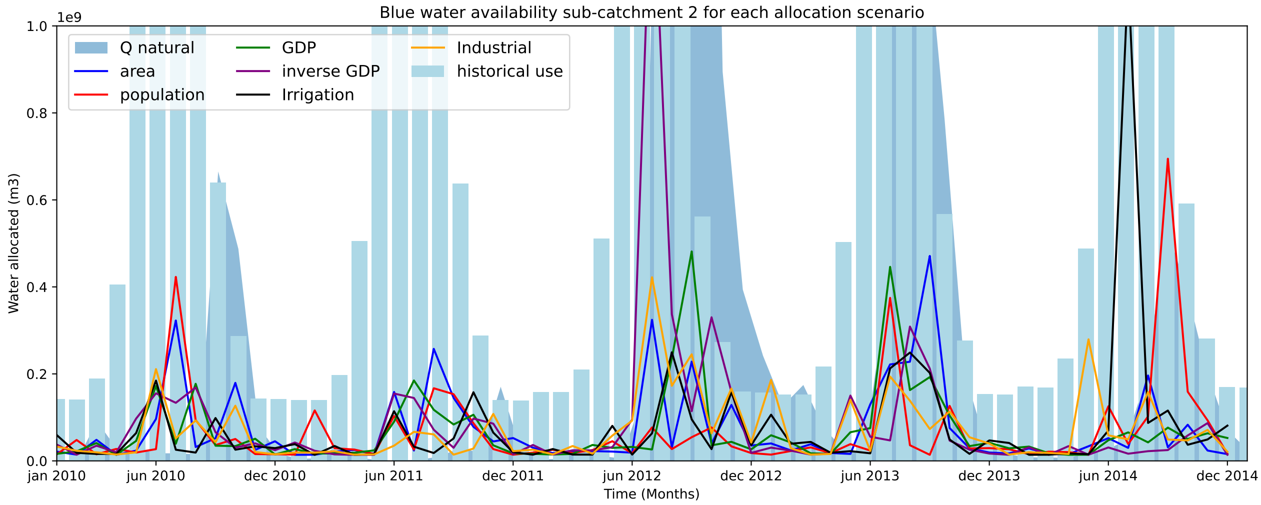


Figure 3: The blue water availability in sub-catchment 2 for each allocation scenario indicated by the lines, the light blue histogram indicates historic use, the dark blue shaded graph indicates historic natural flow, Albers et al. [2021].

Sub-catchment 23

Sub-catchment 23 is a sub-catchment located in a side-stream. The side-stream is small in size and has a large natural run-off. This run-off is primarily put into perspective when comparing to sub-catchment 17 which is the second farthest upstream sub-catchment. Due to a large natural run-off in the sub-catchment the historical usage is also significant. Agriculture is a large component of this usage, thus the blue water reserved for irrigation should reflect this. This is not the case which could have a multitude of reasons, the primary reason is the irrigation water use compared to the total irrigation water use over the basin. Especially sub-catchment 2 has a large demand for irrigation water and thus will skew the metrics for fair distribution. Secondly because sub-catchment 23 is located in a side-stream it cannot receive any form of additional water except for water transfers which are not taken into account. Furthermore the YRB is home to many reservoirs, more than 200 in total. Only 5 reservoirs are taken into account in this comparison, so actual water flows and usage may differ greatly from what is depicted in this particular study.

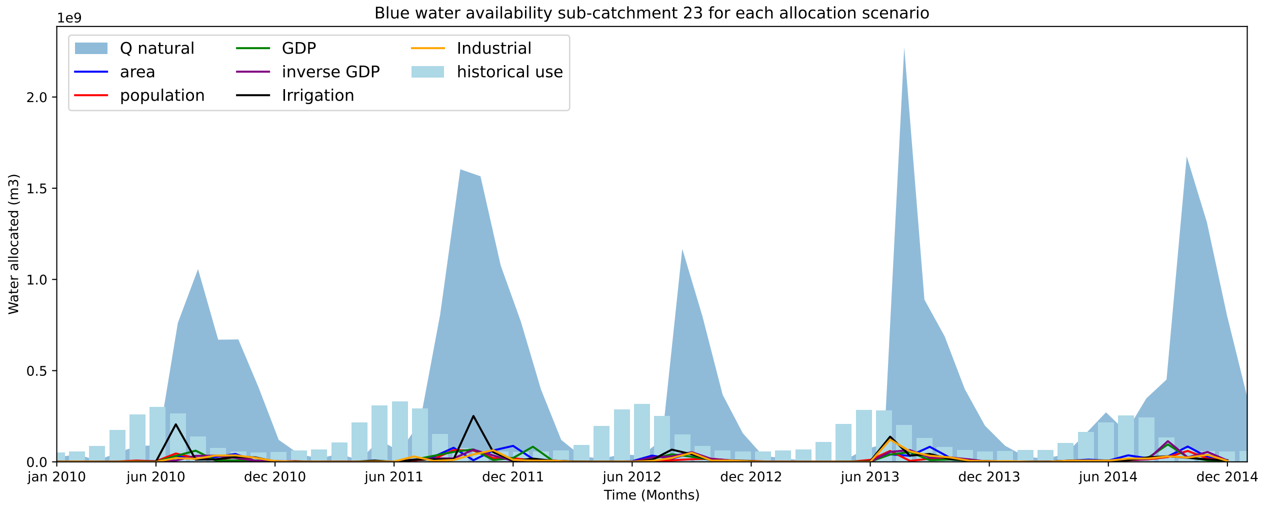


Figure 4: The blue water availability in sub-catchment 23 for each allocation scenario indicated by the lines, the light blue histogram indicates historic use, the dark blue shaded graph indicates historic natural flow, Albers et al. [2021].

Sub-Catchment 18

Sub-catchment 18 is a sub-catchment with a large population and high GDP and industrial demands. Topping all these metrics for each Allocation strategy compared to the other sub-catchments in the YRB. This results in a distribution which reflects these characteristics. Because of these characteristics the allocation scenario will allocate large amounts of water to the sub-catchment, which can be observed in Figure 5. Although the observation of this trend does not satisfy all the allocations which are observed. The Allocation strategy for the inverse GDP should result in an allocation which should be on the lower end of the scale in most cases, for the GDP component is large. Although this can be observed in specific months where there is some form of interaction where the GDP allocation is large inverse GDP is low. However when comparing the water availability between sub-catchments the amount of water which is made available in sub-catchment 18 is relatively large, Figures 2 - 4. The obvious explanation is the maximisation of water usage within the model itself. The trade off between optimising for Fairness and water usage is explained in Section 4.6 .

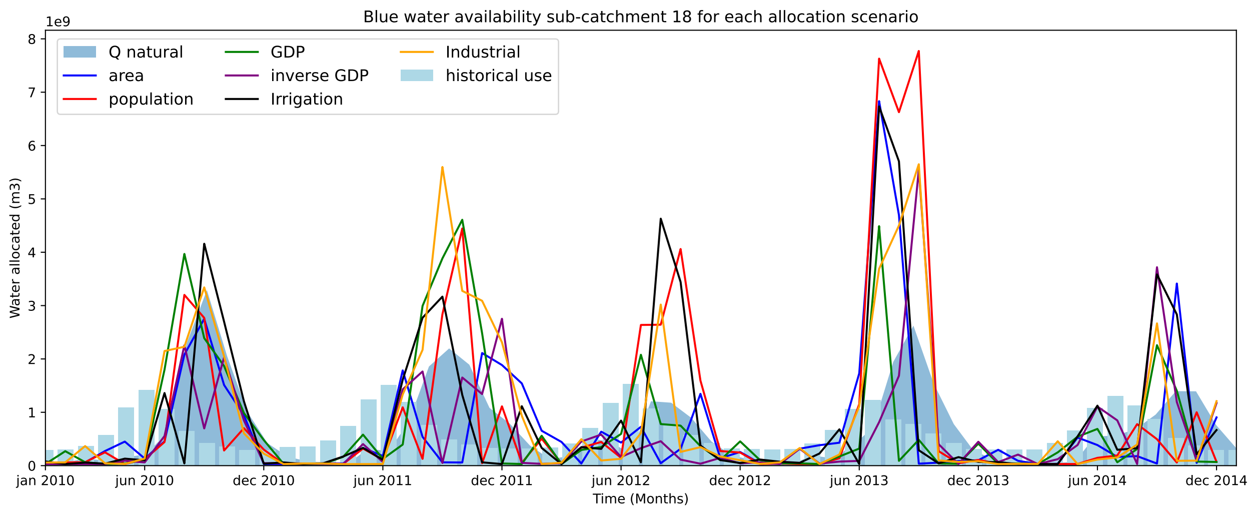


Figure 5: The blue water availability in sub-catchment 18 for each allocation scenario indicated by the lines, the light blue histogram indicates historic use, the dark blue shaded graph indicates historic natural flow, Albers et al. [2021].

4.2 Allocation strategies in space

The allocations shown in Figures 2 - 5 show the changes in time for a specific sub-catchment. These changes in time offered insight into the distribution changes as a result of water availability. However the distributions in space show the difference between the sub-catchments in greater detail. The distributions in space give insight in the impact of reservoirs, catchments located on side-streams on the blue water availability. The spatial distribution is shown in Figures 6 - 9 These spatial distributions show the change in distributions over a year, but a general pattern emerges. Sub-catchments located in the side-streams of the YRB show a severe lack of water which gets distributed compared to the main stream of the river, while the historic water usage is significant in these sub-catchments. The spatial comparison shows a select few months within the observation period, months which are scrutinized are months in the wet season and dry season, to determine the ability of the algorithm for a fair distribution in both cases.

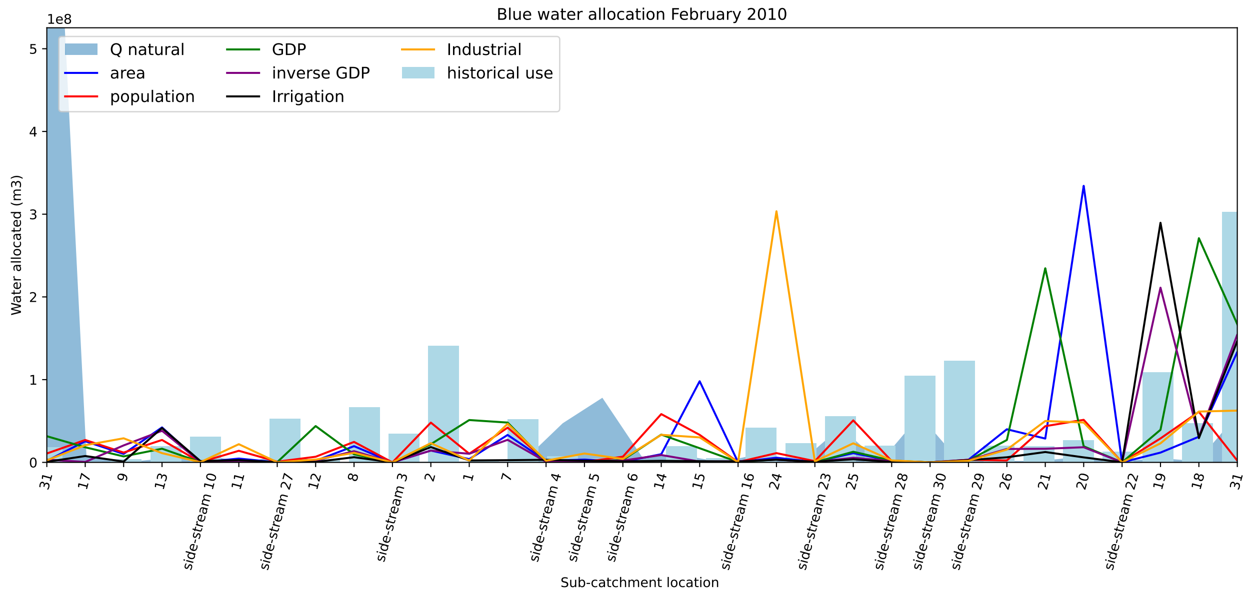


Figure 6: Blue water availability in each sub-catchment for all allocation strategies in February 2010, the histogram indicates historic use in the sub-catchment, the dark blue shaded graph indicates historic natural flow, Albers et al. [2021].

Figure 6 shows the water distribution in the dry period of the year, the month February of the first simulation year 2010. Firstly the amount of water which is allocated is small, while in most cases the amount of water ranges from $0.2 * 10^9$ to $4.5 * 10^9 m^3$ the amount of water allocated is smaller. The main reason is the lower amount of water available: the natural flow is almost non-existent in most sub-catchments, resulting in a low distribution. Secondly the previously mentioned lack of side-stream allocation also shows in this Figure, with an exception for side-stream 5. In this sub-catchment water available in the sub-catchment is allocated to the sub-catchment in the same manner water is allocated in sub-catchment along the main stream. This particular exception to the observed behaviour could be due to sufficient water availability.

