SUSTAINABLE GROWTH IN URBANISED DELTA AREAS

THE OPPORTUNITIES OF A GEOGRAPHICAL APPROACH TO THE PEARL RIVER DELTA
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ABSTRACT

The attractions of delta areas have boomed economies and founded major cities, but the threats of the adjacent water have persisted and natural resources have declined. The objective to facilitate sustainable urban growth in delta areas can only be met by a simultaneous approach of all the stakeholders concerned. This paper will demonstrate the result of a geographical design approach for a fast growing, often flooded and environmentally endangered area: the Pearl River Delta in China. It will be shown that with a careful analysis of the local situation (geography) and local requirements translated to geographical elements, solutions can be found that blend in with their surroundings and meet the needs of present and future.
1 INTRODUCTION

River deltas have always provided unique opportunities for settlement with their fertile plains and natural infrastructure, but at the same time the water remained a threat. Flooding by the river or the sea is a permanent risk for many deltas worldwide and global climate changes aggravate local weather extremes. As part of the Royal Haskoning Delta Competition this paper will investigate the relation between urbanization and flooding aimed at a sustainable coexistence of people and water in the future.

The scope of the investigation favoured a multidisciplinary team and the use of an integral design approach. The team consists of an architect, mechanical, civil and aerospace engineer and the design approach used combines different aspects in a geographical manner. China’s Pearl River Delta (PRD) is chosen as an example to investigate the relation between urbanization and flooding. This delta develops at extreme speeds and faces many of the problems associated with modern delta areas. A solution is sought that matches the local priorities with the need for space for water and growth.
Sustainable coexistence of people and water in urbanized delta areas means that development meets current needs and does not compromise the ability to meet future needs. This requires the evaluation of all needs of a delta and integration of the different problems to yield 1 set of requirements. To be able to cope with such different aspects a geographical design approach is used based on the philosophy of Ciro Najle. This design approach combines an integral perspective with the use of inspiration from other fields to serve as a starting point for the solution. This means that many different aspects of the site are summarized in maps. The combination of these maps demonstrates the main problems of a site but also integrates problems of a different nature to a specific location. This offers the opportunity of identifying synergy and combined solutions. The philosophy also stresses the importance of inspiration from other fields like natural phenomena, history or culture. These can all provide ideas for systems that fit well within the local circumstances. This yields an integration of spatial planning with technical solutions to the problems encountered at a specific location.

This paper will use this method on two levels. First the Pearl River Delta (PRD) is considered as one problem area. An analysis illustrates the general solution procedure and yields the framework and the main requirements for sustainable growth in the PRD. But, within the scope of this research it is not possible to achieve the required detail for the entire region. Therefore a specific location is chosen as an example to demonstrate the full capabilities of the design approach. The background information of this location is combined with the framework and requirements found in the analysis of the entire PRD. The combination yields 1 set of requirements for sustainable growth.

Most requirements are related to water management. Therefore numerical model is developed to calculate the effects of water management and check the applicability of proposed solutions. Inspiration from other fields is used to find possible water management systems that can be integrated within the area according to the calculations of the numerical model. This yields a specific set of water management systems that can be applied within a framework of spatial planning aimed at sustainable growth.
3 THE PEARL RIVER DELTA

Figure A: The Pearl River Delta is situated in the Guangdong province in the South of China

3.1 Why Pearl River Delta?

Urbanized river deltas demonstrate different characteristics depending on their local climate, geographical position, economical and political circumstances. Therefore not all deltas can easily be compared to other deltas. But many deltas have developed along the same patterns and have experienced the same problems as other deltas did at the same phase in their development. Although not always to the same extent. A general pattern for transition can be derived from the main benefits that attracted people to the deltas: fertile plains and fishing allowed agriculture and high population densities; transport over river and sea enabled trade; sea harbours, sufficient fresh water and the presence of a local market and distribution network favoured industry and recently water has been recognized for its recreational potential and has become a major asset for housing projects.

China’s Pearl River Delta (PRD) was chosen because it develops at a different pace compared to European deltas. It can be reviewed as a delta in its industrial period, but developing much faster than the European deltas. Therefore the lessons learned in Europe can be used to understand the developments in the PRD but the pace of development is so high that the effect of change can be seen much faster and therefore considered as a test case for European deltas. The PRD is also an interesting site to investigate due to the variety of problems associated with the rapid growth, the political urgency of water quality problems and flooding and the financial opportunities for change.

