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Nomenclature

SDG	Supply Demand Gap
SDR	Supply Demand Ratio
WBM	Water Balance Model
DBM	Dynamic Behaviour Model
ABM	Agent-Based Model
GCM	Global Climate Model
UN	United Nations

1. Introduction

1.1. Motivation

In July 2010, the United Nations General Assembly explicitly recognised the human right to water and sanitation [48]. Furthermore that year, the 2015 Millennium Goal for water was reached before schedule, to halve the proportion of people without access to improved sources of water [47]. These developments have brought the water crisis closer to the forefront of global priorities, inciting international recognition, collaboration and political awareness.

Global freshwater resources are in finite supply, but unevenly distributed around the world, with a large proportion locked up in glaciers and other impenetrable places. Water is an indispensable substance to life and has extensive influences in many sectors, such as sanitation, hygiene and food security [18].

The world population is fast approaching the 7 billion mark and beyond [28], with almost all of the growth occurring in urban areas of developing countries, leading to slums and urban sprawl. Such dense concentrations create the biggest challenges in water infrastructure and management, resulting in wastage, pollution and unsustainable use of water sources [30].

The majority of water originates from precipitation and runoff. Climate change has lead to unpredictable forecasts and an increase in global temperatures, melting locked up supplies of water and causing floods and droughts [57]. Other climate related hazards are on the rise, striking and causing considerable damage in densely populated areas, thus bringing in to cause the vulnerability and resilience of cities of the future. For instance, Hurricane Sandy travelled up from the Caribbean to hit the megacity of New York in October 2012, causing significant damage and disruption in one of the world's most developed and populated cities.

A declining unreliable supply coupled with a growing demand has lead to many areas of water stress (where annual water supplies drop below 1,700 m^3/person), water scarcity (below 1000 m^3/person) and even absolute scarcity (below 500 m^3/person). Today, around 700 million people in 43 countries suffer from water scarcity, which is shaping up to be one of the main problems faced in the 21st century. By 2025, it is estimated that two-thirds of the world's population could be living under water stressed conditions, with 1.8 billion people in absolute water scarcity [28].

1.2. Objective

A megacity, as defined by the United Nations (UN), is a city of more than 10 million inhabitants. Other definitions exist of equal validity [43], due to the difficulty of choosing an urban boundary. As of 2011, the UN has recorded 23 such megacities and estimates that by 2025 there will be 37, with 10 cities passing the 20 and even 30 million mark [9]. This continual shift to dense urban living, where even China's urban population surpassed its rural population at the end of 2011, is causing unprecedented challenges [44]. In some areas however, the rate is slower due to problems of congestion, cost, pollution, environmental degradation and decay of infrastructure [33].

The water management infrastructure of these cities must adapt to the water crisis by sharing a regional finite resource in order to survive. Predictions of future runoff are uncertain causing further complications regarding the nature of arrangements that should be made. The aim of this project is to analyse the water management strategies of megacities and explore how they should interact for the mutual survival of all.

Water quality is an important factor to consider and is related to quantity, where higher grades and therefore more treatment and separate piping are needed for domestic use compared to types of industrial use and agricultural use. This project will not recognise the full extent of the quality issues, but will assume that the volumes supplied to the megacities are of a higher standard, as most of the water use is domestic and industrial, and not agricultural.

Another issue discussed only qualitatively in this project is the economic aspect. The cost of water should not be free but fair, and thus acts as a tool for policy and management decisions, which will be covered in the later part of the project.

1.3. Previous work

In her Nobel Prize winning book, Elinor Orstrom explored diverse historic models where humans and the ecosystem successfully interacted for long-term sustainable coexistence [40]. Water is one of the 'commons' or natural resources shared by many individuals, and this project thus equally seeks to establish successful sustainable behaviour rules between cities that share a common resource.

The issue of governance in society, who should control the water flow, can fall to centralised supplies, empowered citizens or a combination of public, private and civil bodies. In reality, a mix of governance is found [38]. There is also an increasing number of international treaties and conventions for cross-border water supplies, to prevent ecosystem collapse, insecurity and social unrest [12]. Models and frameworks to analyse international conflict have been carried out [19], but there are few regulations in place for subnational conflicts, lead on from sectoral, fragmented or missing basin authorities [12]. A need for regional river or basin management is thus becoming increasingly important.

In particular, megacities within a basin transcend their boundaries [34], affecting the rural communities around them, and often have a 'floating population' of short- or long-term commuters from the surrounding regions [33]. Studies have been made on catchment based integrated water management, such as the impact of deforestation or dam construction on other areas of the catchment [51]. Alternatively, the concept of virtual water has been used to analyse interactions [25][35], where a water poor area may import food and electricity from a water rich area, and thus conserve its own supplies of water [7]. The impact of water-consuming megacities on each other within a catchment is thus important, and this project develops a novel method of analysing these relationships.

Water footprinting of countries, businesses and individuals is widely used, as are water balance models, especially on basin scales, which incorporate as main parameters precipitation and temperature to predict runoff (for example on the Sacramento Basin [20]). Urban hydrological cycles are also used which equally incorporate precipitation, evapotranspiration and storage as well as piped-in water [23]. Human and climatic influences can also be included [52]. Hellström et al. even did a system analysis framework for sustainable urban water management, by modelling cities, relevant systems and scenarios [24]. A study by Van Rooijen et al. on the megacity of Hyderabad includes the water inflow from reservoirs and ground water, the city water uses including loss coefficients and the urban water recycled for irrigation, but concentrates mostly on the latter [41]. A need was thus identified to create a water balance model for a distinctly urban environment such as a megacity, charting its supplies and demands explicitly from hydrological cycle processes.

However, a city's water balance is affected by many factors, including social behaviour. The move towards integrated water management has been made in recent years, recognising the need for designs to satisfy multidimensional criteria: water and health, social and cultural, environmental, economical and technical issues [24]. Other frameworks such as urban modern hydrology [39] and water sensitive cities [8] equally combine all of these aspects in the face of climate change and emphasise cooperation between user groups. However, it has been argued that these integrated management ideologies have not actually made a significant impact in the world [37].

In order to analyse issues concerning social behaviour dynamically, agent-based models (ABM) have been used in many water management applications, simulating interactions between numerous stakeholders over a finite reserve of water as well as intervention strategies for particular case studies, such as the EOS project on the Fraser River watershed [4]. The FIRMA project applied ABM to simulate the natural, hydrological, social and economical management of water basins, with interactions between consumers, suppliers and government, to various levels of aggregation [4]. Ducrot et al. also lists other models that have been developed, mostly emphasising the interactions between farmers and water suppliers for the case of irrigation [11]. Looking at particular future scenarios can also be done, such as business-as-usual, privatisation, technocratic or green [36]. This project takes a new approach of concentrating on the growing urban water-users within a basin, simulating the megacities as user-agents.

Within the scope of this project, agent-based modelling will be used to look at the behaviour of urban megacities in terms of their water balance and regional basin water management strategies, with the aim to explore sustainable interactions between cities and their environment under different scenarios, including climate change.

2. Project development

Before the scope of the project can be fully outlined, a brief discussion on the issue of uncertainty in climate change needs to be discussed and its impact on the direction of the project, as well as some preliminary work on the idea of a city water signature.

2.1. Climate modelling uncertainty

A change in climate leads to a change in the hydrological cycle. The uncertainty in climate models is well known, but they are frequently used to support management decisions and policies and are as diverse depending on what information is needed [29].

Some preliminary work was carried out on analysing global climate models and their future predictions of change in runoff. Global models use historic data to validate their current models and project into the future, taking into account many factors such as medium term precipitation, evapotranspiration and near-surface storage. They are useful in providing a broad overview, before deciding whether more data or a more regional model is required. Obtaining and processing data straight from monitoring stations was complex (for example GRDC runoff data 47]), so the data in Sperna Weiland et al. paper was used [55].

Individual models were compared, in particular noting areas where models disagree on the direction of change, as in an increase or decrease in runoff. These locations will experience a significant amount of uncertainty, which is problematic in terms of water management planning, whether to forecast more or less future runoff. These areas have been pixelated in green in *Figure 1*, as well as the location of the UN estimated 2025 megacities as red dots.

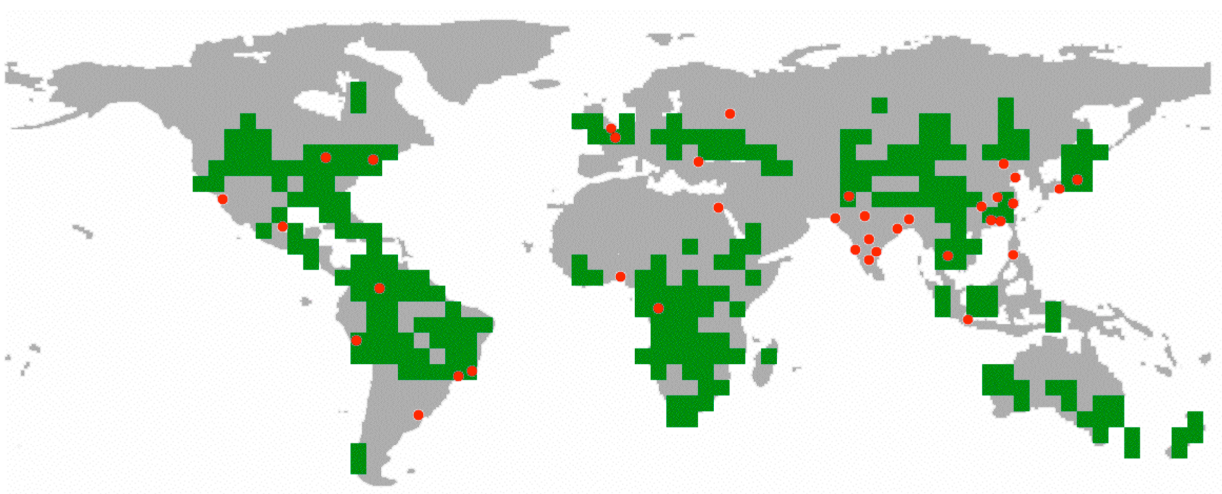


Figure 1: Location of the 2025 UN megacities [9] with areas pixelated in green representing areas of significant uncertainty in future predicted runoff, based on Sperna Weiland et al. [55]

2.2. Refining scope of problem: case study

A data matrix of the 37 megacities was produced to analyse environmental, social and economic relevant topics such as location, climate, population growth, GDP, water consumption, political system, presence of conflict and risk of disasters. However, due to the large amounts of data needed, it was decided to narrow the scope of the project and focus on geographically closely interacting megacities.

It can be seen in *Figure 1* that by 2025, the main clusters of megacities occur in India and China, both with booming economies, large growing populations in diverse environments and a history of heavily polluted and mismanaged but abundant reserves of water [1][3]. Water consumption is in turn increasing coupled with rising standards of living, with domestic use increasing compared to a decrease in agricultural and industrial uses [22].

China's megacities are predominantly located on the East coast and are supplied by three major river basins: Yangtze, Yellow and Pearl rivers. India is supplied by many smaller basins but equally suffers from unequal distribution. Cross-border and inter-state or inter-provincial tensions affect both countries.

The Yangtze Basin was chosen as case study as it involves three competing megacities on a single basin: Shanghai, Wuhan and Chongqing. Another possibility could have been the Ganges-Brahmaputra-Meghna basin, which equally needs cooperative water management in one of the poorest regions of the world, and is looking for a 'win-win' situation between agriculture, power and flood prevention [6]. However, according to *Figure 1*, the Yangtze Basin has a more unpredictable climate. It is also particularly interesting due to its historical abundance of water now at risk and the presence of major developments such as the controversial Three Gorges Dam. In addition, Wuhan and Chongqing have similar populations, allowing for interesting comparisons of other aspects that affect their water demands and supplies.

Basin	Megacity	2025 Population (million) [9]
Yangtze	Shanghai	28.4
	Wuhan	12.7
	Chongqing	13.6
Ganges-Brahmaputra-Meghna	Delhi	32.9
	Kolkata	18.7
	Dhaka	22.9

Figure 2: List of major river basins with megacities and their populations of 2025 [2][10]

2.3. City water signatures

The concept that water management involves many factors is not new. A city water signature encapsulates not only the physical resources and demands of a city, but also the social, economic and political tendencies that influence city water management. Individual cities will adapt to universally better strategies whilst adhering to their own particular situation and culture.

A model was thus constructed with the aim of gaining an overview feeling of a city signature. Ten different categories of demand, supply and management were outlined, as well as an overview category, each with a list of applicable criteria (see *Figure 3*). Cities were then scored on a 5-point system per criteria, with the total score per category normalised over 10 to allow for fair comparisons between categories. The total score over all categories is also calculated. The process of scoring cities was done by comparing and thus ranking the megacities amongst themselves. The fewer the points, the better managed the system.

1	*Overview*	Economy and evidence of action and commitment
2	*Agriculture*	Impact of current and future usage and reuse capabilities
3	Domestic	Impact of current and future usage
4	*Industry*	Impact of current and future usage (low/high water intensity)
5	*Population*	Current and future population and water consumption
6	*Surface Water*	Current and future withdrawal impact and capacity, effect of climate
7	*Ground Water*	Current and future withdrawal impact and capacity, recharge capacity
8	*Treatment*	Wastewater treatment, treatment of natural bodies of water, quality
9	*Network*	Efficiency and availability of information, rainwater harvesting
10	*Management*	Current evidence of action and future planned action, evidence and effectiveness of a management system
11	*Incentives*	Awareness and promotion, presence of international (UN, World Bank) projects or incentives or classified special area

Figure 3: Categories of city water signature

Research into individual cities was therefore needed, looking at a wide range of sources in literature, reports, personal communications and others, and obtaining a feel for its signature. This was done for the case study Yangtze River basin cities as can be seen in *Figure 4*.