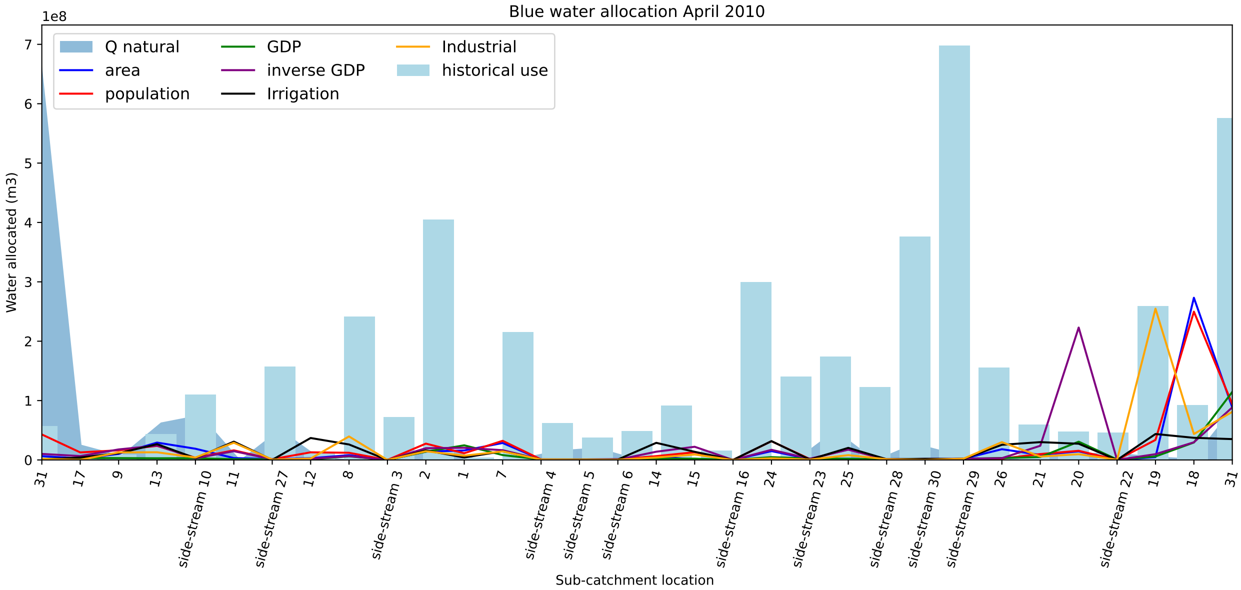


Figure 7: Blue water availability in each sub-catchment for all allocation strategies in April 2010, the histogram indicates historic use in the sub-catchment, the dark blue shaded graph indicates historic natural flow, Albers et al. [2021].

The mismatch between the demand for water and the availability is a clear definition in Figure 7. The amount of water which can be allocated is small still and the water demand is large. What can be allocated is allocated to the sub-catchments which are selected by the algorithm for creation of the largest equity. And while the selected sub-catchments skews towards the most downstream sub-catchments, the historical water demand is low here. The under-prioritisation of the side-streams is also prevalent in this scenario, even when in most cases there is some locally available water it will be allocated towards the downstream catchments of the mainstream.

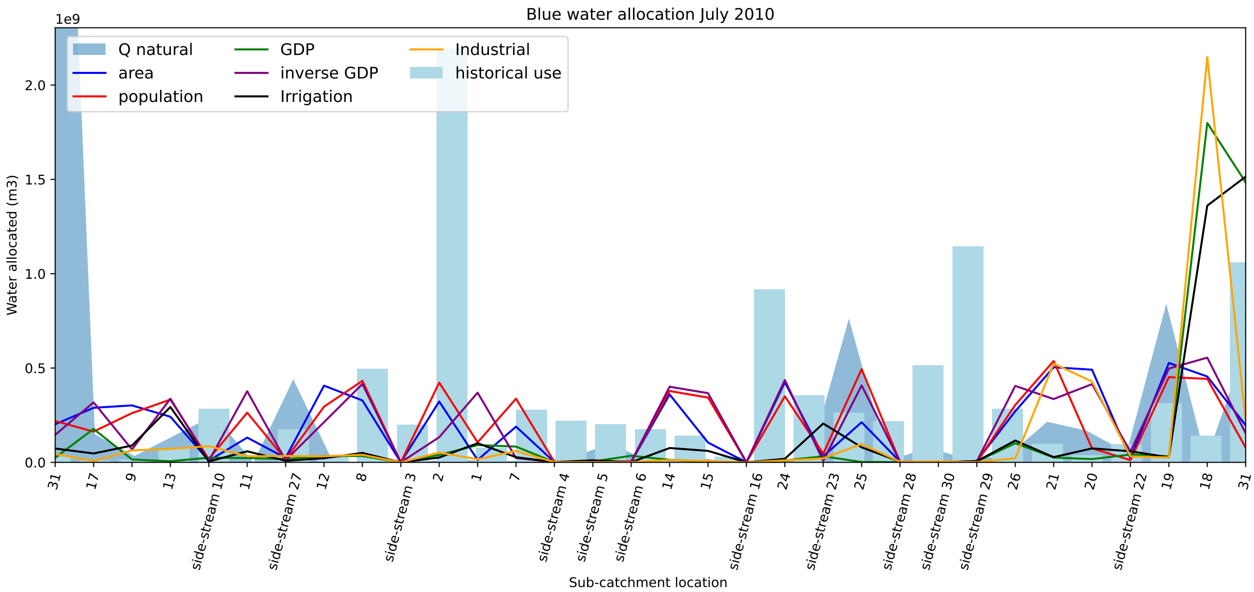


Figure 8: Blue water availability in each sub-catchment for all allocation strategies in July 2010, the histogram indicates historic use in the sub-catchment, the dark blue shaded graph indicates historic natural flow, Albers et al. [2021].

Figure 8 shows some differentiation between the allocation strategies. The allocation strategies prioritising the larger sub-catchments downstream still exist, however in most cases the distribution evenly spreads the water over all sub-catchments located on the main stream of the river. What is mainly of interest is that this particular distribution does not occur often, the predominant distribution as a result of the algorithm is one with solitary peaks and overall close distributions. When looking at the month of July over the years this particular distribution does not occur more than once. Which could indicate an anomaly within the modelling process. The side-streams in the situation behave as expected with the model with a noticeable under-allocation.

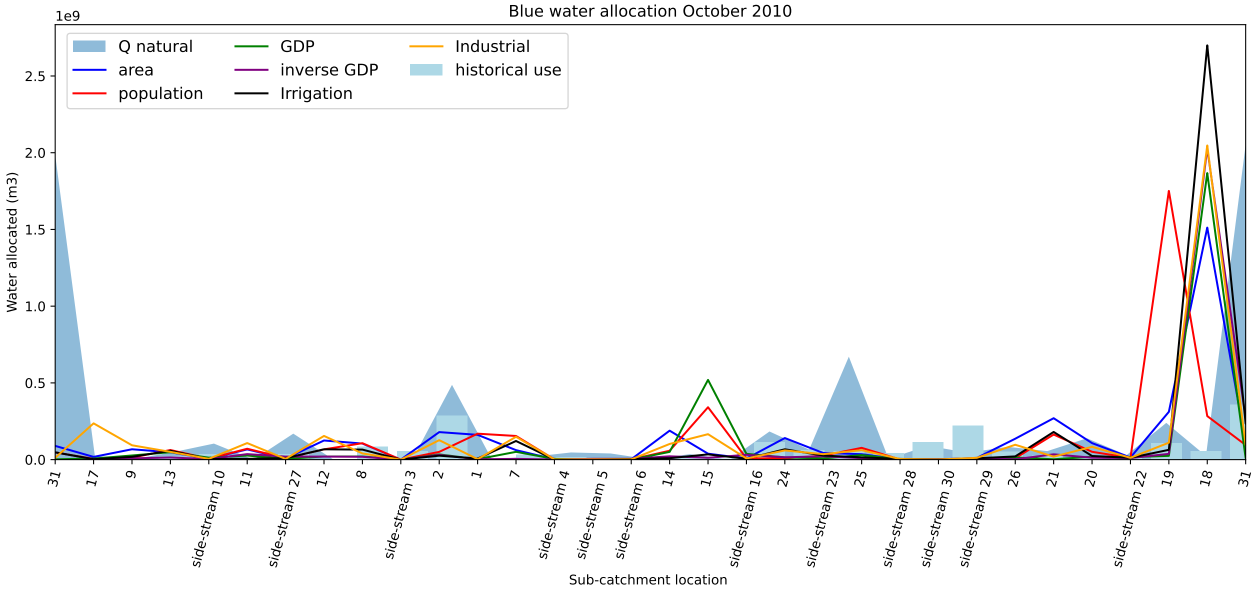


Figure 9: Blue water availability in each sub-catchment for all allocation strategies in October 2010, the histogram indicates historic use in the sub-catchment, the dark blue shaded graph indicates historic natural flow, Albers et al. [2021].

The month October shows the dominant distribution of water to the downstream sub-catchments, Figure 9. Furthermore it shows the increasing water availability for the sub-catchments, when compared with the dry season depicted in Figure 6, 7. The main takeaway from this particular distribution is the historical water usage which is almost non-existent in this case, so the blue water scarcity which occurred during the dry season does not occur in this case. The appendix shows the changes in allocation throughout the years in Figures 22 - 25. The changes over the years give an indication for the differences between a wet and a dry year. For the year 2012 the amount of water which can be distributed is lower as a result the available blue water is distributed more evenly over the sub-catchments in the main stream of the YRB. In years with a large blue water availability, the year 2014, the allocation severely skews towards the lower parts of the basin. all distributions favour this particular interpretation, while one would expect some significant variation between the GDP and the inverse GDP allocation strategies.

4.3 Performance indicator

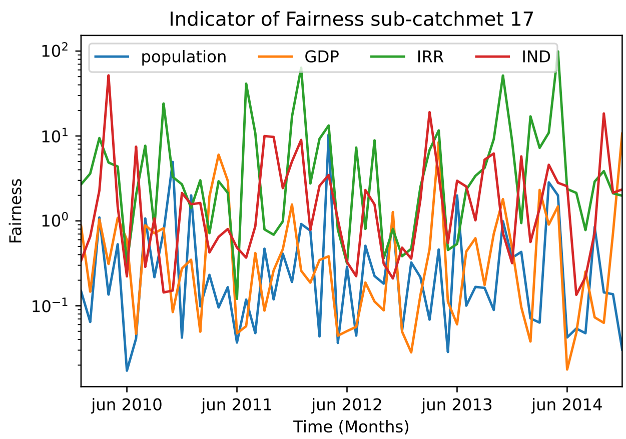
The performance of implementation is an indicator for the ability of the algorithm to incorporate equity based on the Allocation strategy. Specifically it determines how well the fairness coupled to each Allocation strategy is achieved. A good implementation of fairness in the model is the best possible scenario in regards to a fair distribution, which directly overlaps with the Allocation strategy. This indicator results in a general performance for every Allocation strategy which is observed in Table 4. The performance indicator is determined using Equation 4.

The main takeaway from this table is the fact that the range of the values is the same for almost all allocation strategies. Thus, the wide range of values may not indicate a well implemented Allocation strategy. However, the fact that all allocation strategies show the same behaviour does show the implementation of the allocation strategies is similar. Thus, a comparison between the allocation strategies is valid. The large range in performance, where the best performance of the model would result in a value close to one, does indicate the model have a strong tendency for deviation. A value close to one is an indicator that the blue water allocation of the model is in correspondence with the intended equity. As indicated by the table the values for the 25th and 50th percentile are in proximity to the ideal equity indicator. But the deviation this represents, Equation 4, is still significant. The 50th percentile of the blue water availability is three times as large as the ideal Fairness. In figure 10 the individual Fairness is schematized for the Representative sub-catchments. The main deviations will be as a result of the physical limitations such as side-streams or general water availability.

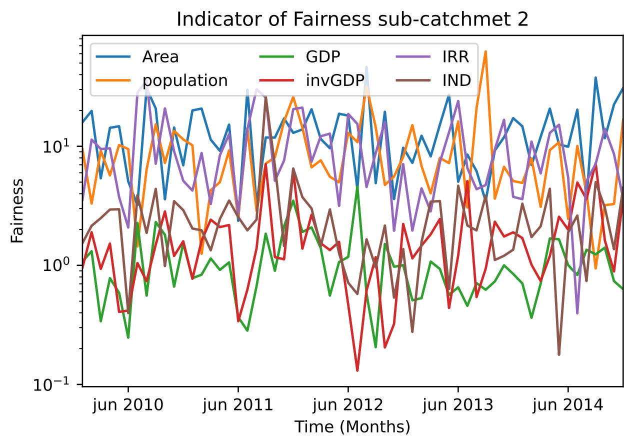
Performance indicator scores for the BWA						
Scenario	area	population	GDP	invGDP	IRR	IND
Mean	1947	1460	2120	1568	1702	3009
std	2.2E4	1.8E4	4.8E4	2.3E4	1.5E4	6.6E4
25%	1.03	0.87	1.00	0.71	1.53	1.72
50%	5.4	4.62	4.65	3.62	5.83	6.86
75%	34.6	24.18	29.74	25.44	34.82	37.56
min	0.001	0.001	0.017	0.003	0.024	0.037
max	6.3E5	5.6E5	1.9E6	8.6E5	4.2E4	2.8E6

Table 4: Performance indicators for each allocation scenario in time for the BWA, showing the ability of the algorithm to translate the allocation strategies into an equitable distribution.