3.2 Background information on the Pearl River Delta

Historically the PRD is created by man. Early farmers channelled the rivers to use the fresh water for their crops and this network of small dikes and channelled streams resulted in a land reclamation process that gradually changed the PRD to a delta with broad flat plains intersected by streams and rivers. The highly fertile soil and subtropical climate allow three harvests a year and the PRD has long been important as an agricultural power within China. Villages were small and scattered over the entire PRD with Guangzhou as only regional urban centre. Guangzhou was part of the sea bound trading route for silk and was involved in small scale international trade. These opportunities for trade also attracted the Portuguese and British in 1557 A.D. and 1843 A.D. respectively. Their settlement on the coast of the PRD led to the foundation of Macau and Hong Kong. The British Hong Kong superseded Macau’s position as trading port and became the largest city in the region.

Recent developments are mostly related to political changes in the last 30 years that have boomed the economy. The first important change was the reform of the economy in 1978 from a centralized plan-economy to a system that allowed local authorities to decide what they wanted to do with a large part of the tax revenues (up to 70%). In
addition two areas in the PRD (Shenzhen and Zhuhai) were appointed as ‘Special Economic Zones’ with entirely open market economies and Guangzhou was appointed as an ‘open city’ in 1984, followed by the entire PRD in 1985. An ‘open city’ was open to foreign investments, but less open than the Special Economic Zones. The second important change was a reform of the land policy. For a long time land use had been virtually free of charge, but from 1987 the Chinese government started experimenting with the lease of state-owned land. The lease of land increased the income of local governments that used this money to improve the infrastructure, thereby increasing the value of the rest of the land and facilitating further economic growth.

An important consequence of the local control of a large part of tax income is the large competition between the cities and villages within the Pearl River Delta. Cities try to develop better circumstances to attract industry like harbors and airports and are reluctant to enforce environmental and social legislation. Another aspect of the competition between the cities is a strong branding of their own identity to distinguish themselves from the others. In this respect the PRD has become one of the few regions in China that values its own culture and history.

At present the PRD is one of the most important economical forces in China. Since the first political changes in 1978 the economy grew with almost 20% per year and changed from a predominantly agricultural economy to industry and services. The current division in the origin of the Gross Domestic Product (GDP) illustrates this change with only 5.8 percent of GDP originating from the primary sector, while secondary and tertiary sector account for 49.6 and 44.6 percent of the GDP. This has also given rise to concerns for the reduction of agricultural land and the associated reduction of food security. The connections of Hong Kong to the Western markets and to the PRD led to many joint ventures of Hong Kong industrialists and the labor force of local communities. As the economy grew the villages grew as well, which yielded a scattered urbanization. At the same time the economic circumstances have resulted in a strong migration from the rest of China to the PRD. The labor force in the PRD is thus constantly growing.

The subtropical climate in the PRD is dominated by seasonal rainfall from May to September, differing from earlier in the north (Guangzhou) to later in the south (Shenzhen). More than half of the total precipitation falls between June and August, while the main season for typhoons is between July and September. The smaller tropical storms occur approximately 27 times in a year, while severe tropical storms occur 9 times a year. Tropical storms are usually accompanied by heavy rains and storm surge. The heavy rainfall can cause flooding in urban areas, transport problems or flooding of rivers and the storm surge can cause serious flooding by the sea around the estuary.

Water pollution is an important problem for all of the PRD. The water consumption divided between 70% municipal and 30% industrial water usage. Only 9% of domestic wastewater receives treatment before discharge and although 85% of industrial wastewater is treated heavy metals and chemicals are still part of the non-treated 15%. Combined with agricultural runoff of fertilizer and pesticides the water quality has severely deteriorated. In times of drought the low water quality is further affected by salt intrusion. A dry season of the catchment area of the Pearl River causes a salt tide to move upstream and affects the water supply of more than 15 million people in the Delta.

3.3 Geographical analysis of the main cities in the PRD
The geographical analysis of the PRD is used to form an impression of the developments and main problems in the region. The location is foreign to all group members and therefore the initial analysis was aimed at a general insight to the region. Next to this impression the general analysis provides the information required to choose a specific location for the next phase of design.