Shanghai has a total of 42 points, Wuhan 34 and Chongqing 50 (normalised over 100). We can see that Chongqing has a similar supply to Shanghai and Wuhan, but does not manage the demand as efficiently [31]. Shanghai scores similar to Wuhan but suffers from a larger and higher consuming population, but equally has a higher GDP [15].

These categories are most useful for general comparisons between cities, but the concept of a city water signature will be further developed in the Dynamic Behaviour Model (DBM) as a list of rules or water management strategies a city may choose to follow over time.

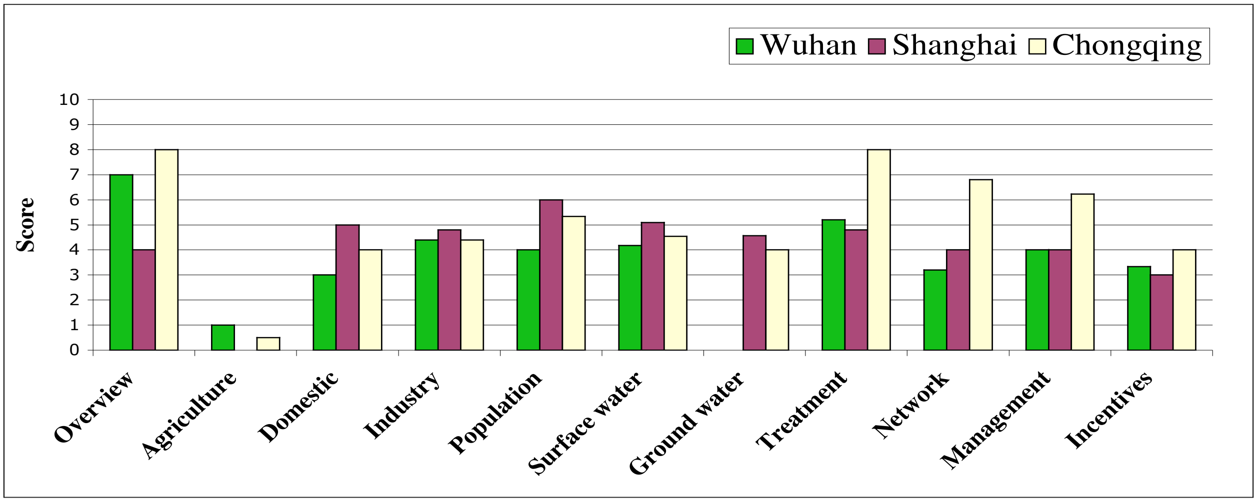


Figure 4: Yangtze River basin city signatures

2.4. Scope of project

- Establish the needs of a city in terms of water demands and supplies: create a steady-state city *Water Balance Model* (WBM)
- Consider how these needs may change in the future due to management decisions or external factors, turning the steady-state motel into a *Dynamic Behaviour Model* (DBM)
- Explore how several cities interact to satisfy their needs, thus looking at an agent-based *Aggregate Dynamic Behaviour Model*

3. Case study: Yangtze basin

The Yangtze Basin was chosen as a case study as it involves three competing megacities on a single basin in an unpredictable climate, as discussed in section 2.2. Further details on the megacities as well as issues of case study data are considered here.

3.1. Yangtze River basin

The Yangtze River basin includes Shanghai, Chongqing and Wuhan (see *Figure 5*). Historically, the basin offers abundant supplies of water to all three cities, but it is now facing problems, especially with pollution. It is one of the longest and biggest discharge volume rivers in the world, originating in the Qinghai-Tibet Plateau and emptying in the East China Sea at Shanghai.

Shanghai, sitting on the estuary of the Yangtze basin, is one of China's richest cities, often referred to as its commercial and financial centre, with plans of continual expansion of its international presence. However, heavy industry accounts for much of its economy and high water consumption, coupled with a corresponding large population. Shanghai is nevertheless proactive in implementing a wide range of water sensitive measures [13].

Wuhan is upstream of Shanghai, has a lower population, but is one of central China's most productive economic centres. It is also a major transport and logistics hub, having the country's largest inland river port. Following its rapid industrial growth, the Chinese government designated it as an experimental zone for sustainability policies. In this respect it has strong policies on water efficiency and quality monitoring [13].

Chongqing lies most inland, upstream of the Three Gorges Dam (one of the largest hydropower dams in the world), and serves as the economic, manufacturing and transport centre of the upstream Yangtze River. Although a small population reported by the UN, other sources suggest a more expansive agglomeration including industrial and agricultural sprawl [31]. Chongqing is implementing its 12th Five-Year Plan on Water, but with limited improvements yet compared to its growth [17].

Figure 5: Map of Yangtze River basin [45]

Summary of case study cities:

- Shanghai – large population, large consumption, large supply, medium network
- Wuhan- small population, medium consumption, medium supply, medium network
- Chongqing- small population, low consumption, medium supply, low network

3.2. Data

	Population *P* (M)	Consumption *C* (lpcd)	Losses *L* (%)	Surface water *S* (Bm^3/year)	Ground water *G* (Bm^3/year)	Other water *O* (Bm^3/year)	Treatment T (%)	Reuse *R* (%)
Shanghai	20	410	10	10	0.0	0.0	78	13
Chongqing	9.7	210	20	2.9	0.7	0.2	60	13
Wuhan	10	280	14	3.8	0.2	0.0	90	13

Figure 6: Case study of the Yangtze River basin cities, for the estimate year 2010 (SEE APPENDIX D for data sources)

City demand and supply quantity estimates should match. However, reliable data is not always available, especially on a city level. Therefore, in most cases, an estimate based on various sources (literature, reports, personal communications) over different years is used, as well as regional and sometimes national estimates. Difficulties stem from limited sources, fragmented water authorities and language barriers, an issue in China. Applying a water footprint calculator to a city was considered, however this has not been done systematically before and individual or country calculators need specific data inputs [26][53].

This project will therefore concentrate on the methodology of developing a consistent model framework with explicit boundary conditions, after which if reliable data is acquired, more meaningful conclusions can be obtained. Simple validation calculations performed in the Water Balance Model (WBM) are for demonstration purposes only; for example the 2010 Supply Demand Gap (*SDG*) for the city of Wuhan is negative, where in reality it is reported that Wuhan has an abundance of water [32]. Estimates of the 2010 base values will be used to make a first comparison between cities in the WBM and validation case matrix (see *Figure 6*).

4. Water Balance Model (WBM)

In this project, an urban water balance model is needed that concentrates on the quantity demands and supplies of water to a city, and not on precipitation, temperature and runoff. As exposed in the literature review in section 1.3, water balance models are widely used over large geographical areas such as basins, or in more urban contexts with links to the hydrological cycle or added emphasis on water recycled to irrigation. There is thus a gap in literature for an urban water model that considers the hydrological cycle implicitly within the input quantities, for which estimates are needed and often carried out ad hoc in industry. Alan Travers, water sector director of Buro Happold, presented his team's approach to the problem at Wadi Hanifah, with the water demands and supplies of the city of Riyadh [46]. The model and its validation are presented here.

4.1. City WBM

A simple overview of a city's water footprint is established here, which can then be compared and integrated with other nearby cities.

The balance focuses on the Supply Demand Gap (*SDG*) of the city as shown in the flow chart *Figure 7*, and later the Supply Demand Ratio (*SDR*). The demand side includes the total city population, water consumption per capita per day in various forms (agricultural, domestic, industrial) and an allowance for network losses and other unaccounted water. The supply side includes water obtained as surface and ground water (which may be climate dependent) and from other human additions to the hydrological cycle such as desalination. Water may be treated and reused as well, which is based on supply, giving an effective total supply for city use.

The tool needs to be simple and easy to use, so is implemented in Microsoft Excel, with the city base values for a given year as inputs and the *SDG* for that year as output. The WBM definition is given in *Figure 8*.

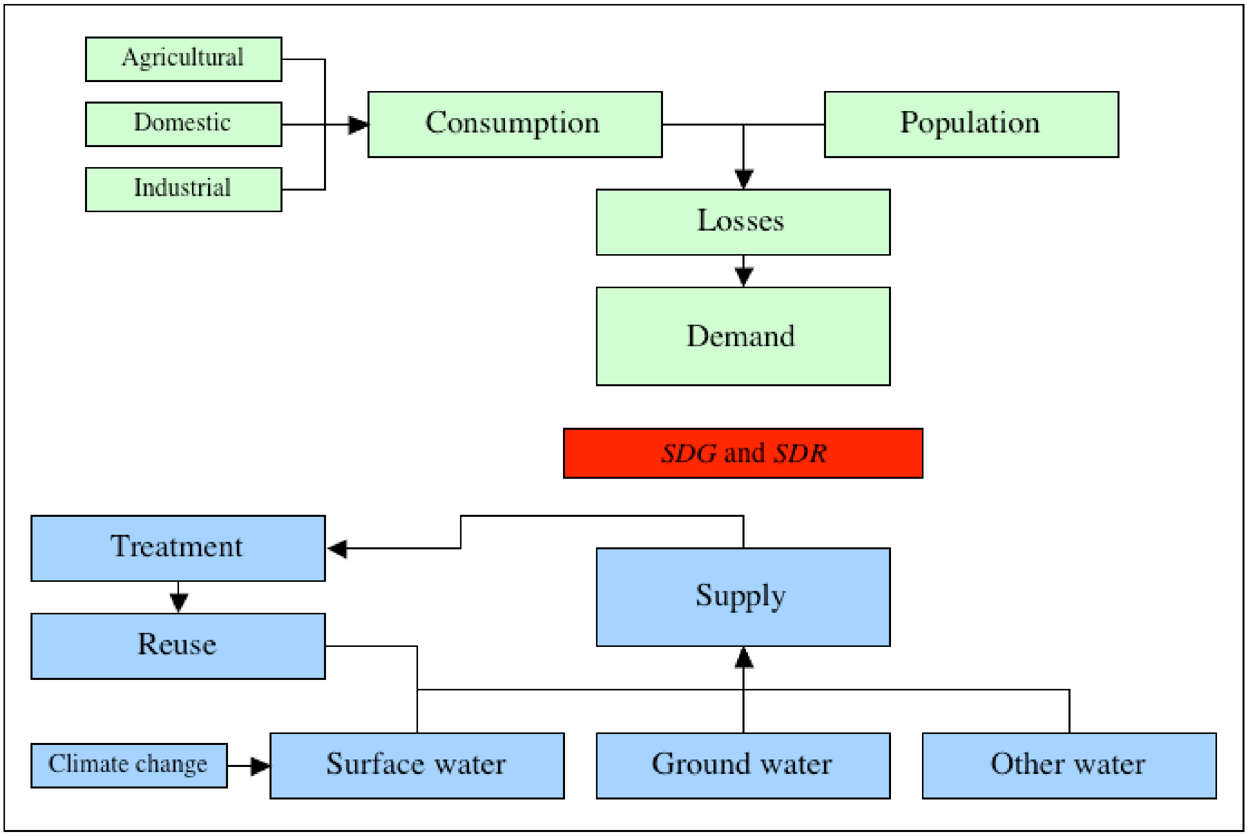


Figure 7: City WBM

Inputs	Demand	Population *P* (M), Consumption *C* (lpcd), Losses *L* (%)
	Supply	Surface water *S* (Bm^3/year), Ground water *G* (Bm^3/year), Other water *O* (Bm^3/year), Treatment *T* (%), Reuse *R* (%)

Outputs	Demand	$\frac{PC}{1000}\left(1+\frac{L}{100}\right)$
	Supply	$(S+G+O)\left(1+\frac{T}{100}\frac{R}{100}\right)$
	SDG	$Supply - Demand$
	SDR	$\frac{Supply}{Demand}$

Figure 8: WBM Definition

4.2. Validation case matrix

In order to test the sensitivities of the WBM, and thus help validate its use, a validation case matrix was constructed and tested on the case study (an example of which can be found for Shanghai in APPENDIX B.1.).

Primarily, this involved looking at changes of 75% and 125% to the base value inputs (for example at year 2010), with an analysis of the outputs of total supply and demand, and the *SDG* (the *SDR* relays equivalent information). Combinations of changes can be applied, thus emulating different possible scenarios that reflect possible supply, demand and management patterns. Different projected climatic situations can be applied, as well as extreme disruption scenarios.

4.2.1. Results

It was found that the sensitivities of the model depend on the input combination of base values, leading to varying results (the extent of which could be quantified); so it is most useful at comparing between cities with known reliable data.

Population and consumption had the most impact on the *SDG*, followed by the surface water. This is due to the fact these quantities involve the largest numbers. Changes in treatment, reuse, ground and other water had limited impact, as their base values are small. It is also interesting to note in the model the coupling of population and consumption, as well as reuse and treatment, where for instance a percentage change in either gives the same result.