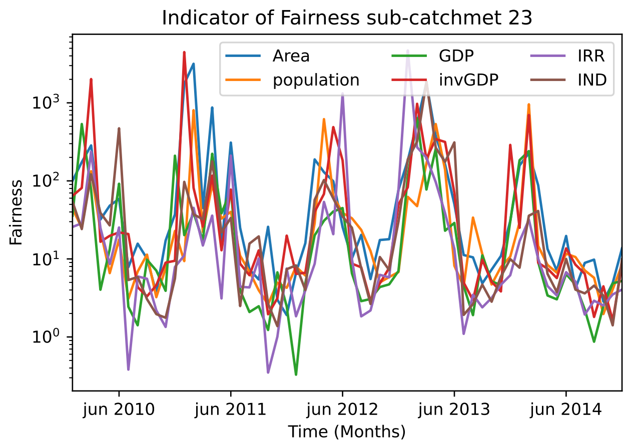
The fairness observed in Figure 10 shows a clear distinction between the sub-catchments. In general the sub-catchments which are located along the mainstream of the Yellow river are better performing than those the sub-catchments representing the side-streams. The main argument for the better performance is the water availability over time, which is higher in the mainstream of the river. This is particularly egregious for sub-catchment 23 which shows a large discrepancy with the achieved distribution and the original distribution. The differences with the original distribution are the largest in the time period just before the start of the wet-season. Which can indicate that in times of low water availability, Figure 4, the model is not able to implement the fairness in these side-streams.



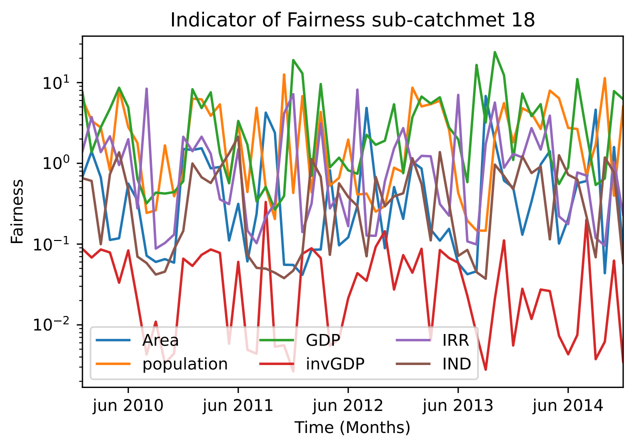
(a) Sub-Catchment 17



(b) Sub-Catchment 2



(c) Sub-Catchment 23



(d) Sub-Catchment 18

Figure 10: Distribution of Fairness for each Allocation strategy in time. The lines represent the ability of each Allocation strategy to implement Fairness according to each ethical principle.

The same phenomenon is also observed in Figures 10a,10b and 10d, although to a lesser extent. The largest discrepancies seem to occur in the time period just before the start of the wet-season. The main explanation for this is the lack of inter-connectivity in the model between the months. The only inter-connectivity that exists is the reservoir component, but this inter-connectivity is indirect. Figure 10a does not show all allocation strategies, for in this particular case certain allocation strategies do not converge into a fairness principle and show the same behaviour as observed in Figure 10c. This behaviour can be observed in Figure 26 in the Appendix, chapter 6. However the algorithm did achieve fairness for most allocation strategies in contrast to the observations in Figure 10c. For some allocation strategies the solution proposed by the algorithm is inadequate as observed by the large peaks. These large deviations from the ideal fairness show the limits in the allocation process. However, for other sub-catchments the fairness is within the margins, Figures 10b, 10d.

Secondly the model prefers certain allocation strategies for certain sub-catchments in regards to the fairness score. Figure 10b shows that the allocation strategies for the GDP and inverse GDP have a lower fairness score than the other allocation strategies. Thus showing that these allocation strategies are more suited for these sub-catchment than the other strategies. What is of interest that every sub-catchment has a different Allocation strategy with a fairness score close to the ideal fairness, industrial need and inverse GDP for sub-catchment 18 and GDP and population in case of sub-catchment 17. What also can be seen is that in the specific case of sub-catchment 17 the area and inverse GDP Allocation strategy do not suit this specific sub-catchments, Figure 26.

The fairness distribution in space continue showing the same phenomenon for all sub-catchments in the YRB. Side-streams have a low fairness score even when aerially averaging the results, further reinforcing the idea of side-streams and their dominant impact on fairness. One particular sub-catchments stands out in Figure 11. Sub-catchment 3, located in a particularly arid area within the basin, has a structural under-representation of the amount of water which is allocated. The underestimation for this particular sub-catchment persist over time, Figure 12a. Showing clear underestimation in the wet as-well as the dry season. The overestimation shown in Figure 11 shows that in most cases the water need can be fulfilled for this particular sub-catchment. Sub-catchment 11 is very small compared to the other sub-catchment and thus the specifc needs are met in most cases.

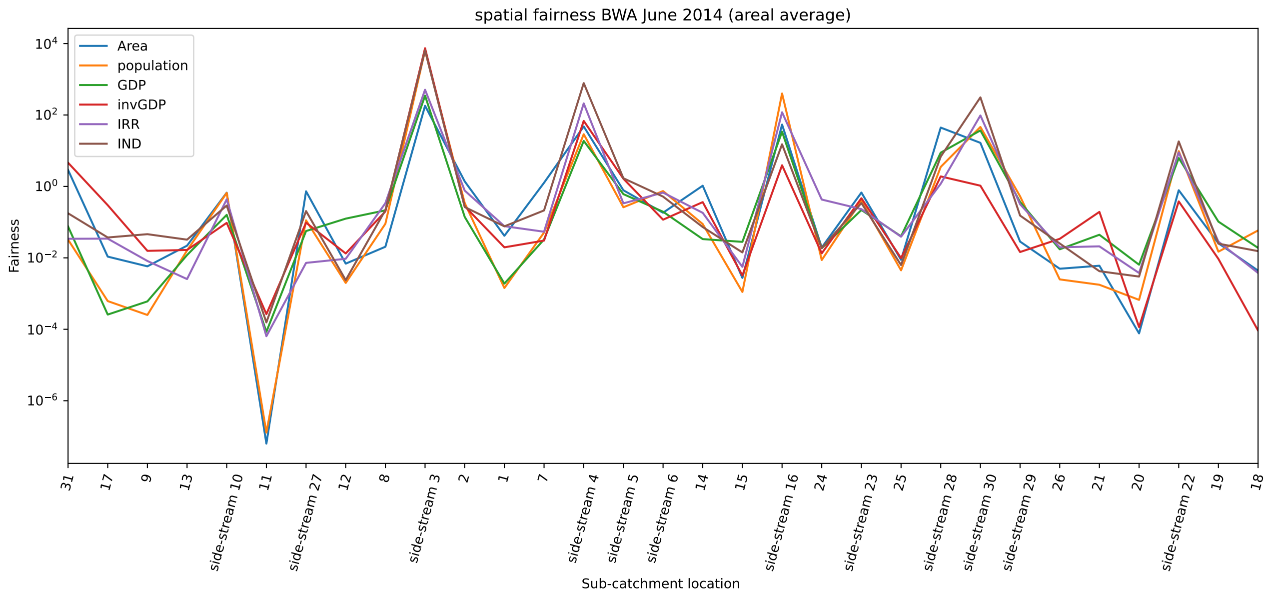
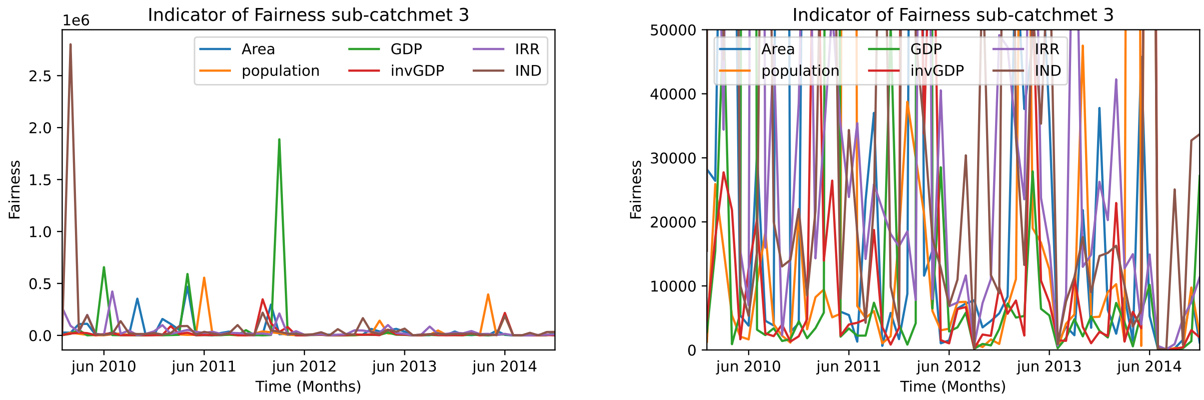


Figure 11: Spatial fairness of the blue water availability for the month June 2014, using a logarithmic scale. The lines represent the ability of each Allocation strategy to implement Fairness according to each ethical principle.

Fairness and implementation

Although sub-catchment 2 has a good fairness score compared to other sub-catchments. The implementation of this fairness has impact on the fairness of the overall feasibility of the system. The large water consumption in sub-catchment 2, Figure 3, is not represented in the fairness of the system. A System may be considered fair, as in a well implemented equity equation, but the usefulness of this fairness should also be considered. For this particular catchment the fairness of this equation results in a large shortage of water when comparing to historical usage. The fairness of a sub-catchment is dependent on the amount of allocated water of a sub-catchment in relation to the allocated water in other sub-catchments. The amount of unfairness observed in

Figure 12a shows that a fair distribution in current circumstances is hard to achieve. Although it could be that only certain distributions show large inequality the total inequality is still large for all allocation strategies in sub-catchment 3, Figure 12b.



(a) Sub-Catchment 3 (b) Sub-Catchment 3 in detail

Figure 12: Distribution of Fairness for side-stream sub-catchment 3. The lines represent the ability of each Allocation strategy to implement Fairness according to each ethical principle.

Table 5 shows the difference between the allocated water and the amount which should be allocated. This results in an interesting distribution which clearly shows the preference in distribution for sub-catchment located downstream along the main branch of the river. Furthermore it shows that certain sub-catchment located on the side-stream expect a level of water, sub-catchment 16, which would result in a fair distribution but would require significant amounts of water.

location	population	pop_ethic	stream
sub 31	1.359557	0.409313	main
sub 17	1.372810	0.090767	main
sub 9	1.784725	0.123659	main
sub 13	2.780745	1.493349	main
sub 10	0.242465	3.575548	side
sub 11	1.450075	0.003591	main
sub 27	0.518073	1.781546	side
sub 12	1.740746	2.228387	main
sub 8	1.923895	3.683972	main
sub 3	0.004447	2.168577	side
sub 2	2.541574	8.255844	main
sub 1	1.858884	0.408970	main
sub 7	3.203837	3.966008	main
sub 4	0.108191	0.669050	side
sub 5	0.223058	0.637648	side
sub 6	0.223423	0.723348	side
⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮
sub 14	1.997809	1.816110	main
sub 15	2.048900	0.828792	main
sub 16	0.409634	11.367203	side
sub 24	3.203086	3.091525	main
sub 23	0.422540	1.911321	side
sub 25	2.892068	2.382015	main
sub 28	0.514283	5.127225	side
sub 30	0.426690	16.240839	side
sub 29	0.572853	2.804624	side
sub 26	2.586178	1.638232	main
sub 21	5.085281	1.099539	main
sub 20	8.455936	1.101522	main
sub 22	0.260791	6.336334	side
sub 19	13.572521	3.315752	main
sub 18	36.214924	10.719389	main

Table 5: The share of water which is allocated to the sub-catchment and the share of water which should be allocated to the sub-catchment for the Allocation strategy based on population

4.4 Reservoirs

The reservoirs included in the study have been described in 3.1, the Sanmenxia reservoir is of interest due to its use pattern. High sediment loads within the YRB upstream from the Sanmenxia reservoir has halted regular operation of this reservoir and changed the predominant goal to sediment flushing. The effect of changing this goal is observed in Figure 13. The Sanmenxia is the second largest reservoir, Table 2, within the basin the effects of the reservoir on the YRB would be significant. However this reservoir has been included in the modelling process due to the potential impact of the reservoir on the distributions.