The available information of the PRD is often not sufficiently detailed to make continuous maps and the time required to make such maps is simply not available. Therefore the analysis of the PRD is limited to Hong Kong, Shenzhen, Dongguan, Guangzhou, Foshan, Zhongshan, Zhuhai and Macau combined with some overall data.

The population size and growth are visualized in figure B to identify the cities with a recent history of growth and compare the growth to their current size. The economical size and growth of cities in figure C are used to find the opportunities for investment and future financial
perspectives. The impact of flooding on the different cities is summarized with the number of mortalities per year due to flooding, rain storms or typhoons as visualized in figure D. This is used as an indication of the severity of water related problems for the cities. To find possible reasons for the water problems figure E and F present the land elevation and major land reclamations for the entire PRD respectively. The land reclamation also illustrates the growth potential of the land itself. Figure G gives the land use in the PRD as an indication of the distribution of the economical, functional and social land value.

Figure B demonstrates that Guangzhou and Hong Kong are the main urban centers in the region. Although the population of more established cities grows slower only Macau has actually stabilized in size; all other cities are growing. Most of the growth of Hong Kong has moved to Shenzhen in recent years; Guangzhou and the surrounding cities all demonstrate a high growth. The cities on the west side of the PRD are of a smaller scale and relatively scattered.
Hong Kong is the main economical power of the PRD, but the smaller centers demonstrate the highest growth.

The economical size of Hong Kong (GDP 166 USD in 2004) is almost four time that of Guangzhou (GDP 46 USD) and Shenzhen (GDP 41 USD). Foshan (GDP 20 USD) is next in line while Dongguan (GDP 14 USD), Macau (GDP 10 USD), Zhongshan (GDP 7 USD) and Zhuhai (GDP 7 USD) are truly of a different size. The economical growth of Hong Kong is partly situated in Shenzhen which is comparable to the situation described with the population growth. The economical growth of the established cities is considerably lower than the growth in the younger cities. From the younger cities only Zhuhai has figures below 20% growth in GDP between 2003 and 2004 although it still grows much faster than the adjacent Macau (11 versus 3% respectively). The overall picture demonstrates a strong economic activity with high growth rates spread over multiple urban centers in the entire PRD.
Figure D: mortalities due to flooding per year between 1997 and 2005

Flooding is mostly threatening the largest cities

The largest water problems manifest themselves in the most populated cities. This indicates a strong relation between population density and the mortality due to flooding, but also confirms the assumption that water problems increase if the space for water is decreased.
The PRD consists of large flat plains with a few hills and mountains.

The difference in land elevation for most of the PRD is limited to 1 or 2 meter and most of the area consists of flat plains. But the presence of a few hills and mountains change the local circumstances considerably. Hong Kong has a much higher precipitation due to the mountains between the Hong Kong peninsula and the main land and has a limited area suitable for urbanization. Macau, Zhuhai, Guangzhou and Shenzhen are all in the vicinity of higher ground (above 200m NAP), while Foshan, Dongguan and Zhongshan are situated in the middle of flat plains with Zhongshan on the lowest ground. Water management systems will have to be adapted to these conditions.
Figure F: land reclamation

Land reclamation in the PRD continues to add cultivated land to the delta

There are no major land reclamations near large cities. Hong Kong has used land reclamation to increase its urban area directly, but only on a scale that cannot be visualized in figure F. Most of the reclaimed land is used as cultivated land situated in the PRD itself or on the coast line. They fit the historical land reclamation pattern of the PRD although on a modern scale.
The PRD is dominated by rice fields combined with some fish ponds, forests and scattered urbanization.

Figure G illustrates the scattered position of urban areas within an overall green environment. Next to some large forests most land is in use for agriculture. More specifically the agricultural land is reserved for rice. The floodplains are used as flat rice fields (paddy) while the surrounding areas are transformed to terraced rice fields (terraced paddy). The diked ponds are a combination of fish farms with commercial agriculture on the surrounding dikes (bananas, sugar cane, silk, eg). This kind of agriculture is typical for this climate and has a high protein yield.

If these maps are considered simultaneously, it can be noted that the problems with flooding seem more related to the number of citizens and urbanized area than to the local land elevation or presence of mountains. Therefore spatial planning within cities and their vicinity could make a significant change to the impact of floods. The space for water should be an integral part of spatial planning and design. Land use is also not directly related to the differences in land elevation. Although forests correspond to hills and mountains the differences in elevation of the flat plains can not be matched with the land usage. This suggests that land use is relatively flexible and different types of land use can be chosen for a specific location. This increases the flexibility of spatial planning.