The total water available supply to a city is considered outside the scope of the validation case matrix, although it will be included in the dynamic models, where supply values of surface and ground water are taken as proportions of the total water available. This was deemed appropriate as the total water available and the water used in a city are linked, where an impact on the total water would be reflected in the surface and ground water supplies. For example, if the basin becomes more polluted or climate change causes less runoff, the city would in turn change its supplies or use less water.

Combining cities in the validation case matrix could have been done too, by assembling base case runs or more complicated runs and checking aggregate sensitivities of the model, but this was not deemed necessary as the project assumes that the single city validation is adequate to explore the aggregate and even dynamic model potentials.

4.2.2. Statistical analysis

SDG	BASE	MEAN	STANDARD DEVIATION	COEFFICIENT OF VARIATION
Chongqing	1.65	1.32	0.94	0.72
Shanghai	1.87	0.74	3.20	4.31
Wuhan	1.23	0.82	1.18	1.44

Figure 9: Statistical analysis of case study cities

Separating the analysis into demand and supply scenarios was not useful, as the model includes a limited number of variables, therefore each output is dependent on the scenario given and an amalgamation of like scenarios can be easily pushed one way or the other. An overall average of all the scenarios seemed more appropriate, to gain a global view of the city (see *Figure 9*). In terms of this case matrix, predominantly adverse scenarios were tested, which explains why SDG_{MEAN} is lower than SDG_{BASE}.

Shanghai has a large variance in outputs and a lower mean as it involves larger numbers in general. Wuhan appears less resilient than Chongqing despite having the same population, again enforcing how the demand side (in this case consumption) is more significant compared to Chongqing's lower network efficiencies. Despite testing mainly adverse scenarios, SDG_{MEAN} is still positive, but does go negative within one standard deviation for Shanghai and Wuhan, and two standard deviations for Chongqing, again showing how it is the most resilient city.

Further calibration of the model would need reliable data from a variety of cities in order to do an uncertainty analysis. This would entail further work looking at a particular input thus keeping the rest constant, finding its lowest, best and highest reported base value as well as at a projected future data point, and therefore working from a spread or cloud of curves to make a model prediction. The *SDG* and *SDR* as outputs are hard to verify against reported data, hence why a margin for uncertainty should be established.

4.3. WBM limitations and assumptions

Comparing with the Buro Happold water balance model for Riyadh and Wadi Hanifah [46], the same issues surfaced, such as lack of data and the use of many assumptions (for example, projected targets as inputs), but the approach is similar. It was noted that evapotranspiration, present in their model (which includes the extensive watershed of Wadi Hanifah which passes through the city), was not explored in this city model, therefore assuming less importance in the hard impervious cityscape of a megacity. Quality was also not considered explicitly within their model [46].

This city WBM framework assumes that the water consumption per capita per day includes agricultural, industrial and domestic usage, where the issue of water quality is not defined, assuming the treatment cost is distributed equally across all users. It is then assumed that a percentage of treated water, based on the total supply, is reused straight back into the supply. The effective total supply is thus the total quantity of water piped-in to the city from surface, ground, other and reused water. Fluctuations in the total water available to the city are reflected in the surface and ground water supplies implicitly.

Other hydrological processes such as evapotranspiration, precipitation, runoff and stormwater are assumed not linked into the boundary conditions of the WBM, but occur as part of a different system outside of the city's metered water uses. Some of these effects may be covered by the 'losses' input.

5. WBM: Results

The water balance model was applied to the Yangtze River basin megacities.

5.1. Case study results

The supply, demand and *SDG* are plotted in the following figures. In *Figure 10*, the estimated 2010 values were plotted. The subsequent graphs (*Figure 11* and *Figure 12*) then show how the tool can be manipulated to test alternative scenarios, thus providing an initial test of potential management strategies to try and close the supply demand gap for a foreseeable future.

In addition, the treatment and reuse of wastewater can be incorporated as fraction of the supply (*Figure 13*). The distinction between the amount of wastewater that is treated compared to the amount that is reused is important, where there are high levels of wastewater treatment in some cities (e.g. Wuhan at 90% [13]) but in general reuse is low (China at 13% [58]).

Surface water, and even ground water, could also be related to climate change, incorporating future supplies as a function of the predicted runoff from GCMs (see APPENDIX C.1.).

Each *Figure* builds on from the last.

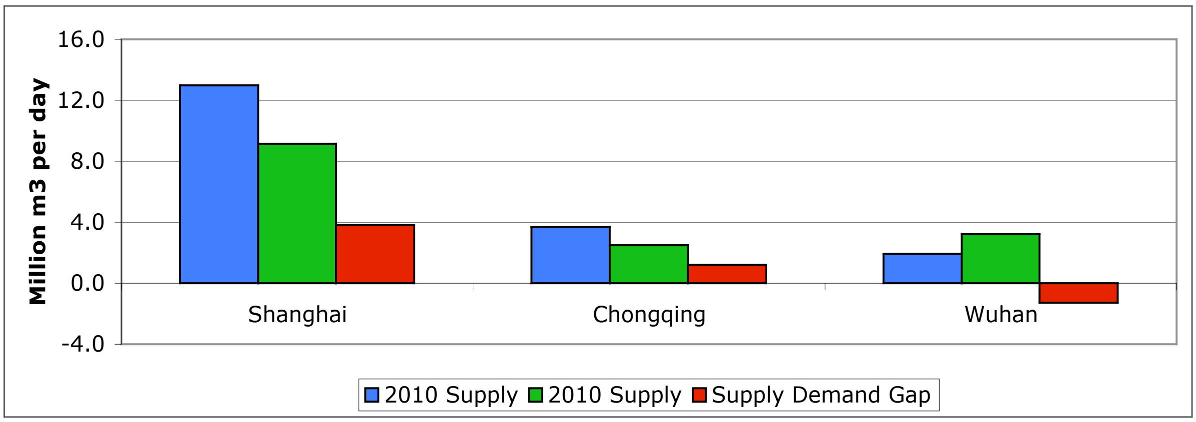


Figure 10: Estimate 2010 WBM for Shanghai, Chongqing and Wuhan, showing the supply, demand and SDG

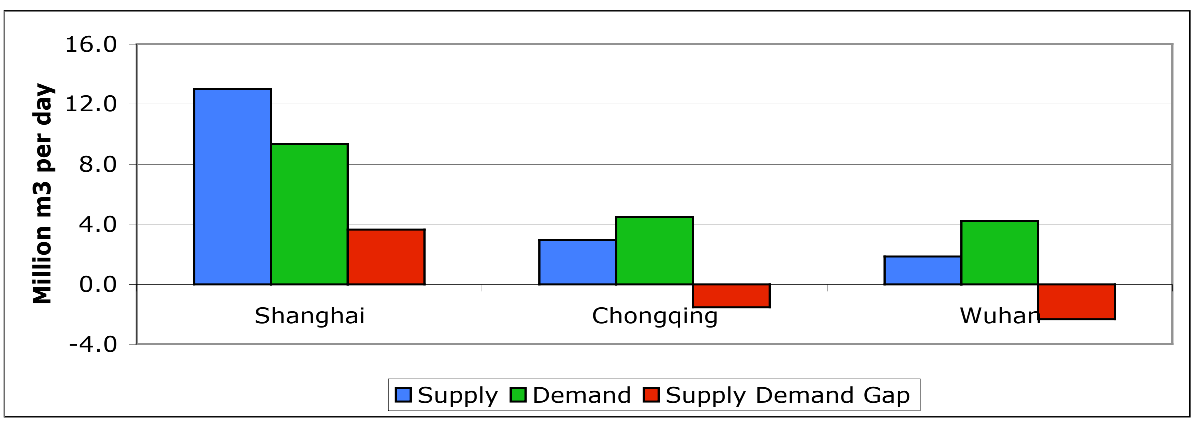


Figure 11: WBM assuming 2025 population [9], loss rate of 0%, 330 lpcd consumption [13] and 0 million m^3 per day ground water resources. This leads to a negative SDG for the cities of Chongqing and Wuhan.

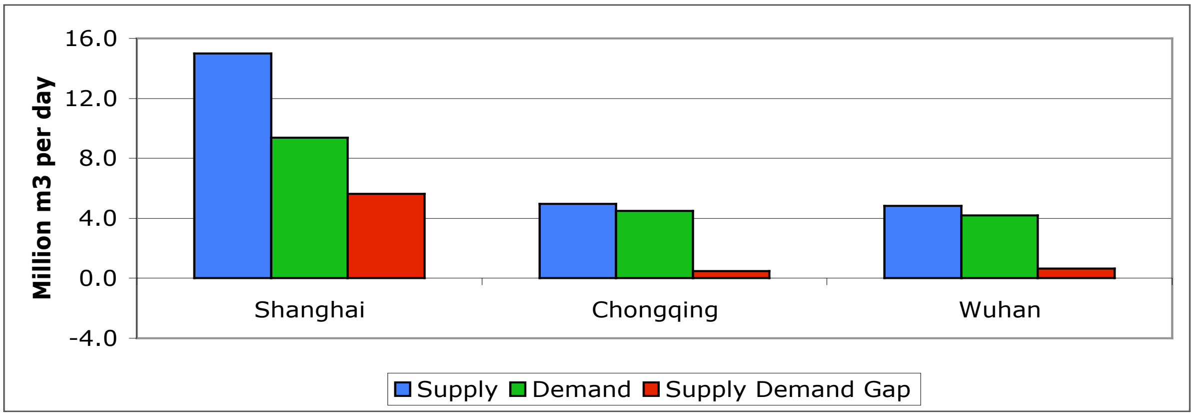


Figure 12: WBM assuming the advent of additional surface water transfers and improved technologies such as desalination, bringing all cities into a positive SDG (for example Shanghai +2, Wuhan +2, Chongqing +3 (million m^3 per day)).

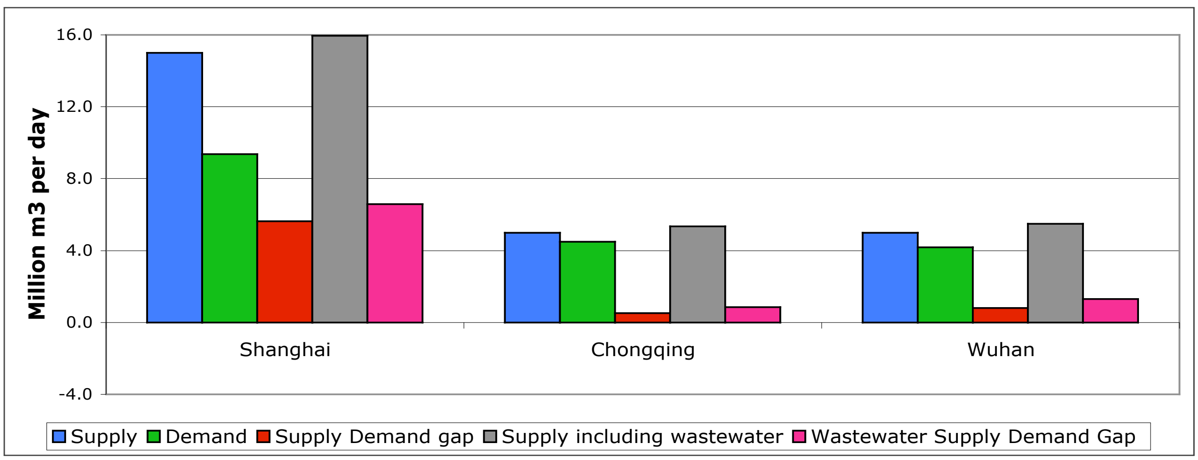


Figure 13: Reusing the percentage of wastewater treated directly into supply creates the grey bar of supply (data as Figure 6)

The WBM is a steady-state model, allowing us to explore the water demands and uses of a city at a fixed point in time, in a distinctly urban context. Next, a dynamic model will be developed, as an extension of the validated WBM but which evolves in time, following behaviour rules according to a city's water signature.

6. Dynamic behaviour model (DBM)

The next aim of this project is to combine the concept of city water signatures to the validated WBM. Further developing the tool from predicting simple scenarios based on fixed points or specific future dates to dynamic projection models is explored, thus creating a dynamic behaviour model. This will then allow us to estimate the development of city water balances following different scenarios, including sharing between megacities. First are some preliminary considerations.

6.1. Peak ecological limit

The WBM does not include any indication of the total water available in the basin, or any reflection of an ecological limit that should be conserved, after which further extraction creates more harm than benefit and the ecosystem cannot recover naturally. The current inputs to the model were thus modified to include this, translating them into city parameters, a population number defining it as a megacity and the hydrological context.

The idea of the total water available thus leads to an additional variable that can reflect climate change effects on a basin, or a declining hydrological supply. The amount supplied to a city would thus be a percentage of the total water availability (surface and ground), and changes in percentage use could for instance reflect moves from surface water to ground water use. Caps on the amount used compared to the amount available can be enforced, as well as analysing a city's efficiency in using its available water.

6.2. DBM city water signature

The city signature model includes overview, management and incentives categories (see section 2.3) that are not present in the WBM. These take into account the effectiveness of policies implemented, levels of commitment and action, amount of awareness and promotion. In effect, how efficient the management system is. As discussed previously, this is the social side of the signature, which needs to be incorporated with the physical hydrological context.

Ideas of how to achieve this were considered, such as using the management and incentives signature scores as a factor that would affect the overall supply and demand, or a global factor that influenced each WBM parameter individually. Or, in order to relate back to the WBM, the social side of the city signature may emerge as a manifestation of the 'other water' (O) human additions to the hydrological cycle.