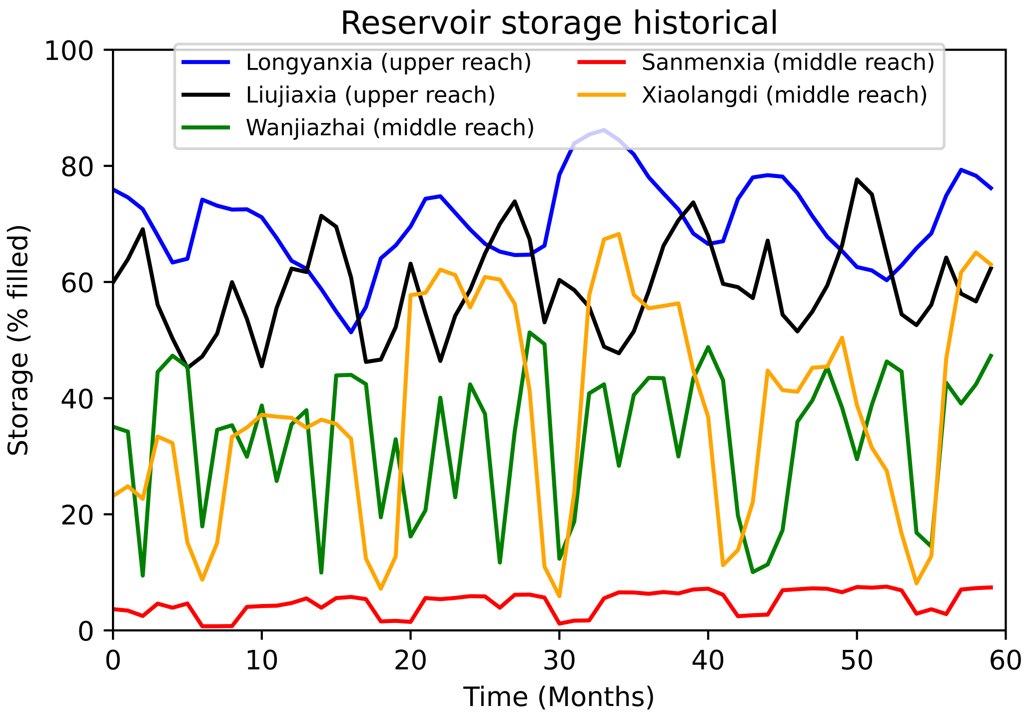
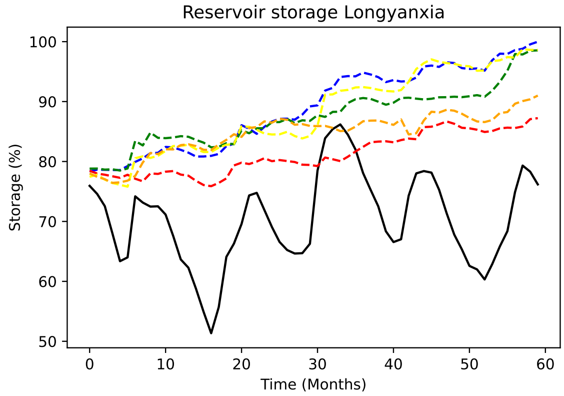


Figure 13: Historical reservoir usage for the 5 main reservoirs in the YRB

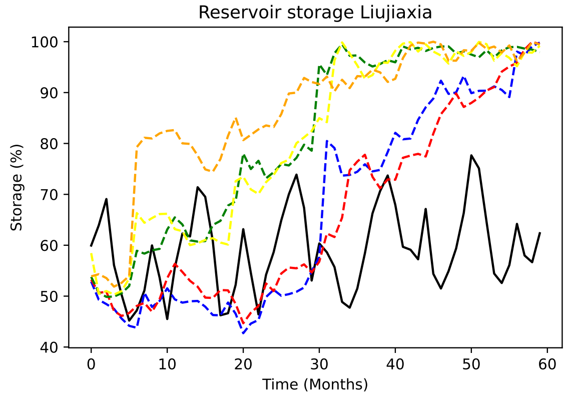
Figure 13 shows the historical reservoir fluxes. The fluctuations in storage percentages roughly align with the seasons. For the time period of investigating is five years, five wet and five dry periods are observed in the data. The Liujiaxia reservoir does have some peaks in the reservoir operation which are not aligned with the operation of Longyanxia. These differences in operation can be explained by the proximity of the two reservoirs, best schematized in Figure 1, due to the close proximity the storage of the Longyanxia reservoir acts as a buffer for the Liujiaxia reservoir. Thus, water which is needed for irrigation can be subtracted from the Longyanxia reservoir and flow to the Liujiaxia reservoir. The main seasonal fluctuations are observed in the larger reservoirs in the basin. This being the Longyanxia and the Xiaolangdi reservoir, where the latter reservoir also shows some inter-annual fluctuations. These reservoirs have both a storage capacity larger than 10 billion m^3. The smaller reservoirs, Liujiaxia and Wanjizhai don't observe these seasonal patterns as much for their size is smaller and can thus be kept at a more stable level throughout the year.

The comparison between the Historical and the observed model Fluxes is schematized in Figure 14. For all reservoirs the same trend can be observed, the increasing amount of water stored in the reservoir. These observed water changes do not follow the regular expected patterns compared to the historical water storage fluxes. The main understanding of this phenomenon is: Large amounts of water is allocated to entering the reservoirs, and less water from the reservoir is allocated to sub-catchments further downstream. There can be several explanations for this particular behaviour. The genetic algorithm prioritises water usage and fairness, allocating water to reservoir increases water usage and does not decrease fairness thus achieving both objectives in the objective function. A second explanation is an oversight in the distributive component of the model, the water reserved in the reservoir for further use during the dry season or a dry period is not used in allocation. Although the algorithm could allocate this water to the sub-catchments downstream it is not used in the maximum available water for distribution.

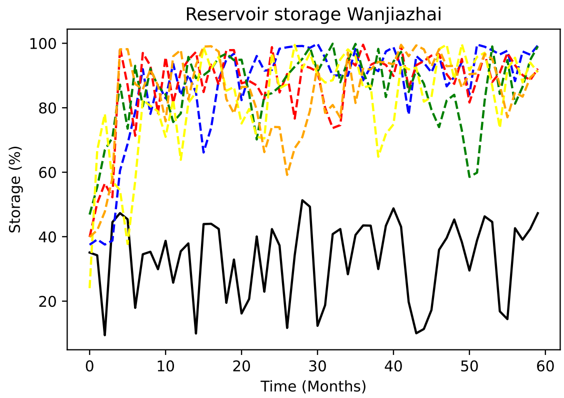
The impact of the algorithm operation procedure on the model is significant and has several consequences.



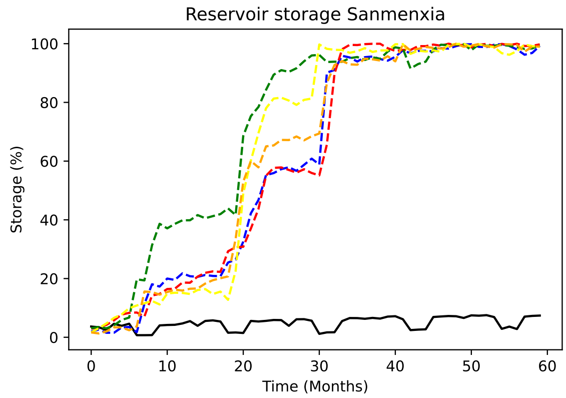
(a) Longyanxia reservoir



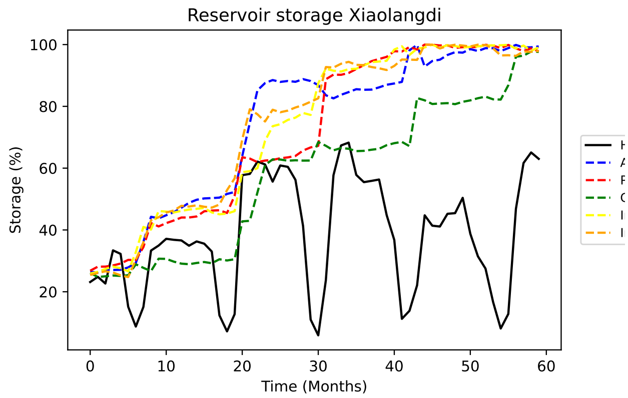
(b) Liujiaxia reservoir



(c) wanjiazhai reservoir



(d) Sanmenxia



(e) Xiaolangdi

Figure 14: Water levels in the 5 main reservoirs in the YRB as a result of the allocation scenarios

Firstly the severe lack of seasonal fluctuations in reservoir levels. The effect of the lack of seasonal fluctuations is multitude, the primary is the water use in the reservoir. The reservoir should be used for water storage so a dry period can be mitigated by releasing the water stored in the reservoirs, apart from the Wanjizhai reservoir this is not the case. Additionally the impact of reservoir to mitigate floods and other disturbances in the flow is lessened. A second consequence is the effect on model behaviour, especially when looking at Figure 14c. When the reservoir is filled, which happens quickly because of the small size, fluctuations do seem to occur. This could indicate that a certain warm-up period is needed before reservoir operation in the model can function. A counterargument is the lack of seasonality observed in Figure 14d as soon as the storage capacity plateaus. However the lack of fluctuations after 40 months in Figure 14d could also be explained by the Xiaolangdi reservoir which is located directly downstream from the Sanmenxia reservoir.

4.5 BWF-cap and Fairness in the BWF-cap

The Blue Water Footprint Caps are created by taking the 25th percentile of the allocated blue water. Thus, the patterns observed for the blue water allocation will cascade into the Blue Water Footprint cap. Which also results in that annually specific peaks in the allocated blue water are not allowed as actual usage, for then the usage would exceed the cap. The caps themselves are shown in Figures 15 - 19, these represent all the caps for the system. The historical water usage and natural flow through the river varies wildly per sub-catchment and can be observed in full in figures 2 - 5.

The fairness in BWF caps is an improvement on the fairness observed in the blue water allocation. The fairness values are closer to one, which is the optimal value, for the fairness which is created is than the most in line with the intended fairness. An improved fairness score is logical for the BWF-cap is determined based on the 25th percentile of the main blue water allocation strategies. The 25th percentile of the blue water allocation is not directly related to the 25th percentile of the equity performance of the BWA. For, the 25th percentile used for the BWA is on a yearly basis distributed over the sub-catchments while the equity performance indicator uses the sum off all sub-catchments. Table 6 shows the equity performance indicator for the BWF-Caps for all the sub-catchments.

Performance indicator scores for the BWF-Cap						
Scenario	area	population	GDP	invGDP	IRR	IND
Mean	203	291	101	156	358	269
std	1.3E3	3.5E3	625	1.0E3	2.3E3	1.4E3
25%	0.32	0.35	0.37	0.26	0.60	0.63
50%	1.43	1.18	1.45	0.89	1.48	2.04
75%	10.6	10.4	9.92	8.09	11.8	14.6
min	0.001	0.001	0.010	0.004	0.022	0.026
max	1.6E4	6.7E4	1.0E4	1.5E4	2.9E4	1.1E4

Table 6: Performance indicators for each allocation scenario in time for the BWF-Cap, showing the ability of the algorithm to translate the allocation strategies into an equitable distribution for the corresponding Equity Principle

The equity performance indicator for the BWF-Caps shows the same trends as for the BWA. There are some larger differences between the allocation strategies, meaning certain strategies have a better performance than other strategies. Overall sub-catchment observation the same pattern occurs, See Section 6.2 for Figures of blue water availability in space. The sub-catchments located on the main stream have a better fairness score than the sub-catchments on the side-streams.

The BWF-Caps for Sub-catchment 17, Figure 15, have a double peak for the GDP, irrigation and inverse GDP Allocation strategy. The double peak could be because of the reservoir located directly upstream from the sub-catchment which allows for water access outside of the wet season. The industrial scenario shows a distribution which is gradual over the year. However this scenario allocates the water later in the wet-season which could be an argument against its use fullness.

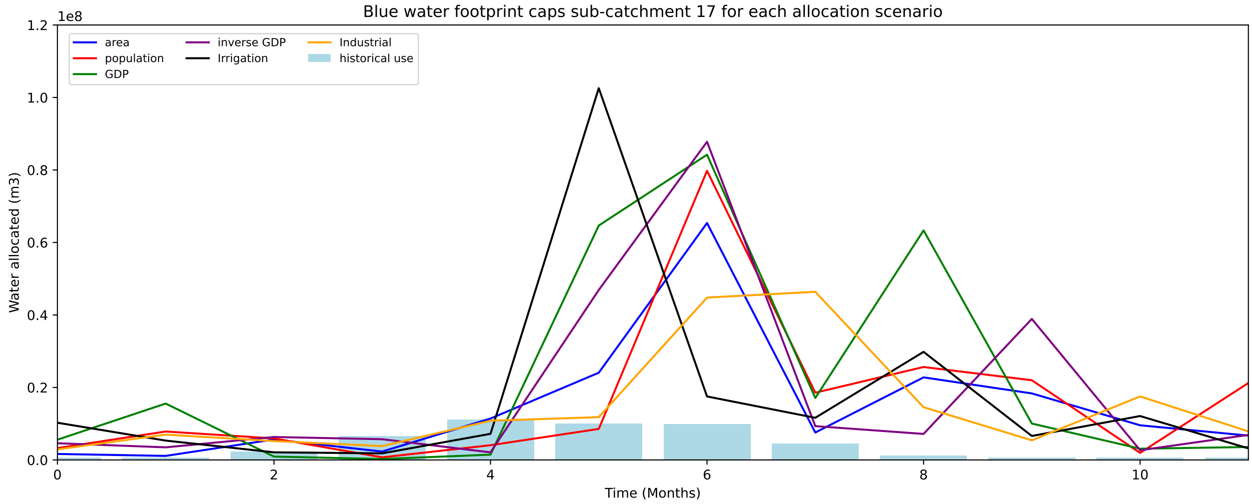


Figure 15: Blue water footprint caps for each Allocation strategy for sub-catchment 17, the histogram indicates historical water usage in the sub-catchment, Albers et al. [2021].

Sub-catchment 2 has a historic water demand which is much larger than the proposed cap, Figure 16. Showing the severe underperformance of the model to accommodate for this consumptive pattern. The double BWF-cap peak for sub-catchment 17 is not present, further reinforcing these are the result of the reservoirs. Furthermore the location of the peaks is spread out over the wet period for the allocation strategies.