This leads to the conclusion that sustainable urbanization in the PRD should anticipate growth in both economical sense and population size and should include the space for water in its design as one of the main requirements. The economical and political independence of the local governments makes it possible to realize designs that require major spatial and financial commitments as long as they also match the cities perceived branding or give it an competitive edge.
4 EXAMPLE: GUANGZHOU

To demonstrate the effect of a geographical problem definition in finding local solutions Guangzhou is used as an example. This city combines most of the evaluated problems and is relatively well documented.

4.1 Background

Guangzhou (also referred to as Canton) is said to be founded in 214 B.C. as Panyu. It was the only city in an agricultural area of small villages and after the foundation of Macau and Hong Kong it remained the regional capital as only Chinese city. Therefore the tertiary sector has always been relatively important, combined with small scale international trade (silk, luxury items). At present the city is inhabited by approximately 8 million people and grows quickly both economically and in population.

Guangzhou has a strong local government that wants to develop Guangzhou as a green city within the PRD with an ecological zone that connects all major parks and nature reserves. A strong historical and cultural awareness is also used to distinguish the city within the PRD and the local government is involved in several programs to develop the city in accordance with these objectives. Therefore any solution to flooding and rapid growth related problems should also match these city objectives.

Most water related problems in Guangzhou are either directly related to the heavy rains or indirectly by the rise of the river due to heavy rainfall upstream. The high surface runoff leads to a surface flow to the river and inundation of the lower areas, while the flow of the river can barely be contained within the diked space. Another important water problem is drinking water. Pollution is a big threat to drinking water facilities. In 1998 only two of Guangzhou’s nine water treatment plants could supply drinking water quality, the other seven could not meet this standard due to contamination. Urban water supply, sewage discharge and waste water treatment are managed by different organizations. This complicates the construction and operation of non-industrial waste water treatment plants.

4.2 Requirements for sustainable growth

Aim is to develop a sustainable growth strategy that integrates the concern for the decreasing agricultural space, limits the effects of heavy rains, matches historical values, incorporates green into the city and protects the urbanized areas from flooding by the river. The different water aspects are evaluated to find specific targets and the other requirements are also further specified.

To be able to grow in a sustainable manner the water management should keep the citizens safe and provide sufficient drinking water in a way that does not deteriorate in the future. Since the city is constantly growing the solutions should be an integral part of the urban region, because otherwise the load on the (shrinking) surroundings will constantly increase. Therefore water retention and space for the river will have to be an integral part of the cities spatial planning. Only drinking water resources are on a scale that can be met outside the city boundaries.

The threat of flooding by the river can be illustrated with the mass flow of the Pearl River. Officially the maximum mass flow that can be contained within the current waterways is 33,000 m$^3$/s. This occurs approximately once in five years, while 40,000 m$^3$/s statistically happens only every 20 years and 47,000 m$^3$/s only every 100 years. In reality Guangzhou floods every 10 to 20 years.

For the growing city these statistics should be improved because the consequences of flooding increase for higher population densities and higher economical land value. The amount of water concerned is too large for storage; therefore the threat of the river can only be reduced if there is more space for the water to flow. This can be accomplished with a green river. This is a dry river that can be used as extra river channel in case of high water. It should be placed as bypass for the most vulnerable parts of the river side and be wide and deep enough to accommodate the extra water.
To reduce uncontrolled flooding in official numbers to once every 20 years:

maximum flow velocity \( u = 2 \text{ m/s} \)
additional mass flow \( Q = 7.000 \text{ m}^3/\text{s} \)
maximum water depth of green river \( d = 4 \text{ m} \)

with width \( w = \frac{Q}{u \cdot d} \)

Therefore the width of the combination of green rivers should be at least 875m. This space should be provided along the river either at the river sides or in dry streams that empty directly into the estuary or on a part of the river that can contain that amount of water.

Excessive rain and drought can be moderated by retention areas. These areas are filled in time of rain with direct rainfall and with the runoff of their surroundings and the water can be used in times of drought. For Guangzhou these retention areas would have to be able to cope with the average yearly maximum precipitation of one month. Evaporation and a connection to the river should make it possible to manage the water level in a way that maintains the buffer function of the retention areas. Appendix A gives the numerical model used to test these assumptions.