Alternatively, by reorganising the signature categories to match the inputs of the WBM, the signature scores could be used together with the corresponding base value inputs to the WBM to dictate future behaviours of the city. For instance, a city with a population of 10 million and a population score between 0 and 3 could have a population decrease by 2% a year, whereas a population score of 7 to 10 could increase by 5% a year.

A problem with this method is that the signature scores have been designed to encompass current and future trends, which together is represented by a single score. This means that for example, a high water consuming city with distinct aims to reduce its consumption would have the same score as a low water consuming city with high expected growth in consumption. As a score, this may reflect an overall similar effect, but in terms of predicting dynamic future behaviours, would produce contrasting outcomes which need to be differentiated (it is as if cities lie at different points on a city lifetime curve, for example in water consumption in Asia [13]).

A city signature score could also translate straight into base model inputs, for example, a population score of 1 could translate to 1 million people, 5 to 15 million, 10 to 30 million. Or, given an approximate base level, the signature score could adjust the base value by say +/-25%, similar to the validation case matrix. However, for all of these methods, calibration of the model is needed, by finding data for a current or future date coupled with the expected growth rate and thus matching this to its signature scores. Cities are however to a certain degree unique, therefore this would not be a reliable method.

Looking at the validation case matrix, it can also be argued that each run is an implementation of a city water signature that modifies the base model inputs. The runs in the case matrix could be interpreted as the result of a chosen behaviour at a fixed single future date. More useful would be a model that could predict several future dates based on certain behaviour rules or management strategies that a city may choose to follow over time. If these rules were dynamic with time and related between each other, some interesting behaviours may result for city interactions in a same basin.

These signatures are therefore strategies of how cities change their water usage under good, average or bad conditions, either by management choice or by human nature, such as behaviours of how people may react as limits are reached, from inherent lack of resource or environmental and other pressures. The rules could be based on the inputs only or also on the outputs through a feedback system, or adhere to strict management rules.

6.3. Dynamic behaviour rules

Simple rules could include an even increase in inputs with time, scale-free behaviour or preferential attachment up until an input threshold is reached, after which behaviour may change.

A city signature includes behaviours which change with time depending on the model output, where the model output chosen is the *SDR*. The *SDR* was taken as a more appropriate output to analyse than the *SDG*, where in this case the graphical gap was not needed and negative outputs could be misleading. An interesting threshold in this respect would be when the *SDR* falls below 1, or approaches 1, as this means that the demand will outstrip supply.

Other behaviours can be explored as well, such as a lag in response to a threshold being reached. For example, it may take time for a management system to react or for its policies to take real effect. Alternatively, if water supplies are low, industries may stagnate for a few years as they readjust to be more efficient and decrease their water footprint requirements, or deal with economic downturns.

Decays can also be introduced, for instance a first-order decay in the total water available due to glacier melt or an increased abstraction. Ground water supplies may also reduce with depletion of reserves and a reduced water table depth. In either case, a threshold value may be needed for long-term simulations. In addition, as a city runs out of water, people may start moving out of the city at a rate which would accelerate as the *SDR* falls further below 1.

A random factor can be introduced, where decay constants or yearly decrease rates vary within a number of deviations from the mean, thus taking into account climate variability or the unpredictability of reaching management targets. Management strategies themselves can be tested, such as reaching a target by a fixed year or making a fixed target decrease per year. For example, aiming to decrease water consumption to 10 lpcd by 2025, or decrease losses in the system by 5% a year till it is at 5%.

More drastic scenarios can also be simulated, for example a failure in a water treatment plant or dam, a natural hazard disrupting a supply network or harsh climate changes drying up supplies. The resilience of cities can then be assessed in this way with respect to water supply, an issue of rising concern for the future [27].

6.4. Defining interesting scenarios

The main issues reported by the people living in the Yangtze basin are contaminated water, therefore a lack of sanitation and inadequate hygiene leading to disease [16][42]. For instance, apart from constant reports of the high levels of pollution in China's waterways, as well as land and air pollution, this was recently brought to the attention of the international media when authorities claimed that the discovery of thousands of dead pigs in Shanghai's water supply posed no risk, showing on World Water Day Friday 22 March 2013, the scale of the global water and sanitation crisis [50]. This could be modelled as a drastic interruption of supply, and the increasing pollution as an exponential decay of the total water supply.

6.5. Aggregate scenarios: agent-based modelling

Ultimately, this project aims to investigate how user-agent cities interact with each other within a confined water system or basin, that is how people will react collectively as supplies get more scarce in the future, with impacts on regional governance and investment.

Different regional scenarios can be developed, exploring aggregate behaviours, tradeoffs and pressures which may arise. Dynamic city behaviour rules would then incorporate the regional dynamic aggregate *SDR* as well as the individual city *SDR*. Regional policies can then be applied, for example a regional cap on population growth, where the effects on individual cities can then be analysed. In this way, a limit on the sum of behaviours can be applied, that is being attentive to behaviours that might become unreasonable together. In addition, regional climate changes can also be investigated.

Other interactions could include looking at the effects one user-agent city may have on others, if for instance an upstream city decides to build a dam or increase its use upstream, or invests in better treatment facilities or in more industry. The effects of the national government prioritising one city over others and thus pouring more money into it or diverting more water to that city can be analysed, for example Beijing during the 2008 Olympic games [5]. Other scenarios can be developed too, looking at the effect if only two out of three cities cooperate on saving water, or the effect of a strategy that involves taking as much water as possible now to the detriment of others, compared to strategies that involve full cooperation.

7. DBM: Results

The dynamic behaviour model was built up systematically, where after introducing a new variable or scenario, it was made sure that the model could crash, stay stable and rise for all input base values. Instances where the model did behave unexpectedly, the solutions or reasons found will be detailed now. Focus will be put on showing examples of what the model can do, before applying it to the case study and looking at current concerns and potential future scenarios. Many model parameters can be adjusted, as can the rules, making it flexible to diverse situations, where the project will focus on creating an adaptable tool more than trying to predict accurate results from present day inputs.

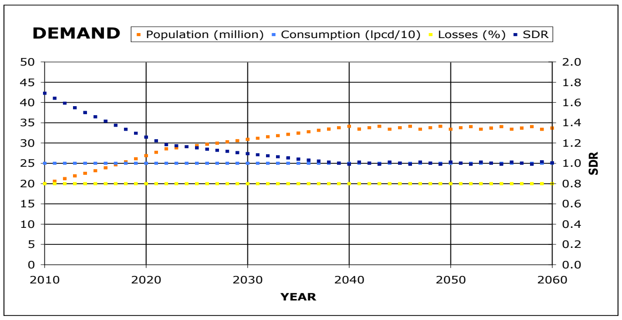
7.1. Results

Graphs of demand, supply and reuse will be shown, where the *SDR* is plotted on each. A timescale of 50 years has been chosen from 2010, with a time step of one year. This length is sufficient to show decent progressive change, after which the situation by 2060 may be different in ways we cannot predict as reliably in the scope of this project.

For the purpose of demonstrating how the model works, a city of average water signature base input values has been used, with some modifications to point out particular aspects of the model. Water consumption per person has been reduced by a factor of 10 for better comparison of magnitude on the graphs. A list of the definition of all the rules explored here can be found in APPENDIX A.

	Population	Hydrological Context		City parameters						
Input	Population	Total Water Available	Surface Ratio	Consumption	Losses	Surface % of Surface availability	Ground % of Ground Availability	Reuse	Treatment	Other water
Unit	M	Bm^3/year	-	lpcd	%	%	%	%	%	Bm^3/year
Base Case (2010)	**20**	**30**	**0.9**	**250**	**20**	**10**	**5**	**15**	**70**	**0.5**

Figure 14: Average city water signature used in example graphs



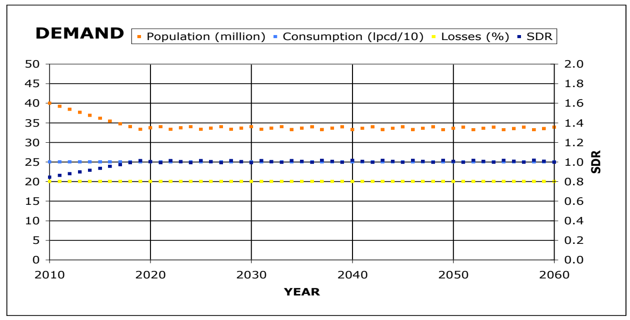


Figure 15 and Figure 16: Population is SDR dependent with no threshold limit (with input values 20M and 40M) – POP1

Figures 15 and *16* demonstrate a dynamic behaviour rule on population, where population will increase by 5% if *SDR*> 1.2, increase by 3% for 1≤*SDR*≤1.2 and decrease by 2% if *SDR*<1 (rule POP1). All other inputs are kept constant, so we can see that the *SDR* moves towards 1 before settling at a steady value of population of 34M (which is the equilibrium value for the given inputs, reached at 2040 from an input of 20M and at 2019 from an input of 40M). The horizon at which a *SDR* of 1 is reached depends on the rule definition, for example having more or different threshold conditions.

For instance, the population growth in Asia for megacities with current populations of 10M to 30M is a 40% increase from 2011 to 2025 [9], although it varies on other continents, and this could thus be used to define a rule.

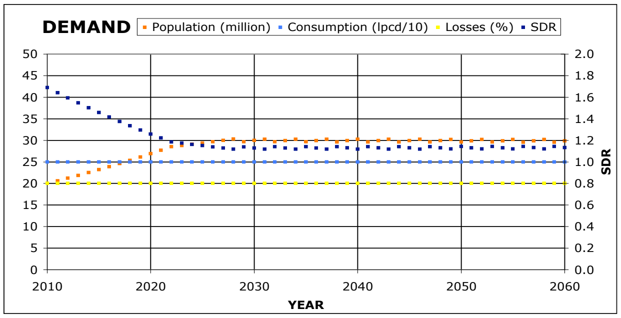
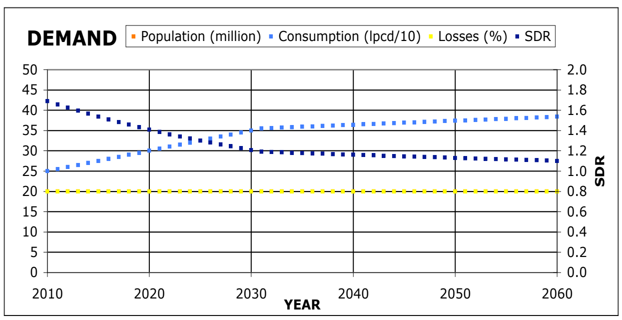


Figure 17: Population is limited at a threshold – POP2

In *Figure 17*, population behaves in a similar fashion as in *Figures 15* and *16*, but this time it does not increase further than a threshold of 10M more than the its base value (rule POP2). In this case, the *SDR* will settle at that point (around 2023 at a *SDR* of 1.15).



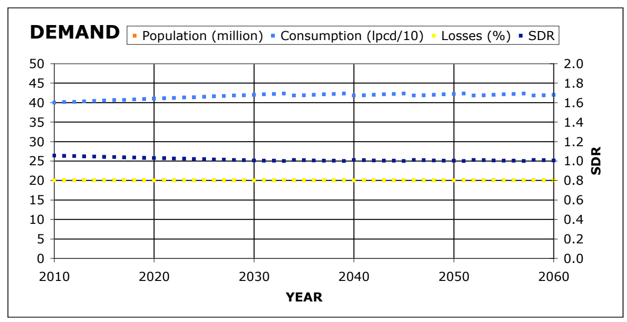
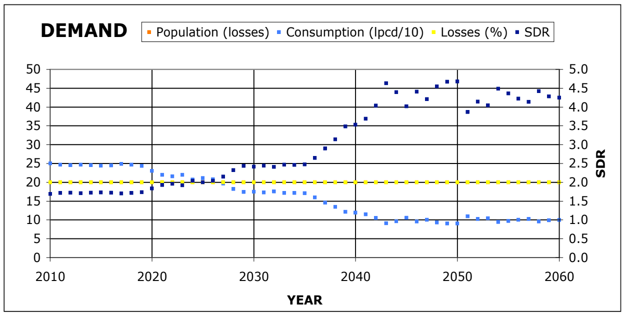


Figure 18 and Figure 19: Consumption is SDR dependent with no limit (with input values 250 lpcd and 400 lpcd) – CONS1

In *Figures 18* and *19*, all inputs are kept constant apart from consumption which follows a behaviour rule per year of an increase of 5 lpcd if *SDR*> 1.2, increase of 1 lpcd for 1≤*SDR*≤1.2 and decrease by 5lpcd if *SDR*<1 (rule CONS1). Again we can see that the *SDR* moves towards levelling off at 1. An increase of 1 lpcd per year is a measure to trigger behaviours, where instead if it were kept constant for certain values of *SDR* with no other changing inputs or randomness introduced, this will cause the model to stagnate.