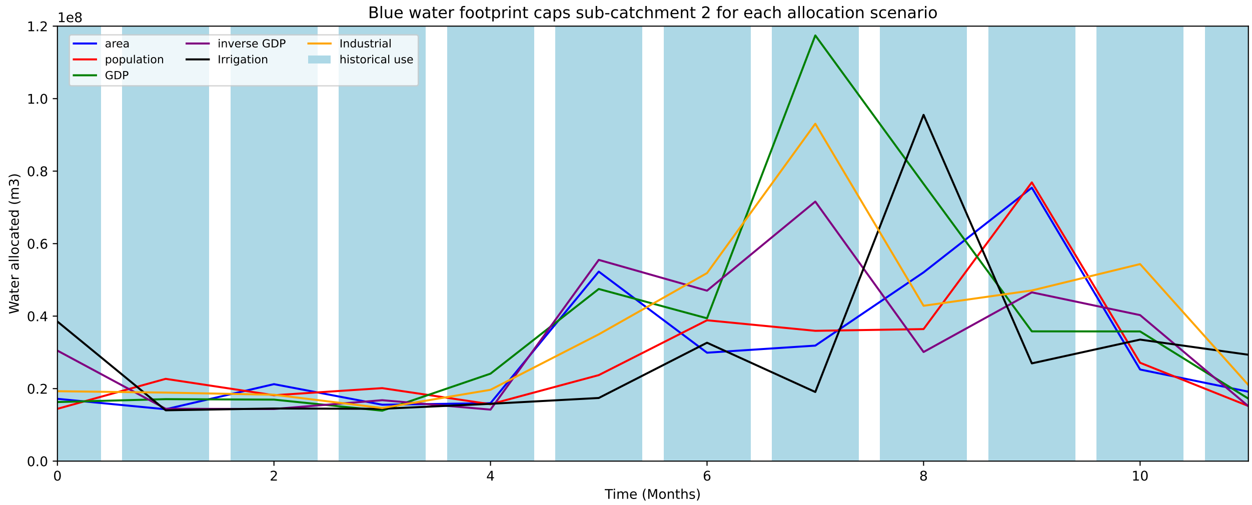


Figure 16: Blue water footprint caps for each Allocation strategy for sub-catchment 2, the histogram indicates historical water usage in the sub-catchment, Albers et al. [2021].

Sub-catchment 23 is a side stream of the main river the allocation shows a water distribution which attributes low amounts of water. The amount of water which is allocated to the system seems to be inadequate to fulfill demand, when comparing Figure 4 with 18. This is further complicated by the population in the sub-catchment. One should expect more water to be allocated to the sub-catchment because there is water available for distribution, Figure 4. Coincidentally the equity performance scores for this sub-catchment are low, Figure 17. A low equity performance could have two reasons, the first is an underestimation of the amount of water allocated to the sub-catchment, the second is an overestimation of the amount of water allocated. The overestimation in the first months of the year would indicate more water should be allocated to the

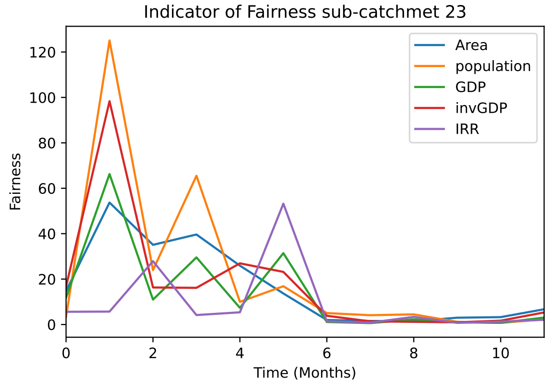


Figure 17: Fairness BWF-cap sub-catchment 23

sub-catchment, but this overestimation is not present in the latter part of the year. Thus, the equity indicator does not explain the lack of water allocated to the sub-catchment. This becomes especially egregious when comparing with sub-catchment 17, where more water is allocated to the sub-catchment while having a lower population.

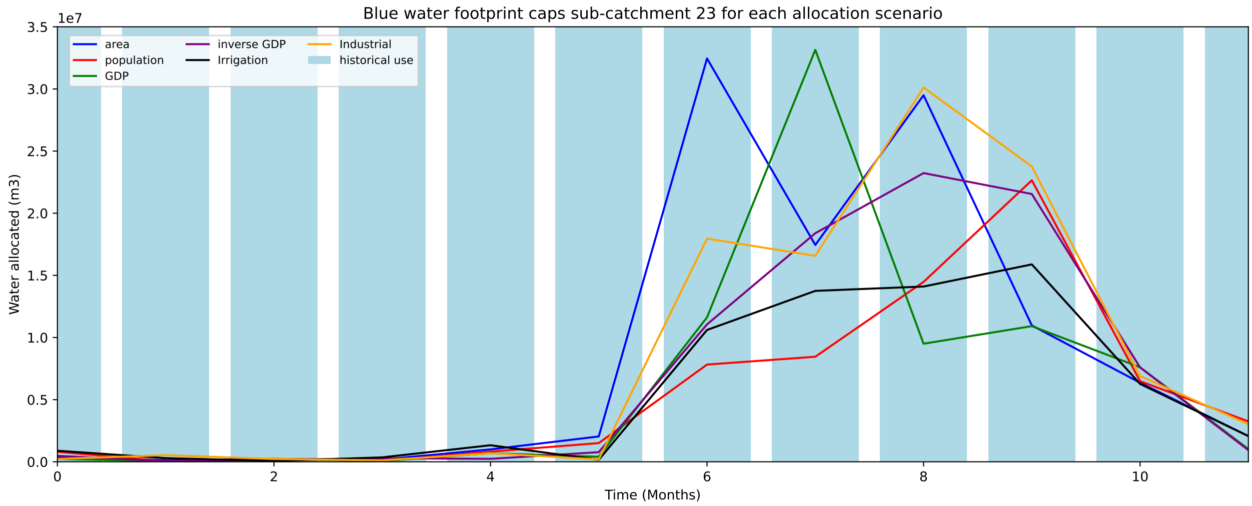


Figure 18: Blue water footprint caps for each Allocation strategy for sub-catchment 23, the histogram indicates historical water usage in the sub-catchment, Albers et al. [2021].

The BWF-cap for sub-catchment 18, Figure 19, shows the effect of the allocation strategies to its largest extent. The allocation of the industrial, population and irrigation have the largest allocations, while the area and inverse GDP are almost non-existent. This is inline with the characteristics of the sub-catchments, where the area is relatively small, Figure 1 Appendix ... . The mismatch between the demand and the allocation can be attributed to the timing of the natural flow, for this is most downstream catchment the wet season occurs later and the allocation will attribute later. The exception of this is the industrial Allocation strategy which does allocate water early in the wet season. However this can again be explained by the large industrial water demand in the area compared to other areas.

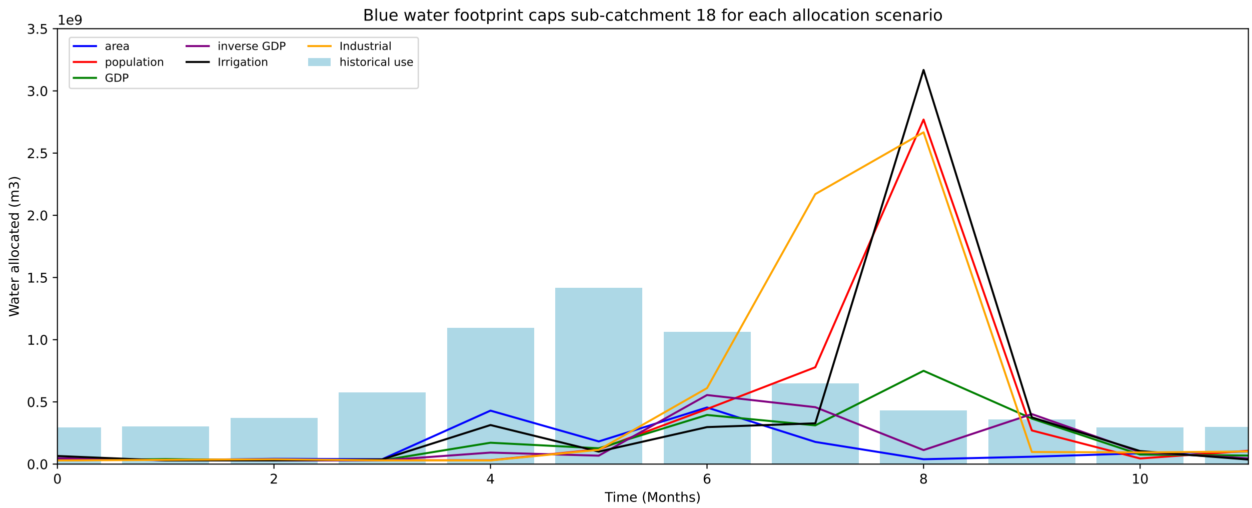
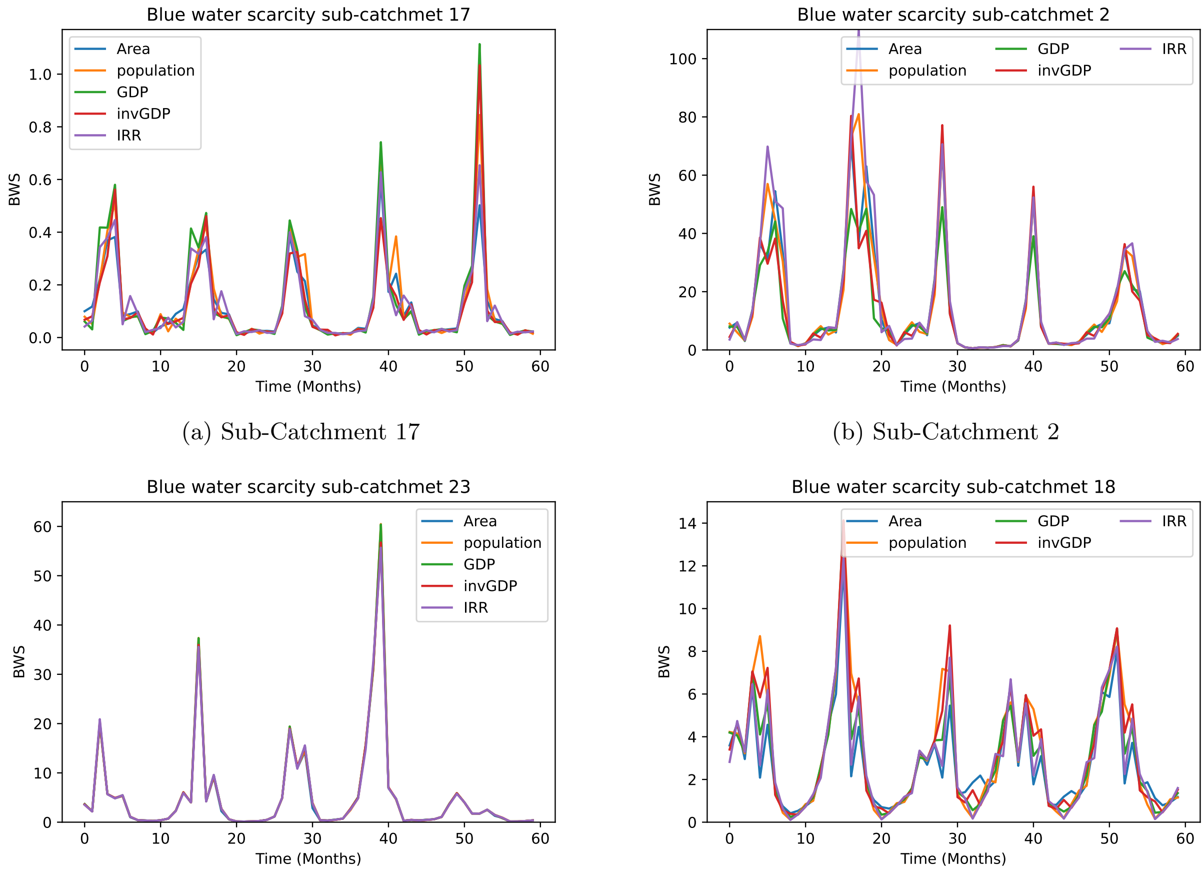


Figure 19: Blue water footprint caps for each Allocation strategy for sub-catchment 18, the histogram indicates historical water usage in the sub-catchment, Albers et al. [2021].

4.6 Trade-off between BWF-caps

The BWF-caps for each sub-catchment is evaluated using the blue water scarcity. The blue water scarcity is the metric for change in consumption patterns to accommodate the water distribution as a result of the Allocation strategy. The general observation is the blue water scarcity metric follows the same pattern as observed during the evaluation of the Fairness indicator. The largest blue water scarcity occurs in the months prior to the wet season, when water need is high and water availability is low. The Blue water scarcity for sub-catchment 17, Figure 20, shows the latter statement quite well. In the wet period from month July to December for this particular sub-catchment no water scarcity is observed. While during the dry season periods with water scarcity can occur.

A second phenomena which can be observed in Figures 20a to 20d is the spread of allocation scenarios. The minimal spread between allocation strategies seem to indicate that the influence of the individual allocation scenarios is relatively small when looking at blue water scarcity. Although in case of sub-catchment 2, Figure 20b there is a small differentiation between the allocation scenarios in the severity of distribution. This is predominantly apparent in the Irrigation water Demand (IRR). The large scarcity observed is in line with the fairness indicator, which also explains the low scarcity in the wet season. The environmental flow is an important part of the scarcity metric and for sub-catchment 2 the environmental flow is large and thus, is able to sustain a large part of deficit caused by a low BWF-cap. Which explains the lower scarcity values for the wet months.