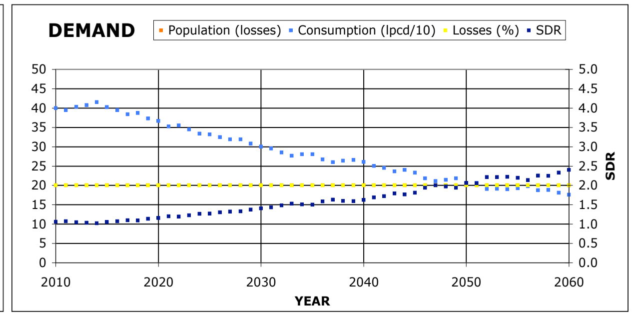


Figure 20 and Figure 21: Consumption follows management rules including a lag and threshold value, with introduced randomness (with input values 250lpcd and 400lpcd) – CONS2

In *Figures 20* and *21*, consumption follows a management rule that from 2015, consumption must decrease by 5 lpcd per year until a threshold of 100 lpcd is reached. In addition, a degree of randomness has been introduced whereby the yearly decrease will be 5 lpcd but the actual value may vary by ±10 lpcd (rule CONS2). This could account for climatic variations as well as human variations. As we shall see in later examples, such randomness can trigger interesting behaviours, as it can cause values to cross over designated thresholds.

For the base value of 250 lpcd, CONS2 implies that the *SDR* keeps increasing and that for a base value 400 lpcd, where initially the *SDR* was balanced around 1, nonetheless it too increases as no other input is changing (note the scale of *SDR* is increased to 5). As consumption decreases, the *SDR* becomes more sensitive to random changes in consumption as would be expected from the definition of demand and a high *SDR*. Other management rules could involve several targets and stages, with different rules to reach them.

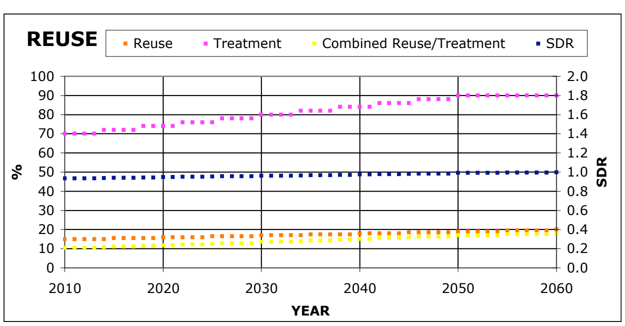


Figure 22: Reuse and treatment of water are SDR dependent – REUSE1

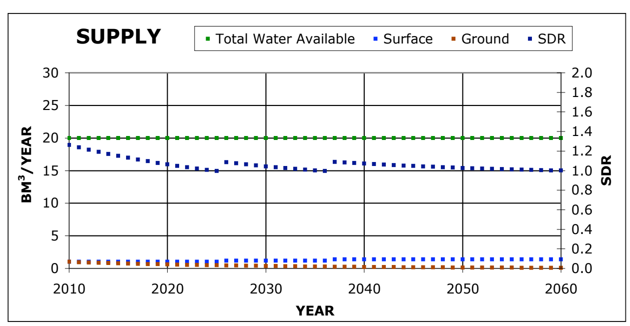


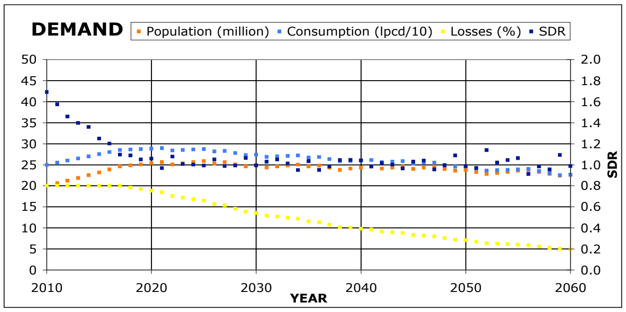
Figure 23: Supply (surface and ground water) is SDR dependent – SUPP2

In *Figure 22*, reuse and treatment percentages are dependent on *SDR*, whereas all other inputs are kept constant. In order to trigger a response, the demand was increased (by a population increase to 30M) and the total supply decreased to 24Bm^3/year. Here, the reuse percentage will increase by 0.5% after a lag of 5 years if the *SDR* is below 1 until a threshold of 25% and treatment will increase by 2% after a lag of 5 years if the *SDR* is below 1 until a threshold of 90% (rule REUSE1). In this particular instance, a *SDR* of 1 is reached in 2060, after treatment has levelled off at its threshold value. Different limits, amount of increase and lag, or even a rule on the combined reuse and treatment percentage can be used.

Reuse in particular needs to be capped, especially if a city has a large water supply, where a high reuse percentage would increase the overall supply considerably. This brings in to question the issue of quality, where the quality of water is always decreasing so perhaps a decay function should be introduced or reuse should be computed differently. In either case, a high investment in infrastructure to move the water will also be needed (additional pumps and pipes).

In *Figure 23*, we are looking at the supply dynamics when all other inputs are kept constant. Again to trigger a response and for easy comparison, the surface and ground water percentages were set at 10%, with a 0.5 ratio between their use and a decreased total supply of 20Bm^3/year. In this example, the surface water was increased by 2% after a lag of 5 years when the *SDR* falls below 1, and the ground water experiences an exponential first-order decay of $e^{-0.05\Delta year}$ (rule SUPP2). This mimics the scenario where when in need, a city may resort to transferring additional water from a new river or extracting more from current surface water sources, but ground water becomes more scarce. In the following examples however, the surface water will increase by 0.5% every 5 years, with an exponential decay in ground water (rule SUPP1). It was found that this usually resulted in the same quantity of water supplied by 2060, but where SUPP1 had smaller but more frequent increases in supply compared to SUPP2.

The WBM input 'other water' (*O*), that is human additions to the hydrological supply, has not featured in this example nor will it in future ones, as it is modelled in a similar fashion to surface water, where for instance a desalination plant could be built instead of transferring water from another area. Investigating the limits on whether a city resorts to surface transfers or more desalination could be explored however, by putting different pressures in the rules governing the decisions. The unit of *O* has been set as base value in Bm^3/year as opposed to a percentage of total water available, which could allow for different rules to be applied.



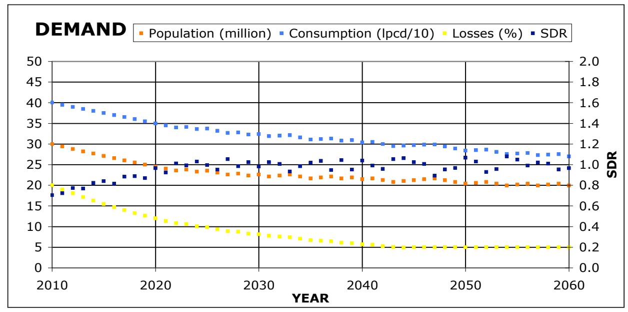
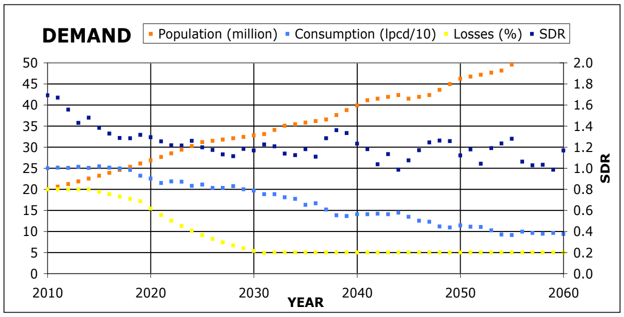


Figure 24 and Figure 25: Demand curves with SDR dependent population, consumption and losses (with input values 20M and 250 lpcd, and 40M and 400 lpcd) – POP1, CONS1, LOSS1, TOTAL2

In *Figures 24* and *25*, population follows the rule POP1, and consumption follow the rule CONS1. In addition, the loss will stay constant if *SDR*> 1.2, decrease by 2% for 1≤*SDR*≤1.2 and decrease by 5% if *SDR*<1 until a threshold value of 5% (rule LOSS1). The best scenario for unaccounted water is 5%, with developed cities ranging from 10 to 15% [21]. Unaccounted water involves many water flows, from leakages and inaccuracies to other water streams such as fire and landscaping [21]. There is also a decay of $e^{-0.015\Delta\text{year}}$ in the total water available with a degree of randomness added of within ± 1.5 Bm^3/year (rule TOTAL2), which is not shown in the demand graphs (but can be seen in later supply graphs). Rule TOTAL1 includes the decay factor of $e^{-0.015\Delta\text{year}}$ without randomness introduced. The TOTAL rules act as important triggers in later graphs, representing a decline in total water available through climate change, pollution or more demand elsewhere.

We can see that in *Figure 24*, the city over consumes water and has a large population growth in the early years, responding to a large supply of water. Population and consumption then accommodate to the declining overall supply, despite reduction in losses. *Figure 25* shows a city with initial lack of supply, where again population and consumption decreases in line with a decrease in total supply, but there is also a drive for a more efficient network from the start.



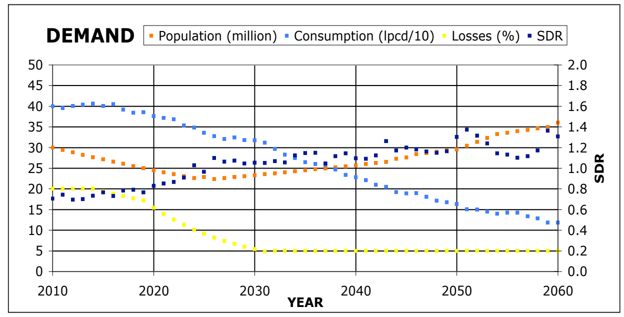
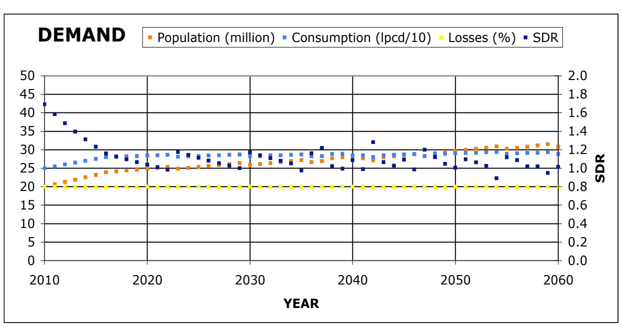


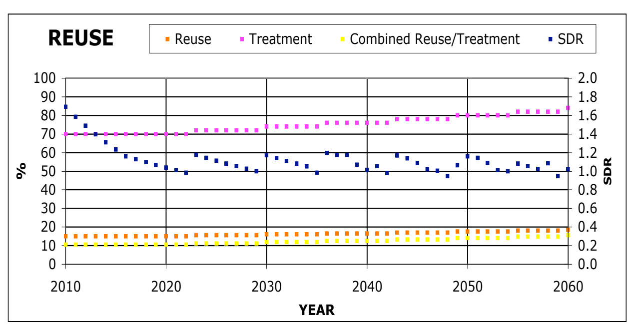
Figure 26 and Figure 27: Demand curves with SDR dependent population but management strategies on consumption and losses- POP1, CONS2, LOSS2, TOTAL2

Figures 26 and *27* follow the same population rule POP1 but instead applies management strategies on consumption (CONS2) as well as a management on losses, with a 3% decrease per year from 2015, followed by a 10% decrease a year from 2020 until a threshold of 5% loss is reached (rule LOSS2). Again, a declining total supply is in effect (TOTAL2).

We can see that due to the randomness introduced in the total supply and in consumption, this allows for unpredictable jumps in *SDR* bringing it pass threshold values thus triggering different behaviours, such as a change in the severity of a rule parameter or even bringing about a change in direction of an input. In reality, this would likely occur with a lag in time.

In the case where the base input for population is 20M, population grows uncontrollably with declining consumption. This alludes to the fact that a change in behaviour may be needed at a certain threshold, either a capping pressure on population like POP2 or even decelerating rules as people move out of the city.





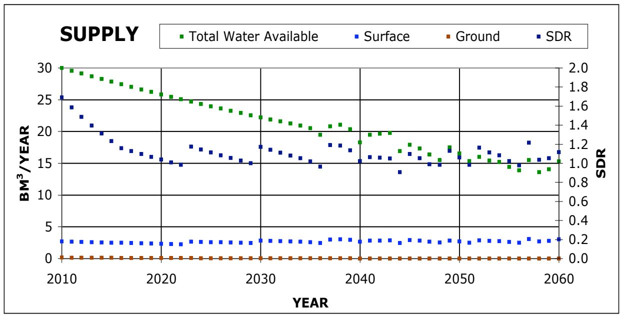


Figure 28, Figure 29 and Figure 30: DBM results for POP1, CONS1, REUSE1, SUPP2, TOTAL1 (2010-2035), TOTAL2 (2035-2060)

Keeping the same rules on population and consumption (POP1, CONS1), adding reuse and treatment (REUSE1), then adding supply (SUPP2) were tested separately. Interestingly, they lead to similar results, where the population and consumption levelled off around 2020 when the *SDR* reaches 1. The supply rule allows for a little more growth. *Figures 28*, *29* and *30* show the effects if both supply and reuse are in effect at the same time with demand. From 2010 to 2035, the total supply decays exponentially (TOTAL1), and from 2035 decays with introduced randomness (TOTAL2).

Again we can see that all variables adjust to maintain the *SDR* around 1 despite a total decline in available water. With no introduced randomness, the effect when the supply is increased (for example a new transfer is built) is apparent, as this is defined in the rule. The rule dictates an increase in the percentage of water supplied, even though the total supply is decreasing. It may be more appropriate in some instances to incorporate an increase in the actual amount supplied.