(a) Sub-Catchment 17

(b) Sub-Catchment 2

(c) Sub-Catchment 23

(d) Sub-Catchment 18

Figure 20: Blue Water Scarcity (BWS) for each Allocation strategy over time for a specific sub-catchment.

The blue water scarcity for sub-catchment 23, Figure 20c, reflects the second principle very well. There is no differentiation between the strategies. The high water scarcity in the dry period is exactly in line with the fairness indicator showing consistency in both metrics. Furthermore the scarcity is low in the wet-months due to a large environmental flow. The large values for blue water scarcity can be explained by the under allocation which occurs in the dry months of the year. Sub-catchment 18, Figure 20d, shows the general pattern of larger scarcity in the dry season. But the pattern of having all allocation strategies resulting in roughly the same distributions is not as prevalent. Differences in allocation strategies occur in some form, where the Allocation strategy for the inverse GDP results in the largest scarcity. This aligns with the expectation that the sub-catchment which has a large GDP, population and Industrial Water Demand (IND) would have a larger deficit when explicitly undervaluing the sub-catchment. However the difference between the allocation strategies remains minimal, and the influence of the allocation strategies on the water distribution is low.

The areal weighted average blue water scarcity is shown in Table 7. The seasonal trend is quite clearly visible, furthermore the allocation strategies are consistent over the seasons. Showing the same trend observed in the BWA, BWF and their respective fairness.

There is a large difference between the reaches and the ability to fulfill or adept to reduce the water scarcity

Season	area	population	GDP	invGDP	IRR	IND
Spring	62.9	62.7	63.3	63.7	63.1	63.3
Summer	36.7	38.6	37.2	37.6	39.2	37.7
Autumn	6.7	6.7	6.7	6.9	6.7	6.9
Winter	17.1	17.0	17.0	16.8	17.0	17.1

Table 7: Areal average of the blue water scarcity

in a current scenario. The largest scarcities are observed in the upper reach of the YRB, Table 8. The lower scarcity in the middle and lower reach is also what is to be expected as a result of the distributions shown in Figures 6 - 9, where most water is allocated to the downstream sub-catchments. Secondly the differences in scarcity changes consistently over the year. The change between spring and summer between the upper- and middle reach is roughly the same. Showing a consistency within the allocations.

Season	reach	area	population	GDP	invGDP	IRR	IND
Spring	*upper reach*	70.3	69.3	70.2	72.1	71.2	69.0
	middle reach	57.2	58.0	58.2	57.1	56.9	59.5
	lower reach	4.4	6.4	5.4	5.9	4.8	6.3
Summer	*upper reach*	41.4	45.5	42.9	42.4	46.7	43.3
	middle reach	32.9	32.5	32.3	33.7	32.5	33.1
	lower reach	2.3	2.4	2.5	2.9	2.8	2.3
Autumn	*upper reach*	10.3	10.2	10.4	10.7	10.4	10.7
	middle reach	2.9	3.0	2.9	2.9	2.8	2.9
	lower reach	1.1	0.7	0.7	0.8	0.6	0.7
Winter	*upper reach*	20.0	20.0	19.9	19.7	19.5	19.9
	middle reach	14.5	14.3	14.3	14.2	14.7	14.6
	lower reach	3.2	3.1	3.2	3.3	3.2	3.3

Table 8: Areal average of the blue water scarcity for each reach

4.7 Water use and fairness

The trade-off between water use, practicality and fairness, where practicality is measured afterwards in the blue water scarcity. The main trade off in the model is satisfying the allocation strategies as well as possible on the one hand and allocating as much of the usable water as possible on the other. The trade off is represented in a multi-objective analysis which is performed with the model. The process of selecting the best solution is represented in Figure 21, showing the iterative process of the genetic algorithm using a Pareto front. For both objectives in the algorithm a value of zero is the optimal value showing a perfect distribution according to the Allocation strategy.

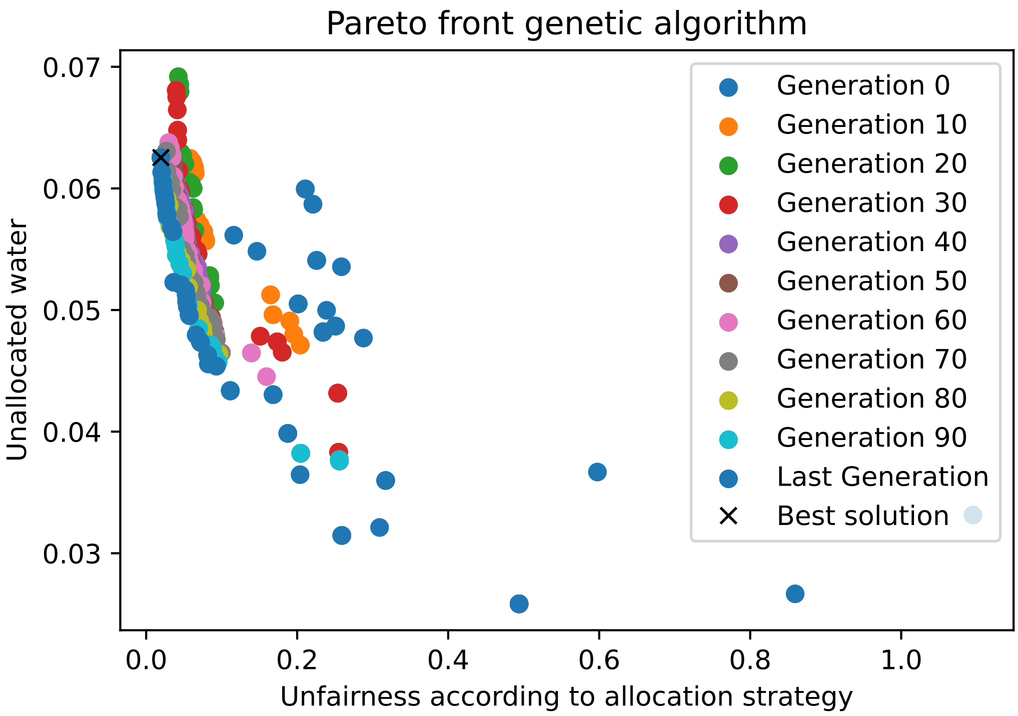


Figure 21: Pareto front for the inverse GDP Allocation strategy at the 60th month of the simulation period. The dots indicate the score over the generations of the algorithm, showing progression of results per simulation cycle.

The water allocation (the avoidance of unused water) has a better performance than the fairness allocation strategies for these values are lower. This can partly explain the absence of large differences between the allocation strategies. Which has been observed in the previous sections. The focus of the model to distribute as much of the water as possible over the sub-catchments overrides the ability to distribute the water according to the Allocation strategy. Although this is less surprising when looking at how both are achieved, a distribution of water based on the notion of using as much as is usable in a sustainable manner is not constrained in a physical sense. While the allocation strategies are constrained by physically impossible water distributions and achieving a fair distribution. The reciprocity between these objective functions heavily impacts the blue water availability of the system and limits the total achievable equity. However reservoirs can positively impact this reciprocity however this is currently not possible in the current model iteration

5 Discussion

The translation of ethical principles into allocation strategies resulted in several assumptions on how an ethical principle can be made operational. While an ethical principle often has qualitatively clear guidelines in quantitative operationalisation, succeeding in a translation has proven difficult. There is no clear way to evaluate if an ethical principle has been implemented successfully, mainly because of differences in what manner the ethical principle is to be achieved. As mentioned previously in the theory section the ethical principle can focus on equity in implementation, process or outcome. In testing for the implementation of the ethical principle in the model multiple of these focuses or even all are tested. It is good to test the ability of the model in this manner but purely from an ethical standpoint it can be sufficient for a focus on only implementation. If the start of the process was equitable than the outcome matters less for certain allocation strategies, even-though trade-offs may be present. Thus, for a standpoint of translating the principles implementation could be marked sufficient.

5.1 Assumptions and limitations

This study contains some limitations and assumptions in the process of setting BWF-caps for the Yellow river basin. The limitations of the study mainly originate from the modelling process and assumptions within this process. The primary impact of the modelling choices are the distributive component, implementation of time and the reservoirs. To start with the first the distribution component.

Allocation scenario data

The data used to create the allocation scenario is based on a yearly time scale or in some cases on a specific year in the simulation time. The yearly time scale in itself can be used to simulate where the water should go, however this does not indicate the time the water should be available. In particular the irrigation water need, the season when the water need is largest does not overlap or partially overlaps with the wet season. Having monthly data or data per unit of time the model simulates would alleviate this issue and result in a more accurate representation.

Distributive component

The distribute component of the model explained in Section 3.3 allocates the amount of water based on the water availability in the sub-catchment with the lowest availability. For the greatest fairness is achieved when every sub-catchment has their proportional amount of the share, no matter how large the total distribution is. Especially in side streams, Section 4, the amount of water which is available for allocation is low and thus lowering the amount of water which can be allocated for the entire river basin. This phenomenon occurs often within the simulation and thus a lot of the water which could be used is not used. As mentioned in Section 3.3 the second objective function alleviates this phenomenon by allocating water which is available for allocation directly to the sub-catchment, but this creates a trade-off between fairness and water use.

However this second objective function creates a Pareto front between the two objective functions creating a trade-off between creating equity and using all available water. Implementing equity being the focus of the study a reduction in equity due to the fulfillment of water usage could be considered inequitable in some cases. However in distributions based on utility, such as the GDP Allocation strategy or industrial use strategy using all available water has priority, even when it would reduce overall equity. For it creates the largest amount of utility when the available water is used versus when it its not used, although the efficiency of use would decrease resulting in a trade off between objective functions for the utility and GDP allocation strategies. The impact of the side-streams on the equitable water distribution of the water could be diminished by removing the side-streams from the equity distributions. The allocation of water in side-streams can only be increased by additional reservoirs or water transfer projects both of which are not included in this study. Thus the sub-catchment with the lowest water availability in combination with a large water allocation will always dictate the amount of water which can allocated and achieve equity. In the case of the YRB this will be a side-stream due to socio-economic characteristics of the basin.

Time implementation

The model simulates a period of 5 year with a total of 60 months. The monthly time scale is based on the assumption that the resulting BWF caps would be monthly caps for each sub-catchment within the YRB. The assumption was made to simulate each month separately for all the sub-catchments in the river in a chronological order. The monthly time scale also severely shortened run-time of the model compared to a daily timescale used by Albers et al. [2021]. The main impact of reducing run-time the impact of this measure was large. The main impact of this is the travel time of the water, while on a daily timescale travel-time is logical it becomes complicated on a monthly time scale. The travel-time of water is a certain amount of days within a sub-catchment and will then have flown to a downstream sub-catchment. However on a monthly time-scale the travel time between sub-catchments starts to crossover between time steps, and within time-steps. This complicates the calculation for the water availability especially in the case of water which originates from a reservoir. This is a problem because of the manner in which the water availability calculation processes time.

Each time step is simulated separately. By modelling each time step separately the genetic algorithm optimises a small set of variables with a set amount of possible solutions which results in a shortened simulation time compared to simulating everything all at once. However this has impact on the amount of water which can be distributed due to travel-time of the water. Water which is available upstream, and could be assigned downstream in a sub-catchment which has a large water need based on the Allocation strategy, cannot receive this water for it would be assigned to the next month. However the model does not explicitly has a travel time of a month due to the water availability being based on daily time steps, implicitly the reservoir release can only be assigned to the sub-catchment directly downstream limiting this water availability to location (of the sub-catchment) rather than time. To be able to assign the water to the next month there has to be an interaction between the simulation cycles otherwise the amount of water assigned to the next simulation cycle is not based on the Allocation strategy. Creating an interaction between the simulation cycles can be determined by optimising in clusters of months, where every cluster can have interaction. Although yearly clusters of time-steps would be appealing creating a file which is large will significantly impact simulation time due to increasing solutions which have to be tested. A second consequence of simulating every time step separately is the creation of peaked caps for certain sub-catchments, for the water within the time-step has to be assigned to a sub-catchment or a reservoir. Spreading out the cap will help fulfill water needs in months with a natural low water availability.

The monthly time-steps also reduce the impact of the reservoirs on water distribution. The impact of this is twofold. First the amount of water released from the reservoir has a certain travel-time to the downstream sub-catchment. Using a monthly implementation the release from the reservoir will only be able to assign water to the sub-catchment directly downstream from the reservoir. Secondly the monthly time-step does allow for some water allocation to the next month by being stored within the reservoir. But the amount stored within the reservoir, reserved for drier periods in time does not have any predetermination behind it. This lack of predetermination could be good for one does not know how much water will enter the reservoir and how much is needed due to unpredictable weather. However the creation of water footprint caps will be based on historical data and thus, having this uncertainty in the current usage of the model is superfluous. However, as previously mentioned the water reserved in the reservoir can only be assigned to the sub-catchment downstream.