Starting with different base values, all lead to a gravitation towards an *SDR* of 1. Having a high initial *SDR* leads to population and consumption growth (see *Figure 28*), before a *SDR* of less than 1 is reached and triggers eventual decline around 2020. This is how the rule is defined, therefore experimenting with threshold values of *SDR* of 1.1 or 1.2 could be performed, and looking at the year they are reached. Different inputs could also have different *SDR* threshold points. The rules can also be manipulated by changing the percentage increases and decreases per year for example, which would delay or accelerate the point at which a *SDR* of 1 is reached, where in the above example, this is achieved within 10 years.

Next, these individual city water signature rules will be explored within a regional context, allowing for interactions between user-agent megacities in a basin.

8. Aggregate dynamic behaviour model: Case Study Results

In order to analyse regional effects, it was decided to sum the total demands and total supplies of the individual cities, and thus create an aggregate *SDR*. The sum of individual inputs such as total population or water consumption can also be used as rule thresholds. This method was deemed most useful in looking at interactions, compared to looking at effective area water footprints or other methods.

Various interesting scenarios can then be applied to the case study. This includes looking at the effect of dynamic aggregate rules on the individual cities, such as a regional pressurising cap. Major disruptions can also be analysed, as well an investigation into the effects of unpredictable climate change. A list of the definitions of aggregate rules can be found in APPENDIX A.

8.1. Without aggregate dynamic rules

First of all, the dynamic demands and supplies of Shanghai, Wuhan and Chongqing were plotted for later base comparison (see *Figure 31*), using the 2010 data estimates found in APPENDIX D. In all of the ensuing examples, the following rules were applied to each city: POP1, CONS1, REUSE1, SUPP1, LOSS1, TOTAL1. Without randomness, the decrease in total water availability can be easily seen, triggering responses in the other inputs. Boosts in supply and reuse can be noted by the jumps in *SDR*, which are smaller for Shanghai due to its initial larger supply (thus an increase in percentage supplied has smaller effect) and thus leading to less growth in population and consumption. These jumps are smoothed out when combined in the aggregate demand.

Figure 31: Demand curves without aggregate dynamic rules

8.2. Regional cap on population and consumption: all cities cooperate

Aggregate dynamic rules are applied here: a cap on total population at 50M, when if this cap is reached, individual cities decrease population by 2% a year (rule AGGPOP1). Also, there is a cap on total consumption at 500 lpcd, when if this cap is reached, individual cities decrease consumption by 5 lpcd a year (rule AGGCONS1).

AGGPOP1 is a less pressurising cap compared to AGGCONS1, where the base aggregate population in 2010 is 40M compared to a cap of 50M and the base aggregate consumption is 906 lpcd compared to a cap of 500 lpcd. These differing pressures can then be compared in later graphs. Considering 3 cities of equal base values, these caps would be pushing for 3 cities of population just under 17M and of consumption just under 170 lpcd, that is reasonably large and consuming. In fact, the average population of all 37 UN 2025 megacities is 17M [9], and developed cities such as London, Brussels and Berlin consume around 150 lpcd now, which is why a regional cap of 500 lpcd was imposed for added pressure [14]. Interestingly however, as a comparison, the Asian Green City Index reported that developed cities such as Tokyo, Taipei and Singapore level off around 310 lpcd [13], and in the worst case of disaster relief, a minimum of 15 lpcd is required [56].

When low-pressure regional caps are applied, the individual city equilibrium *SDR*s of 1 are reached, where the caps are offset by either a decrease in population or consumption as applicable, or less supply and reuse being sought out. As regional caps become more severe, a *SDR* of 1 takes longer to reach. Caps lower than 50M or 800 lpcd lead to significant change, meaning supply rules never take effect. As the population cap decreases, *SDR* will stay greater than 1 if there is a pressurising consumption cap in place too. If the consumption cap is not in place, population will remain small, but supply rules will come into play to compensate consumption if needed. In effect, there will be a tradeoff between the two. The same effect applies for visa versa, with consumption caps and population.

Figure 32: Demand curves with AGGPOP1 and AGGCONS2, all cities cooperate

In *Figure 32*, different behaviours are observed per city. All three cities decrease their water consumption until the regional cap is reached around 2050. There is a lower threshold limit of 150 lpcd for individual cities (rule AGGCONS2). This is to prevent Chongqing's consumption from decreasing below 100 lpcd (as it starts off with the lowest consumption and so is most influenced by the regional cap) and therefore to avoid large increases in its *SDR* (demand graphs of these results can be found in APPENDIX E.1.). Thus, to compensate, Shanghai's consumption decreases for longer and settles around 200 lpcd at 2050.

Population increases until the regional cap is reached at around 2020, after which it stays constant for Chongqing and Wuhan as their consumption levels off, but fluctuations are seen for Shanghai as its consumption decreases for longer. The individual *SDR*s remain above 1, until around 2050 for Wuhan and Chongqing, where a jump in *SDR* is due to an increase in supply due to the *SDR* dipping below 1 at that point.

The aggregate *SDR* reaches 1 around 2020, and thereafter is constant, despite the changing individual *SDR*s. The latter represents the water balance of individual cities, showing the need to balance regional environmental goals with the severity of measures individual cities are required to undertake without compromising their own futures.

For example, without a lower limit threshold on consumption, all three cities decrease their water consumption until the regional cap is reached, which is therefore sooner at just before 2040 (see graphs in APPENDIX E.1., rules AGGPOP1 and AGGCONS1). After the cap is reached, Chongqing's consumption (below 100 lpcd) increases to rebalance its SDR of above 2. Population adjusts accordingly and as the *SDR* never falls below 1, increases in supply and reuse do not come into effect.

Another option that could be implemented is differential treatment, where Shanghai must decrease its consumption by 10 lpcd per year instead of by 5 lpcd like the other cities (see graphs in APPENDIX E.2., rules AGGPOP1 and AGGCONS3). In this case, Shanghai takes the burden, leading to a distinct *SDR* rise above 1. Supply and reuse rules do not thus come into play, meaning the *SDR* stabilises and only declines as the total water decreases. The regional cap is reached quicker at 2030, therefore the other cities can stop decreasing their consumption sooner too. In effect, it appears that strict management brings a city's supply above its demands, before climatic influences catch up, but measures must be kept within reason.

8.3. Regional cap on population and consumption: two out of three cities cooperate

In this case, the regional cap on consumption is at 500 lpcd for Shanghai and Wuhan, where if the cap is reached, the individual cities decrease their consumption by 5lpcd a year. However, Chongqing simply follows CONS1 (rule AGGCONS4).

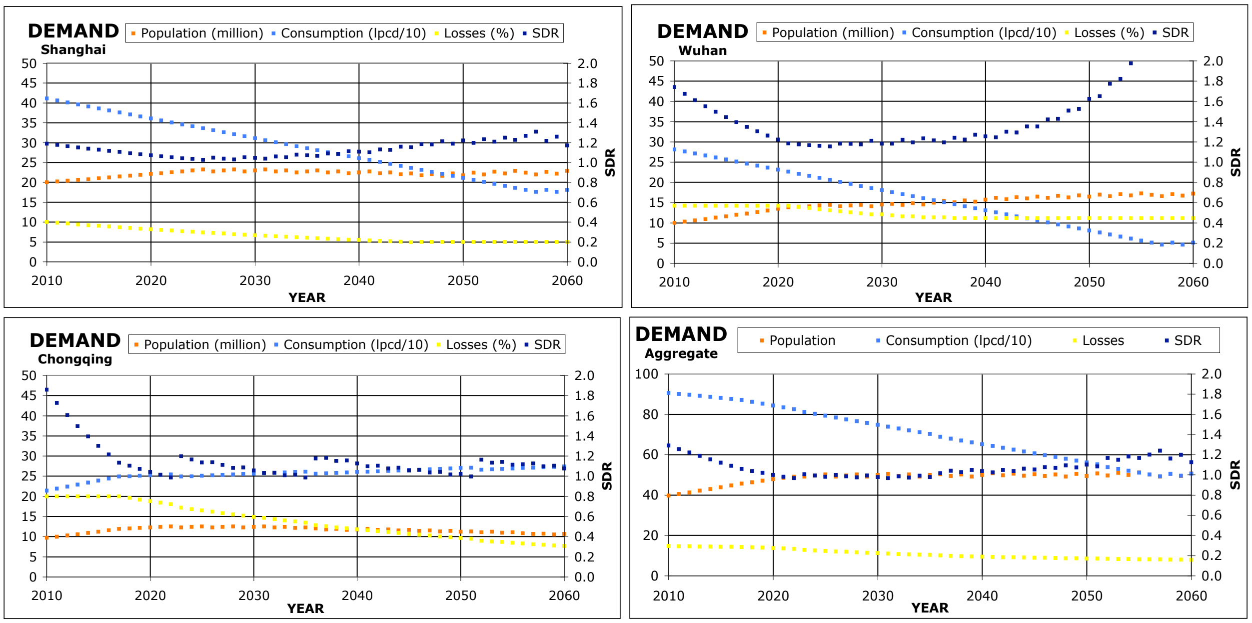


Figure 33: Demand curves with AGGPOP1 and AGGCONS4: two out of three cities cooperate

In this case, the regional cap is reached later at 2060, and the aggregate *SDR* actually increases over time (see *Figure 33*). This is due to the fact that Shanghai and especially Wuhan, have to compensate for Chongqing to reach the regional consumption cap. Wuhan is severely affected as it starts off with a lower consumption, and in this case, there is no lower limit of 150 lpcd on consumption. If there were, Shanghai would try to compensate but it too would reach the limit and the regional cap would never be attained in this time frame. This is because Chongqing's consumption increases slowly, as it lies outside the regional consumption cap (population is fixed and so supply is used here to balance).

Wuhan's *SDR* keeps increasing until the regional cap is finally reached (as population is capped). Alternatively, a decrease in supply and reuse could be initiated, but if the supply and infrastructure were in place, these would become redundant.

When there is not full cooperation between megacities, reaching a more sustainable scenario for the basin takes more time to the detriment of the cooperating cities, if it is reached at all.

8.4. Disruption

Disruptive scenarios can be modeled, such as supply failures, pigs in the river [50] or prioritisation of cities. In this illustrative example, there has been a dam failure in 2020, upriver to Wuhan but downstream to Chongqing (e.g. Three Gorges Dam). At 2020, Wuhan's surface water decreases by 1% and stays at that point for 5 years, before a slow recovery comes into operation at a reduced rate of 0.3% increase every 5 years. Shanghai is more drastically affected being further downriver, with a surface water decrease of 2% at the same year, a similar 5-year stagnation before a recovery of 0.2% increase every 5 years.

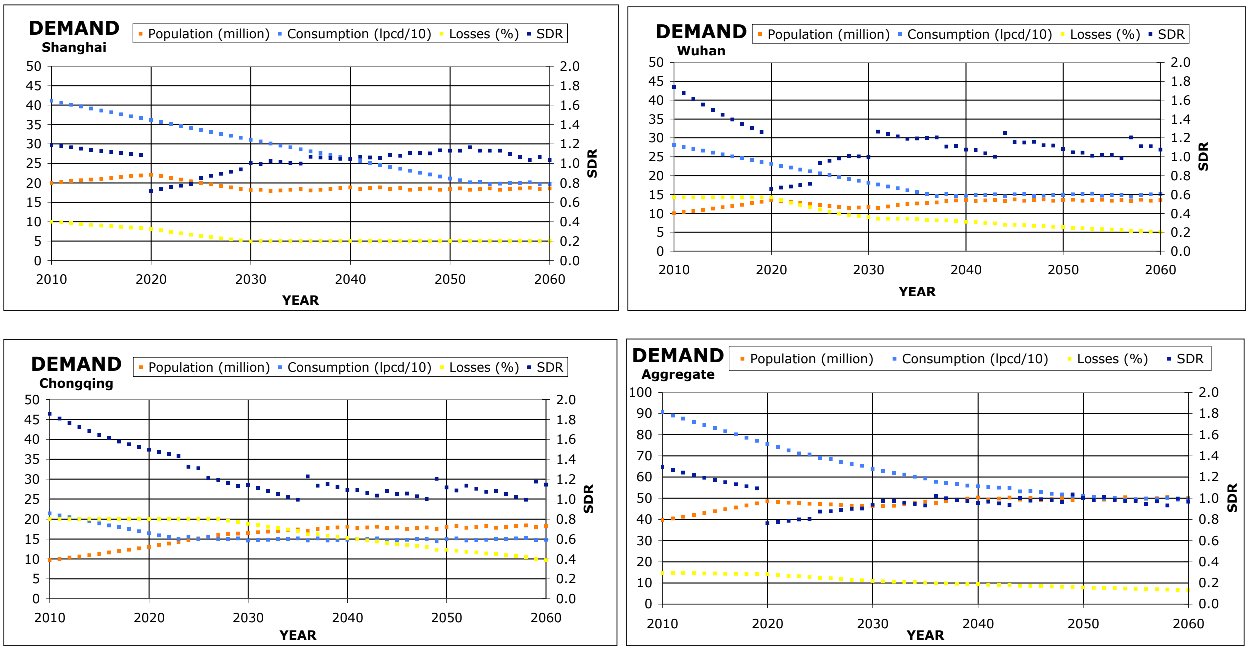


Figure 34: Disaster demand curves with AGGPOP1 and AGGCONS2

The supply disruption for Shanghai and Wuhan is visible by the *SDR* drop at 2020 (see *Figure 34*). The biggest effect is that the *SDR* plummets below 1, leading to a decrease in population for Wuhan and Shanghai and increases in supply to slowly stabilise the situation at 2030, meaning a 10-year period of recuperation.