Reservoir implementation
The implementation of the reservoirs in the model, while being a main goal of the study to determine their effects has been implemented sub-optimally into the model. While water can enter and leave the reservoir the amount of water within the reservoir is not taken into account in the distribution algorithm. The $\sum X_{i,m}$ component in Equation 1 does not include the water available in the reservoir, only the water from the run-off. This means when allocating the water over the sub-catchment water reserved in the reservoir will not be available for distribution when determining which sub-catchments will be allocated what amount. Having a certain amount of water in the reservoir unavailable for allocation dependent on the month or use case could help reserve in the reservoir for future use. Thus, while the water in the reservoir could be used to fulfill the amount of water which should be allocated to the sub-catchment the algorithm will not use the water for it has not taken it into account.

A second limitation of the reservoir implementation is the implementation of only five large reservoirs within the YRB. There are many reservoirs within the YRB although most are small there are 29 large reservoirs which significantly could impact water availability for the sub-catchments in the side-streams during the dry season. This is also in line with the work of Albers et al. [2021] where an underestimation of the available water took place in the side-streams. Incorporating reservoirs in side-streams increases water availability over the year and thus could result in a better water distribution, see the performance indicator Section 4.3.

A third limitation is that the reservoir is only used for water storage in the model. Reservoirs have multiple roles in water management and are also used for sediment flushing, ice control and flood prevention. All these factors have not been taken into account in modelling due to added complexity of the system. The primary goal of the Sanmenxia reservoir is sediment flushing and preventing floods from occurring. This functionality is beyond the scope of this study, but should be considered for the creation of equity in a river basin will also encompass these functionalities. This could be implemented by allocating only part of the release from the reservoir. Aforementioned functionalities enable that the equity which is created using the allocation strategies will last.

The lack of distinguishing characteristics in the overall statistics between the allocation strategies has an overall explanation. The distributive allocation component does not seem to sufficiently redistribute the available water thus, making each Allocation strategy dependent on locally available water. The amount of discernment which than can be achieved while also achieving fairness is small. However the small differentiation's which are observed for some sub-catchments indicate an ability of the system to adhere to the allocation strategies as a result of the ethical philosophies.

5.2 Environmental flow and water usage

The environmental flow requirements incorporated in the model are based on the variable flow method which changes the amount of water assigned to satisfy the EFR throughout the year. Reserving water for the EFR allows for sustainable water use within the basin. However the environmental flow which is guaranteed during this method does have important impact on the distribution. For the amount of water reserved for this flow is dependent on the natural flow at the moment and determining the natural flow for the catchment could result in inadequate distributions. An example is insufficient water for domestic usage, when does the need to satisfy the EFR supersede the right to water. In the current study the EFR is a constraint within the model it must be fulfilled, however in particular situation it could be implemented as a weighted objective function, offering greater flexibility in achieving fairness.

In this study the EFR has been incorporated in the allocation strategies, but in some cases incorporation could be deemed inequitable for it does not contribute to its version of equity. However the balance between human and ecological usage is not within the scope of this study. In general creating a sustainable situation as-in guaranteeing future use of the resource would be considered an equitable use this resonates in particular with the equity philosophy of maximising utility. Although this could also be challenged when taking this philosophy to its most extreme extent. The balance between the EFR and an equitable distribution is a recommendation for further study, especially on the theory side of this question. To a lesser extent the trade-off which has been created in the current situation, which prioritises water usage and thus avoids any unused water should warrant scrutiny regards the impact of this trade-off on the fairness.

Due to data availability and the scope of the study the sub-catchment distribution has been directly derived from Albers et al. [2021]. Although this sub-catchment division has been adequate in its current state for this particular iteration of the model it would be inadequate for further research. Due to large differences in size between sub-catchments the amount of water originating from the sub-catchment varies wildly as well as the need. Homogenizing the size of the sub-catchments especially in case of sub-catchment 11 which has a size a factor 100 smaller than most other sub-catchments should help optimise the algorithm. Furthermore the current layout of sub-catchment does not overlap with the administrative boundaries of the current system impacting the accuracy of the allocation scenarios.

Genetic Algorithm

Using optimisation to create a water distribution compared to the method used by Albers et al. [2021] creates a large flexibility in the modelling process. This flexibility offered pathways for increasing options in water distribution such as implementation of reservoirs and multiple objective functions. The choice for a genetic algorithm was ease of implementation, there are many packages in the DEAP framework Fortin et al. [2012] which can be used in solving optimisation problems. However this particular implementation of the DEAP framework has clear documentation and examples.

However the inclusion of aforementioned functions such as reservoirs and multi-objective functions adds complexity within a system where simplicity is key in creating an understanding of the model. Furthermore simulation times which are manageable at the moment will become an increasing hurdle when further developing the model and adding more parameters. Using a genetic algorithm for water distributions has a clear advantage compared to the model used by Albers et al. [2021]. The first and foremost reason is a distribution which can take water storage and transfer into account. Although both are not fully properly implemented in the current iteration of the model, including these factors should result in a better more usable outcome, although this could also be achieved using other methods. Furthermore this opens up possibilities for examining the impact of both on the a river system at large and the respective impact of these implementations on equity.

Green water

The green water availability, or the green water usage has not been taken into account in this study. However this principle is important regarding certain strategies, especially regarding irrigation and agricultural land-use scenarios. Green water is precipitation water stored in the unsaturated top layer of the soil used by agriculture, forestry and husbandry. The green water component, which can sustuate a part of the water demand of aforementioned sectors, is difficult to quantify. This is also in line with Albers et al. [2021] which excluded this component on the grounds of only impacting specific sectors of productivity and location of productivity. For these green water components cannot be utilized in areas unsuitable for agriculture, forestry or husbandry and are thus hard to quantify.

6 Conclusion

This study investigated the effect of implementing ethical principles in allocation strategies and determining the impact and differences between the allocation strategies. Rooting the distributions in ethical philosophy has created a better understanding in why it is important to use the metrics which create the allocation strategies. At the basis of all allocation strategies is an understanding of human nature and justice and why certain decisions such as maximising utility or favouring the underrepresented are justified. Furthermore it helps emphasize the impact of the allocation strategies. The impact of the allocation strategy is dependent on its manner of implementation and outcome which could drastically alter the ethical view on the fairness achieved. Although there was not a clear distinction between the different scenarios in the temporal allocation of water, differences in space where observed between the sub-catchments. The sub-catchments representing a side-stream have a large under-representation of the overall system, resulting in large scarcities throughout the year. A lack of water allocation to these side-streams is also reflected in the fairness indicator which shows large unfairness for these sub-catchments located on the side-streams. The overall under-representation of the side-streams can be explained by the overall lack of water availability in the side-streams and a relatively large population. This particular combination results in a permanent lack of water in a multitude of side-streams compared with the total water availability in the main stream. By reducing the unused water, and this water being allocated along the main stream, the unfairness is increased.

Interpreting the results from the model show two insights, the first insight regards model skills and shortcomings within the model, the second insight is in fairness and scarcity as a result of fairness. The current model simulates upstream / downstream water availability and temporal changes quite well. However the implementation of reservoirs into the model is inadequate to simulate the workings of the reservoir. The reservoir themselves do distribute some of the water over time, however a reduction in blue water scarcity is not observed in its current implementation. However the operating of the reservoirs is taken into account to some extent and sub-catchments directly downstream of the reservoir do receive water from the reservoirs, sub-catchments further downstream do not receive any water, while in reality water is demanded from upstream for these sub-catchments. Creating BWF-caps based on the blue water availability may increase the fairness of the system, but at a cost of decreasing the overall water used. The trade-off which is created between using the available water and implementing the fairness principles is larger in side-streams and can be quite detrimental in creation of a fair distribution. For the actual usage the current iteration of the model falls short.

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Appendix

6.1 Technical Model Description

The create a better understanding of the modeling process this sub-section will provide technical insight into the step by step process of determining the amount of blue water allocated to each sub-catchment. The first step in the process is the initialisation of the genetic algorithm. The first string of number is then tested for feasibility and in case the solution is infeasible the distance to a feasible solution is determined. Using this distance the algorithm adepts until a feasible solution is achieved.

The initialization of the model consist of creating a string of random numbers with a length equal to the amount of sub-catchments and the amount of reservoirs times two. For each sub-catchment will eventually have a certain amount of allocated water assigned to it. The reservoirs are included in a different manner first the inflow into the reservoir secondly the outflow from the reservoirs to the river. Separating the inflow and outflow from the reservoirs the model is able to variably change this based on the water allocation. The string of random numbers containing the allocation and reservoir data is grouped together to create a set of 40 of these strings.

The amount of water which is allocated to each sub-catchment is dependent on the Allocation strategy and is discussed in detail in section 3.3. In short this result in a general fairness score and a unused water score which the algorithm will both minimise to get the best result. The initialised set of 40 strings is recombined and mutated to achieve the best possible result for this particular month. To guide the algorithm in the choice of selection several constraints are introduced, these constraints are twofold. Both contain the genetic algorithm within a certain range of values which would be deemed realistic. There can be no negative water allocation and flow, secondly there can be no more water in the river than the largest reservoir has capacity. Guiding both the combination and mutation process these constraints reduce the amount of possible solutions in the model, reducing processing time.

The next step is deducing if the proposed solution is feasible. The feasibility check consist of checking if the amount of water attributed to each sub-catchment is present at the current time-step in the current sub-catchment. The first part in determining the feasibility is the natural run-off for each sub-catchment and determining the water availability based on the natural run-off for each sub-catchment. The second part is incorporating the reservoirs subtracting or adding to the available water in the system.

the feasibility check will result in an infeasible or feasible solution. In case the solution is infeasible the solution is compared to the closest feasible solution and a distance to this feasible solution is determined (The closest feasible solution is a random solution not optimised by the objective functions in any manner.). The distance from the closes feasible solution will be used be the genetic algorithm to achieve a better solution in the next optimisation cycle. Each month will be optimised for 100 of these optimisation cycles, Figure 21 in Section 4.7.

The solution will be a set of 40 different strings all with different allocations for the particular month. To determine which solution would result in the best possible allocation the Allocation strategy with the lowest overall score for the objective functions is selected and used as the allocated blue water and reservoir operation procedure. After the first month has concluded the other 60 months are optimised in the same manner, but before this can take place the reservoir content has to be updated based on the water allocation of the previous month. After this process is achieved 60 times the entire simulation period of five years has ran and this particular Allocation strategy is concluded. For each Allocation strategy aforementioned process has to pass, before the allocation strategies can be compared and analysed.

6.2 Blue water availability in space

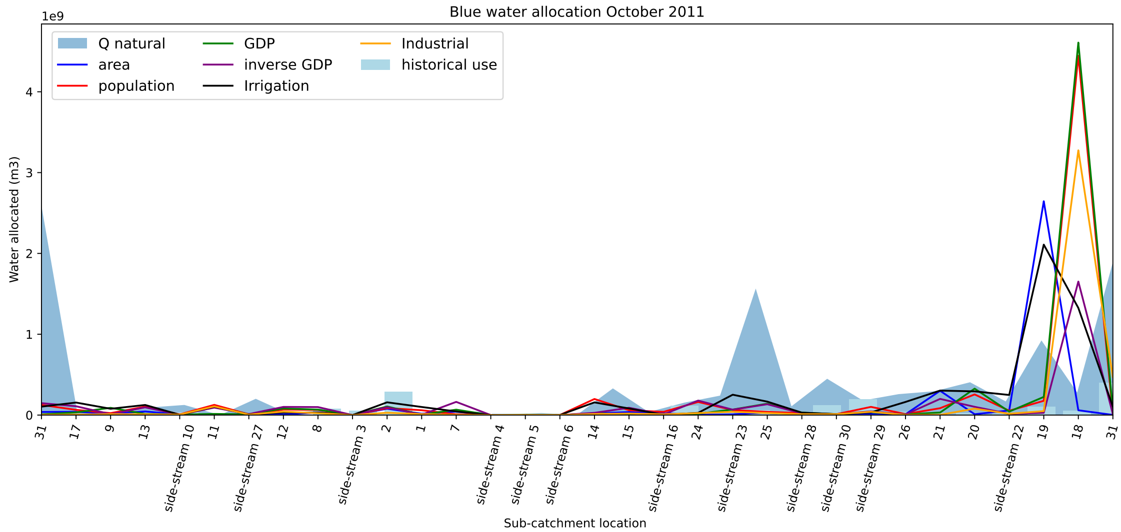

Figure 22: Blue water availability in each sub-catchment for all allocation strategies in October 2011 the histogram indicates historic use in the sub-catchment, the dark blue shaded graph indicates historic natural flow, Albers et al. [2021].