The consumption cap at 500 lpcd overrules the disruption (being a severe constraint), where consumption decreases at a steady rate to meet the regional constraint despite the disruption. This means that there is less demand to fix the dip in supply, as the decrease in demand is enough.

Chongqing is affected by the disaster, as since the population of the other two cities decreases, this gives leeway for Chongqing's population to increase further within the regional cap than if the disaster had not occurred, reaching around 18M by 2050 as opposed to stagnating at 14M by 2020 (see *Figure 32*). Its consumption is unaffected as to be expected, where the regional cap has overridden the disaster.

If there were no regional caps, after years of increase, the population and consumption of Wuhan and Shanghai would both decrease after the disruption and remain at the lower levels (see APPENDIX E.3.). This disaster thus restricts the long-term aggregate population and consumption (compared to *Figure 31*), leading the cities to find a manageable equilibrium with less supply than if the disaster had not occurred. The aggregate population does not reach the level of *Figure 34* either, as the individual *SDRs* do not rise far above 1, reaching a balance after 2030. With no regional cap, Chongqing is not affected at all by the disaster.

Disruptions thus cause megacities to readjust their water balances to cope, by finding alternative supplies, decreasing overall consumption or forcing people to leave. The resilience of cities can thus be investigated, where in this case a period of around 10 years was needed for recovery. Keeping regional environmental objectives going did not compromise the situation.

8.5. Random decline of total water available

In this example, a declining total water has been explored, with introduced randomness into the system. From 2010 to 2035, TOTAL2 is in effect. After 2035, the decay constant is increased by a factor of 3 to $e^{-0.045\Delta year}$, as is the degree of randomness to ± 4.5 Bm^3/year (rule TOTAL3). This simulates a more severe change in climate for the worse, or the increased impact of overuse and pollution.

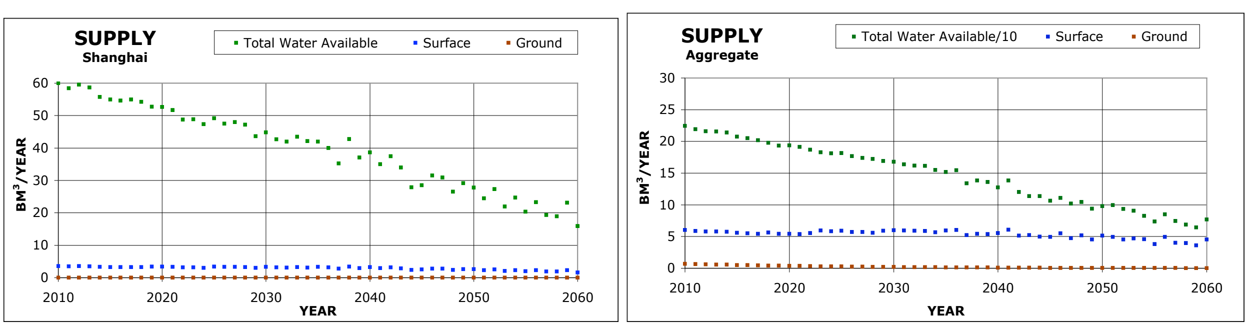


Figure 35: Total water available supply curves with TOTAL2 and TOTAL3, for Shanghai and Aggregate

In *Figure 35*, as the total water available becomes more unpredictable, so does the surface water as would be expected, for individual and aggregate scenarios.

Figure 36: Demand curves without aggregate dynamic rules, with TOTAL2 and TOTAL3

As would be expected, in *Figure 36*, the population and consumption decrease after the climate becomes more unpredictable (compared to *Figure 31*), and considering supply and reuse rules only increase every 5 years (Shanghai is particularly affected as it uses a higher percentage of its total water available). As the total water becomes more or less erratic, the *SDR* follows suit. After 2035, with TOTAL3, an individual city's supply may outstrip its demand one year, but suffer from a lack of supply the next, showing the difficulty of preparing for an unpredictable climate. The aggregate *SDR* is smoothed however, being a summation of individual random factors, as can be seen in *Figure 35*.

Climate will inevitably affect future city water balances, thus analysing worst and best case scenarios should be done in an uncertainty analysis. Introducing randomness to multiple inputs and exploring the spread of outputs could be analysed. Exploring low, best and high base input values as well as a low, best and high behaviour rule parameters could also be done to gain a cloud of model output lines, representing a wide range of potential future scenarios, which would be useful when choosing management strategies and policies.

9. Conclusion and looking forward

9.1. Conclusion

In the face of expanding urban centres and a changing climate, a framework is needed to help us understand the relation between megacities and water. In this way, governing bodies can make informed decisions on the best management strategies to preserve a sustainable future, especially when taking part of a wider regional network of other competing cities in a finite supply of water.

A steady state water balance model was constructed, which gives an estimate of the water demands and supplies in an urban context. Building on from this, a dynamic model projecting into the future was developed, using agent-based modelling to explore the behaviour of megacities individually and under the influence of regional management.

City water signatures, that is an implementation of behaviour rules from base level inputs, were applied to the Yangtze Basin user-agent megacities, and various scenarios analysed, including exploring the horizon after which the *SDR* drops below 1, disruptive scenarios and the resilience of cities, and climate change. It is found to be important to compromise individual city SDRs over the aggregate SDR when applying regional environmental policies. Also, full cooperation of megacities is needed to achieve these environmental goals.

This project concentrates on developing a consistent model framework with explicit assumptions and limitations, thus ensuring its validity across catchments and allowing for fair comparisons. A software numerical model is used to implement the framework, creating a user-operated toolset of governing metrics for testing and analysis, with exemplar dynamic behaviour rules that are adjusted to each catchment.

9.2. Further work

- *Quality*: The individual impacts of agricultural, industrial and domestic water usage have not been considered in the model. The per capita water consumption values used aim to include these three factors as one. However, if the individual impacts were to be analysed, for instance looking at the tradeoffs between investment in agricultural or industrial cuts in water use and infrastructure, this could be incorporated into the model as further work. Concentrating on the issues of reusing water, where quality is involved and always decreasing, can also be made. Investigating the impact of other hydrological processes such as evapotranspiration could also be carried out to verify some of the assumptions made in this project.

- *Economics*: Despite the fact that water is a human right essential for life, the price of water is a powerful and indispensable policy making tool that could be incorporated into the model as a cost function, pushing for properly priced as well as allocated water for all.
- *Uncertainty analysis*: A more thorough uncertainty analysis could be carried out, given that we are considering future predictions. Starting from a full set of assumptions, each of which has a range around its 'best predicted' value for a scenario, a cloud of model lines could be computed at a given point in time, or space-time for multiple cities. This would be useful for management decisions, compromising between either a narrow cloud of reliable model results in an acceptable position or a cloud that allows for a wide variation of possible outcomes but in an optimal position.
- *Surface, ground and other water*: Explore the tradeoffs between opting for increased surface water transfers, ground water extraction or investment in newer technologies such as desalination.
- *Other case studies*: Apply the model to other case studies, for example the Ganges-Brahmaputra-Meghna basin.

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APPENDIX A: Behaviour Rules

Behaviour Rule ID	Definition
POP1	Population increase by 5%/year if *SDR*> 1.2, increase by 3%/year for 1≤*SDR*≤1.2 and decrease by 2%/year if *SDR*<1
POP2	POP1 with upper threshold of 10M more than base value
CONS1	Consumption increase of 5 lpcd/year if *SDR*> 1.2, increase of 1 lpcd/year for 1≤*SDR*≤1.2 and decrease by 5lpcd/year if *SDR*<1
CONS2	Consumption decrease by 5 lpcd/year from 2015 until threshold of 100 lpcd. Values may vary within ±10 lpcd.
LOSS1	Loss constant if *SDR*> 1.2, decrease by 2%/year for 1≤*SDR*≤1.2 and decrease by 5%/year if *SDR*<1 until a threshold value of 5%
LOSS2	Loss decrease of 3%/year from 2015, followed by decrease of 10%/year from 2020 until a threshold of 5%
SUPP1	Surface water increase by 0.5% after a lag of 5 years if *SDR*<1, ground water has exponential first-order decay of $e^{-0.05\Delta year}$
SUPP2	Surface water increase by 2% after a lag of 5 years if *SDR*<1, ground water has exponential first-order decay $e^{-0.05\Delta year}$
REUSE1	Reuse increase by 0.5% after a lag of 5 years if *SDR*<1 until a threshold of 25%, treatment increase by 2% after a lag of 4 years if *SDR*<1 until a threshold of 90%
TOTAL1	Total water available exponential first-order decay of $e^{-0.015\Delta year}$
TOTAL2	Total water available exponential first-order decay of $e^{-0.015\Delta year}$. Values may vary within ± 1.5 Bm^3/year.
TOTAL3	Total water available exponential first-order decay of $e^{-0.045\Delta year}$. Values may vary within ± 4.5 Bm^3/year.
AGGPOP1	Cap of 50M on aggregate population, after which individual cities decrease population by 2%/year
AGGCONS1	Cap of 500 lpcd on aggregate consumption, after which individual cities decrease consumption by 5 lpcd/year
AGGCONS2	AGGCONS1, but with lower limit threshold of 150 lpcd for individual cities
AGGCONS3	AGGCONS1, but Shanghai decrease consumption by 10 lpcd/year, Wuhan and Chongqing by 5 lpcd/year
AGGCONS4	AGGCONS1, but Chongqing follows CONS1

APPENDIX B: Validation Results

B.1. Example WBM validation case matrix results for Shanghai

52 runs were simulated in the validation case matrix as follows, with the aim of best testing the model's sensitivities as well as exploring different possible future scenarios.

Case matrix definition:

- 75% of base value is non-bold input e.g. *P* = 75 % of base value of population
- 125% of base value is **bold** input e.g. ***C*** = 125% of base value of consumption
- *SS* is 50% supply, ***LL*** is 150% loss

Run ID	Definition	Water Supply	Water Demand	SDG	SDR	Run Description
001	Base Case (2010)	11.0	9.2	1.9	1.2	Base value outputs
002	***P***	11.0	11.4	-0.4	1.0	These conditions reflect possibility of some growth or decay (variance of a quarter of the estimated base value), with all other inputs held equal
003	*P*	11.0	6.9	4.2	1.6	
004	***C***	11.0	11.4	-0.4	1.0	
005	*C*	11.0	6.9	4.2	1.6	
006	***L***	11.0	9.4	1.7	1.2	
007	*L*	11.0	8.9	2.1	1.2	
008	***T***	11.3	9.2	2.1	1.2	
009	*T*	10.8	9.2	1.6	1.2	
010	***R***	11.3	9.2	2.1	1.2	
011	*R*	10.8	9.2	1.6	1.2	
012	***S***	13.8	9.2	4.6	1.5	
013	*S*	8.3	9.2	-0.9	0.9	
014	***G***	11.0	9.2	1.9	1.2	
015	*G*	11.0	9.2	1.9	1.2	
016	***O***	11.0	9.2	1.9	1.2	
017	*O*	11.0	9.2	1.9	1.2	
Demand sensitivities						
018	***PC***	11.0	14.3	-3.3	0.8	Continued growth and no adaptation
019	***PC***	11.0	8.6	2.4	1.3	Continued growth but improvement in per capita water

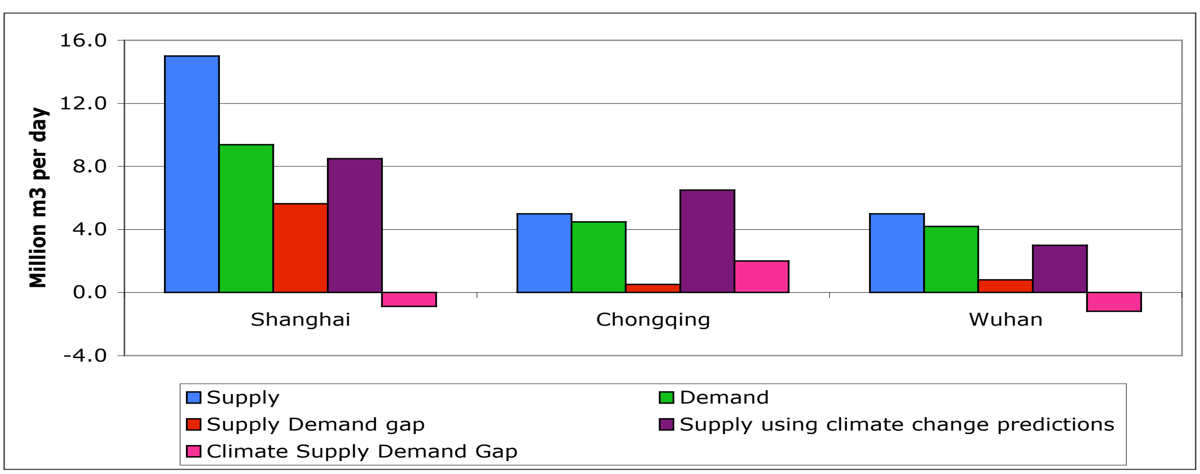
						demand via e.g. education and improved efficiencies
020	***PC***	11.0	8.6	2.4	1.3	Population decreases due to disasters (illness, natural) but still consumes a lot
021	*PC*	11.0	5.1	5.9	2.1	Population and demand decrease due to management strategies or natural phenomena
022	*PCL*	11.0	5.3	5.8	2.1	Population and consumption controlled, but losses in network remain high
023	*PCL*	11.0	14.0	-2.9	0.8	Continued population and consumption growth, but management focuses on decreasing water losses
024	***PCO***	11.0	14.3	-3.3	0.8	Population and growth not controlled, instead more high technology supply is found
025	***PCTR***	11.6	14.3	-2.7	0.8	Treatment and reuse is championed, yet population and expectations still not controlled
Treatment and reuse sensitivities						
026	***TR***	11.6	9.2	2.4	1.3	Wastewater treatment and reuse is concentrated on
027	***TR***	11.0	9.2	1.8	1.2	Treatment is concentrated on, but water not reused directly for humans
028	***TR***	11.0	9.2	1.8	1.2	Treatment is still poor, however more water is reused generally
029	*TR*	10.6	9.2	1.4	1.2	Both treatment and reuse remain poor
030	***LTR***	11.6	9.4	2.2	1.2	Treatment and reuse are championed, yet losses in the network are still high
031	***LTR***	11.6	8.9	2.7	1.3	The whole treatment management network is improved
Supply sensitivities						
032	***SG***	13.8	9.2	4.6	1.5	More surface and ground water is transferred, extracted or there are improved climatic conditions
033	***SG***	13.8	9.2	4.6	1.5	More surface water is found, but ground water decreases
034	***SG***	8.3	9.2	-0.9	0.9	More ground water is found, but surface water decreases
035	*SG*	8.3	9.2	-0.9	0.9	There is scarcity of water
036	*SGO*	8.3	9.2	-0.9	0.9	Supply transfers and extractions decrease, but high technology sources increase
037	***SGO***	13.8	9.2	4.6	1.5	More supply is found overall, but high technology sources decrease
038	***LSG***	13.8	9.4	4.4	1.5	More supply is found, but losses in the system remain high
039	***TRSG***	14.5	9.2	5.3	1.6	More raw supply is found, and more of it is recycled
040	*TRSG*	8.7	9.2	-0.5	1.0	High degree of treatment and reuse, but supply falls
041	*PCSG*	8.3	14.3	-6.0	0.6	Extreme scenario, water is scarce and demand is high

042	***PCLSG***	8.3	14.0	-5.7	0.6	Water scarcity, high demand but low losses
043	***PCTR**SG*	8.7	14.3	-5.6	0.6	Water scarcity, high demand but reuse is championed
044	***PCSGO***	8.3	14.3	-6.0	0.6	Water scarcity, high demand therefore more man-made water available
044	***PCSG***	13.8	14.3	-0.5	1.0	More supply is found, but population and demand increase too
045	***PCSG***	8.3	14.3	-6.0	0.6	Best scenario, lots of supply and low demand
Worst case scenarios						
046	***PCL***	11.0	14.6	-3.6	0.8	Worst Case Demand: Population and consumption not controlled, nor network losses - very mismanaged city
047	*SGO*	8.3	9.2	-0.9	0.9	Worst Case Supply: All types of supply decreases, scarcity and economic poverty
048	*TR*	10.6	9.2	1.4	1.2	Worst Case Reuse and Treatment: Very little water recycling
Resilience/Climate tests						
049	*SS*	5.5	9.2	-3.6	0.6	Supply is cut due to dam failure or climate change…
050	*TR*	10.6	9.2	1.4	1.2	A treatment plant and a reuse plant fail
051	***LL***	11.0	9.6	1.4	1.2	A pipe bursts, or some other channel, leading to high losses of water
052	*PCSG*	8.3	5.1	3.1	1.6	Supply decreases due to scarcity, therefore population and its consumption also decreases to comply

APPENDIX C: WBM Scenario Results

C.1. Surface water depends on climate model predictions of runoff

Runoff assumed linked to surface water with percentage change from the 2010 base values: -50% for Shanghai, +30% Chongqing and -40% Wuhan (only demonstrative values)



APPENDIX D: Base Value Inputs for Aggregate Dynamic Behaviour Model

	Population	Hydrological Context		City parameters						
Parameter	Population	Total Water Available	Surface Ratio	Consumption	Losses	Surface % of Surface availability	Ground % of Ground Availability	Reuse	Treatment	Other water
Unit	M	Bm^3/year	-	lpcd	%	%	%	%	%	Bm^3/year
Shanghai	20 [2]	60[5]	0.99[5]	410[3]	10[3]	6.0[5]	0.0[5]	13[9]	78[3]	0.0[5]
Wuhan	10[2]	100[8]	0.76[8]	280[3]	14[3]	1.8[8]	0.24[8]	13[9]	90[3]	0.0[8]
Chongqing	9.7[2]	64[7]	0.80[7]	210[4]	20[1]	2.1[7]	1.9[7]	13[9]	60[7]	0.24[7]

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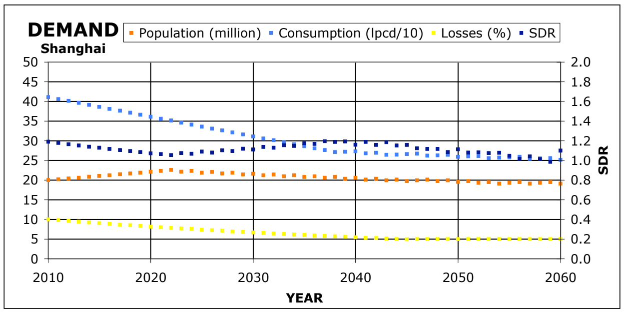
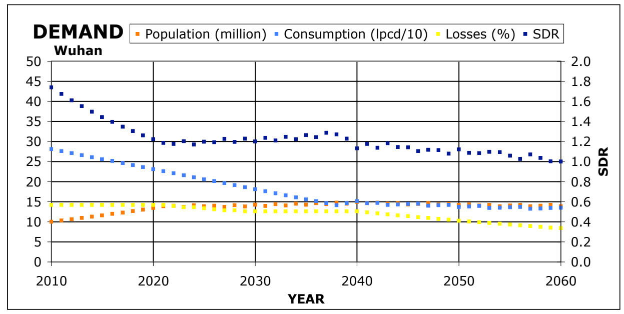
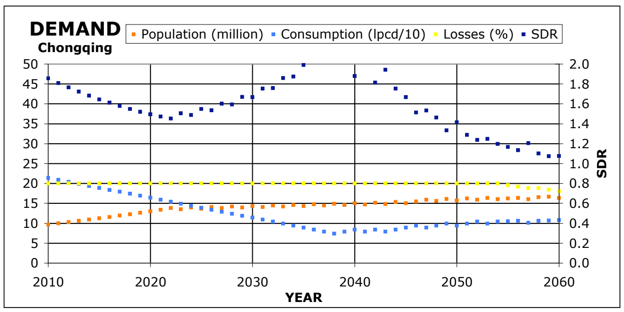
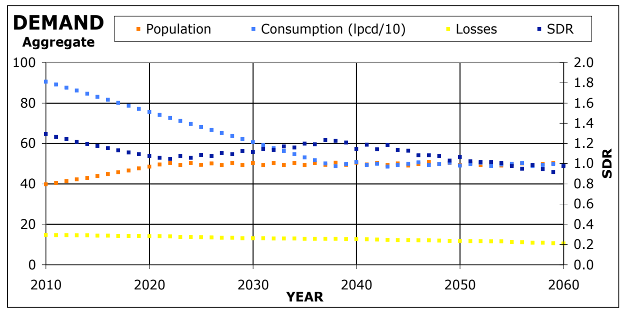
APPENDIX E: Aggregate Dynamic Behaviour Model Scenario Results

E.1. All cities cooperate (AGGPOP1 and AGGCONS1)

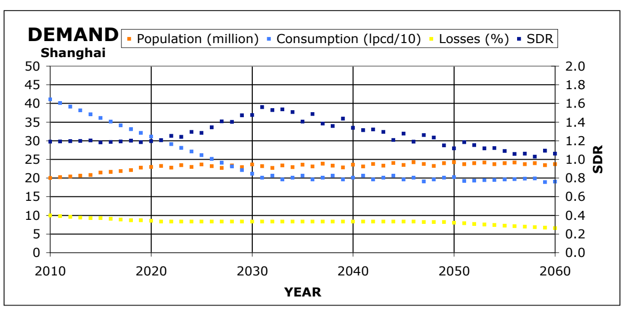


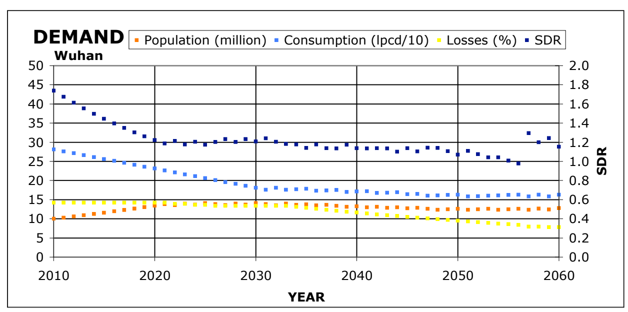


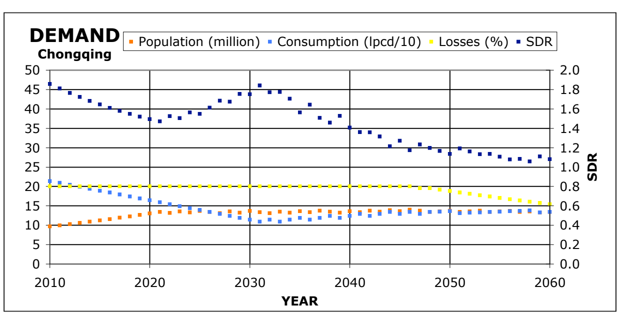


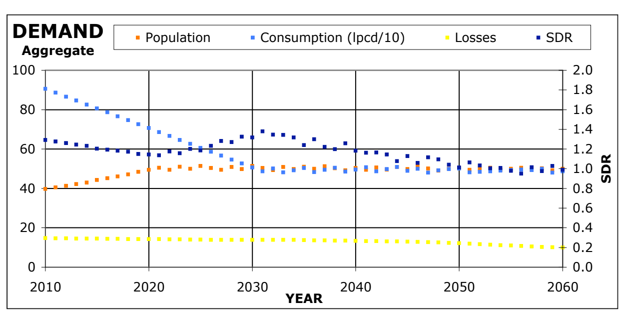


E.2. All cities cooperate with Shanghai on differential treatment (AGGPOP1 and AGGCONS3)

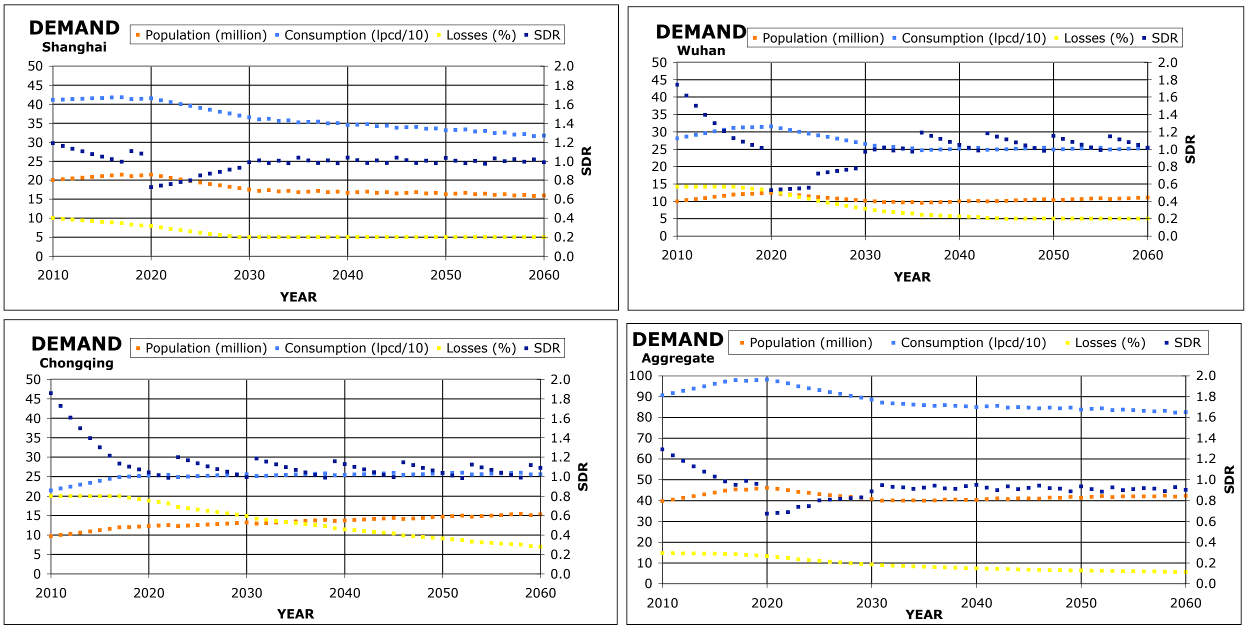








E.3. Disaster scenario, without regional cap



APPENDIX F: Risk Retrospective

The risks and hazards identified in the project risk assessment were limited to those associated with the use of computing equipment (ergonomic issues of workstation and adequate lighting conditions). This indeed covered the extent of the hazards encountered during the course of the project, where relevant measures were taken.