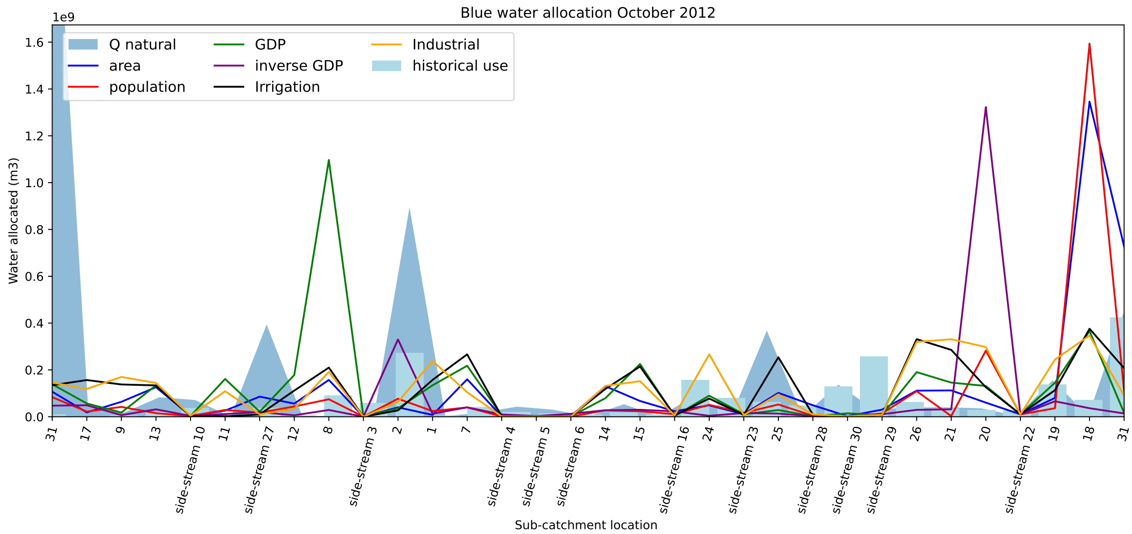

Figure 23: Blue water availability in each sub-catchment for all allocation strategies in October 2012 the histogram indicates historic use in the sub-catchment, the dark blue shaded graph indicates historic natural flow, Albers et al. [2021].

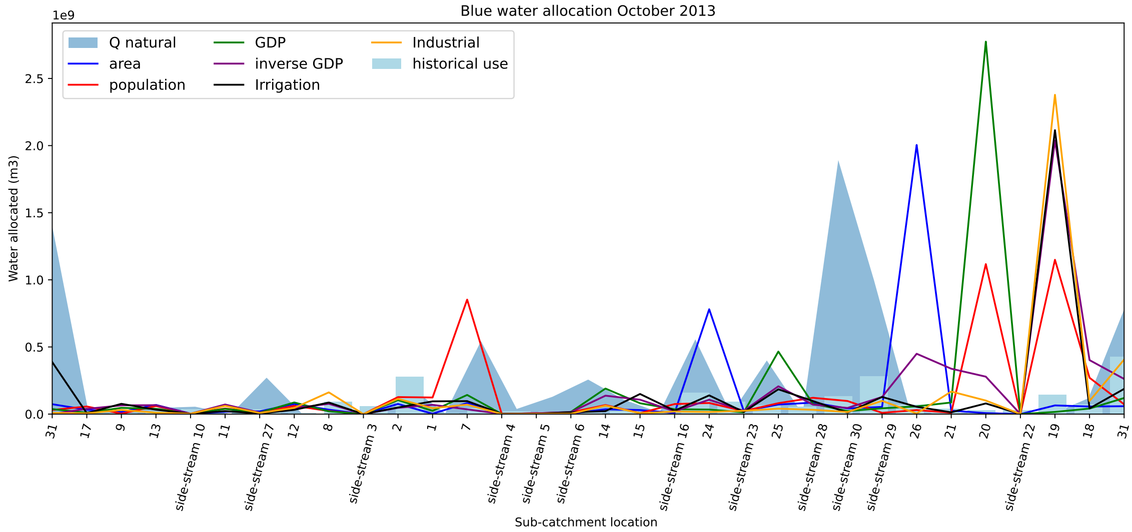

Figure 24: Blue water availability in each sub-catchment for all allocation strategies in October 2013 the histogram indicates historic use in the sub-catchment, the dark blue shaded graph indicates historic natural flow, Albers et al. [2021].

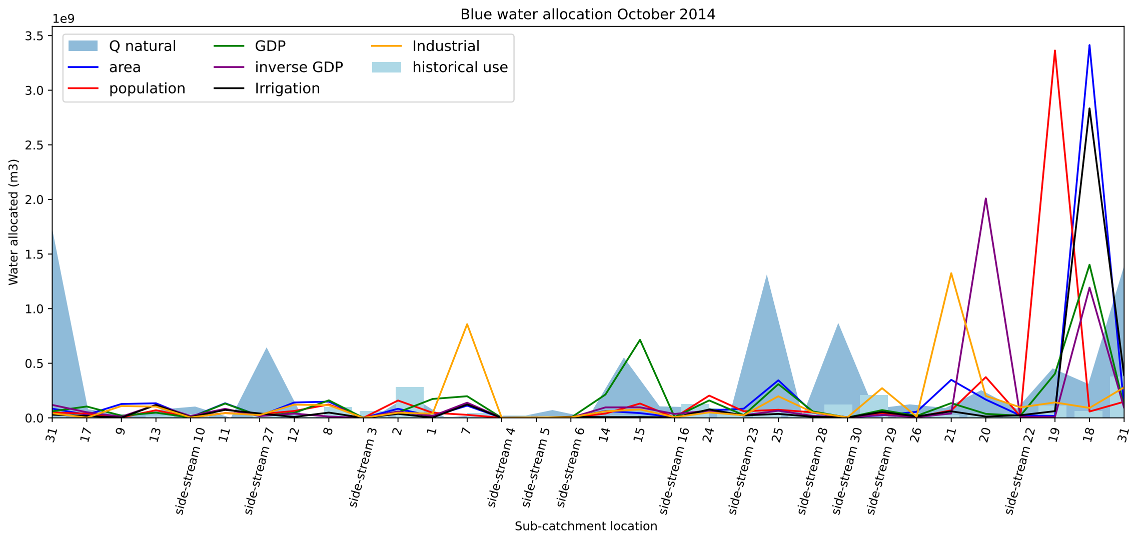

Figure 25: Blue water availability in each sub-catchment for all allocation strategies in October 2014 the histogram indicates historic use in the sub-catchment, the dark blue shaded graph indicates historic natural flow, Albers et al. [2021].

6.3 Fairness of implementation

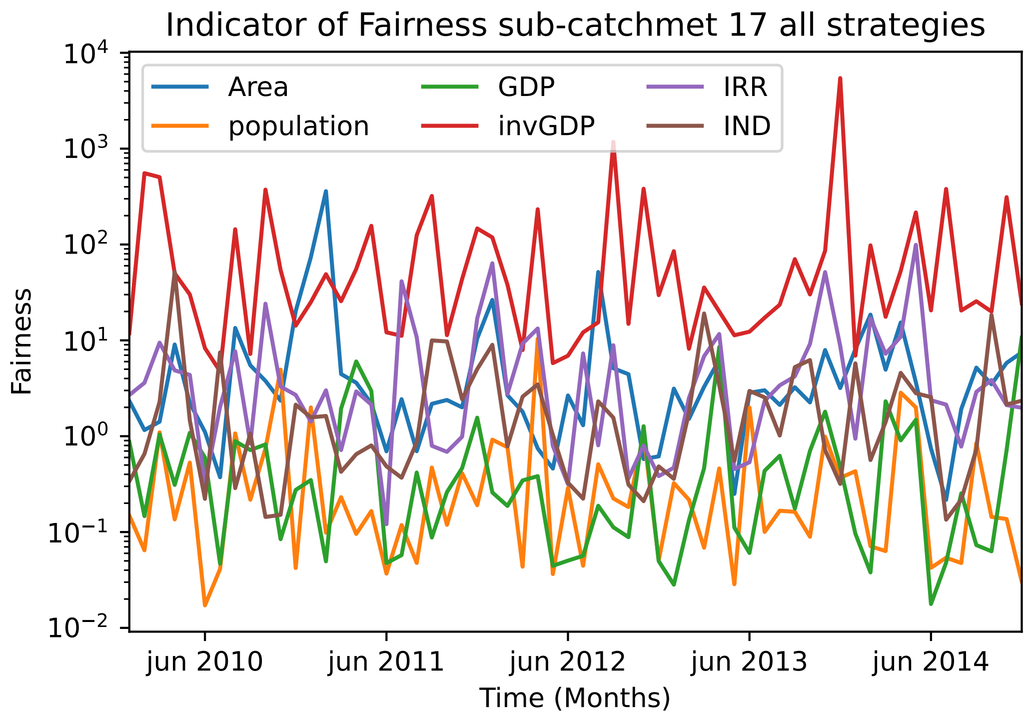

Figure 26: Distribution of Fairness for each Allocation strategy in time for sub-catchment 17. The lines represent the ability of each Allocation strategy to implement Fairness according to each ethical principle.

Location	Area	Area_ethic	population	pop_ethic	GDP	GDP_ethic	invGDP	invGDP_ethic	IRR	IRR_ethic	IND	IND_ethic
sub 31	1.761563	14.781519	1.359557	0.409313	1.588749	0.061003	1.796668	35.261067	2.151840	0.198291	1.260045	1.802342
sub 17	1.502406	1.454283	1.372810	0.090767	1.492263	0.112270	1.531507	19.159528	1.636958	1.275578	1.656541	0.701095
sub 9	1.853708	0.642076	1.784725	0.123659	1.513906	0.260616	1.655127	8.253641	1.699586	1.226714	2.274324	0.790758
sub 13	2.894225	2.547295	2.780745	1.493349	2.209178	1.202252	2.405875	1.789169	3.588146	1.083055	3.271270	2.688301
sub 10	0.293867	4.296011	0.242465	3.575548	0.235044	1.357655	0.241041	1.584373	0.207079	2.386780	0.307128	3.942614
sub 11	1.471933	0.003100	1.450075	0.003591	1.886540	3.753812	2.188613	0.573026	1.685050	1.690701	1.965291	7.286036
sub 27	0.506676	3.310213	0.518073	1.781546	0.425542	1.184815	0.600115	1.815500	0.678016	0.729200	0.396911	4.549573
sub 12	1.654622	0.469971	1.740746	2.228387	1.719585	11.987755	2.190287	0.179436	1.892618	4.038924	2.244602	9.144893
sub 8	2.505896	5.831710	1.923895	3.683972	2.455084	1.340443	2.309106	1.604717	1.992619	4.376207	2.161555	6.611658
sub 3	0.005445	3.418707	0.004447	2.168577	0.005047	1.262953	0.004208	1.703176	0.005697	8.168702	0.008165	6.758877
sub 2	2.906513	13.946306	2.541574	8.255844	2.640541	1.213882	3.480530	1.772027	2.945221	9.726063	2.635894	2.586233
sub 1	2.241381	1.137024	1.858884	0.408970	2.174827	0.699345	2.077523	3.075782	2.332520	3.751464	1.993283	2.343862
sub 7	3.517305	6.135365	3.203837	3.966008	3.797692	1.122859	3.532140	1.915674	3.555675	3.045001	2.884923	1.595017
sub 4	0.101838	3.012039	0.108191	0.669050	0.095144	0.526416	0.107847	4.086179	0.133346	4.419721	0.112710	1.475365
sub 5	0.237082	2.308147	0.223058	0.637648	0.139817	0.606400	0.234191	3.547216	0.309772	4.622195	0.303509	1.333430
sub 6	0.272673	1.076001	0.223423	0.723348	0.377703	1.232110	0.288089	1.745812	0.334936	2.471745	0.269347	0.973745
sub 14	3.880296	3.516006	1.997809	1.816110	3.081032	0.892288	2.598491	2.410693	1.656799	1.320051	2.066858	1.211829
sub 15	2.488586	0.303194	2.048900	0.828792	4.467132	4.788993	2.211016	0.449162	2.193852	5.340799	2.305979	3.094142
sub 16	0.254108	4.672910	0.409634	11.367203	0.216024	4.159200	0.290108	0.517174	0.558946	2.478196	0.330497	2.161453
sub 24	2.988453	1.248080	3.203086	3.091525	2.580869	4.868491	2.417289	0.441827	2.553508	6.015872	2.851159	3.525604
sub 23	0.633369	3.423856	0.422540	1.911321	0.532319	1.065314	0.547109	2.019153	0.753510	1.054811	0.502912	1.442488
sub 25	2.228537	0.781056	2.892068	2.382015	3.077647	5.778284	3.825935	0.372261	2.154955	4.125998	3.030018	2.976110
sub 28	0.551452	5.885252	0.514283	5.127225	0.439841	1.784665	0.538259	1.205286	0.483396	1.515914	0.483409	3.839697
sub 30	0.346675	6.821710	0.426690	16.240839	0.314113	5.049120	0.367143	0.426021	0.583955	2.309776	0.285800	4.211700
sub 29	0.635651	0.778007	0.572853	2.804624	0.654321	7.333806	0.771647	0.293304	0.586503	4.686844	0.692017	2.998442
sub 26	4.144217	0.834649	2.586178	1.638232	8.441196	3.894382	7.147919	0.552342	3.772604	2.817714	3.737906	3.498259
sub 21	7.124429	0.751364	5.085281	1.099539	6.007447	1.234224	5.129160	1.742821	4.540507	3.787284	9.832793	3.606500
sub 20	9.477042	0.301606	8.455936	1.101522	9.827467	7.196120	12.859125	0.298915	9.594902	2.262897	5.976370	3.622384
sub 22	0.361491	2.462908	0.260791	6.336334	0.439781	5.080927	0.267061	0.423354	0.425226	2.288767	0.294823	4.444556
sub 19	13.144977	1.714644	13.572521	3.315752	8.071391	3.342502	12.508221	0.643539	9.937634	1.723298	8.919152	2.855288
sub 18	28.013582	2.134991	36.214924	10.719389	29.092757	15.607097	23.878648	0.137824	35.054623	5.061437	34.944810	1.927750

Figure 27: The share of water which is allocated and the share of water which should be allocated to each sub-catchment according to each Allocation Strategy.