A retention area for Guangzhou should be:

average maximum precipitation \( p = 280 \text{ mm/month} \)
runoff in urbanized area \( r = 50\% \)
urban area \( A_{\text{urban}} = 1 \text{ m}^2 \)
required retention volume \( V = r \cdot p \cdot A_{\text{urban}} = 0.5 \cdot 0.28 \cdot 1 = 0.14 \text{ m}^3 \)

Therefore every 1 m² of urbanized area requires 0.14 m³ retention volume.

The third water aspect is the availability of drinking water. Water pollution is a major concern for Guangzhou since most of the households and still 15% of the industry dispose their sewage directly to the Pearl River. This will have to be changed to achieve sustainable growth, but it is not within the scope of this evaluation. The required measures are comparable to those that were implemented in Europe to limit the same problems. The requirements for drinking water are considered from a perspective that the water quality in the Pearl River is only to low for drinking water intake in the driest season, because of salt intrusion from the estuary.

10% of household water consumption should be of drinking quality. At present Guangzhou uses 785*10⁶ m³ of water for household consumption per year. Therefore in the driest 3 months of the year 19.6 *10⁶ m³ of water should be available of drinking quality. This is comparable to a basin of 2.6 kilometres squared and 3 m deep. To provide clean water a basin should be upstream from Guangzhou, expandable for an increasing urban population and free from direct pollution.

Next to these three water requirements the growing city should include as much agriculture as feasible to alleviate the concerns of decreasing food production. Spatial planning should be inline with the local history and continue the ecological zone of Guangzhou.

4.3 Proposed solution
The first element of Ciro Najles design approach was to use geography to derive 1 set of requirements that includes the needs of a specific location. The second element is to actively search for inspiration. Therefore a broad research was conducted for analogies between a water management system and natural phenomena (eg. water management in cells, salt management of sharks), but also for historical water management systems. This yielded the inspiration for the second part of the proposed solution, since the first part of the proposed solution seems to follow directly from the requirements: use the ecological zone as green river to structure new development. The second part was inspired by a historical water management system that is still in use near Foshan: the fish pond.

The requirement to continue the ecological zone of Guangzhou coincides with the need for green rivers and also makes it possible to keep some agriculture within the city boundaries. A combination of parks, nature reserves and agricultural fields can be connected to act as green rivers in case of emergency and as ecological structure for normal use in other times.
use. American experience with green rivers has demonstrated that they can become a major asset of a city by upgrading the value of the adjacent houses and offices and they can have a strong impact on the cities image.

The extensive fish pond region near Foshan is barely affected by rain or drought, because the fish ponds buffer the water. Fish ponds are a combination of fish farms with agriculture on the surrounding dikes. Especially the combination of fish with mulberry trees for silk production on the dikes has a very high cultural historic value and would strengthen the green image of the city, since silk worms are sensitive to air pollution and can therefore only exist in clean (‘green’) areas. The interaction between the dikes and the ponds allows for a very high yield. The waste of the silk cocoons is extra food for the fish, while the accumulated waste of the fish in the mud on the bottom of the fish pond is used as fertilizer for the trees on the dikes. A comparable relation exists between cash crops like banana’s or sugar cane, small cattle or poultry and fish. This kind of agriculture could therefore reduce the concern for the decreasing space for agriculture by intensifying the use of the space.

Next to the cultural historic value and the high agricultural yields the fish ponds can fulfil another important part of the requirements. They can limit the extremes of rainfall and drought. If the average water depth in the fish pond is 2.5m with a minimum of 1.5m and maximum of 3.5m each 1m² fish pond could retain the water of 14m² urbanized area. Appendix A gives the numerical model that evaluates the opportunities of a fish pond to meet the water needs. To be able to use the fish ponds as retention space for urbanized area the fish ponds should be connected to the runoff water of their surroundings. But the water quality of the runoff water must be quite high not to harm the ecosystem. Therefore a direct connection to the roof of buildings is proposed. This also makes it possible to use the difference in height to power most of the transportation.

4.4 Geographical analysis of Guangzhou
The analysis is based on the spatial expansion program of Guangzhou until 2010. This southbound expansion (see figure I) still has a lot of open space, but is close enough to Guangzhou centre to expect further urbanization in the future.

To identify opportunities for an ecological zone that can act as green river the present green, agriculture and water are considered.
The ecological zone connects the existing green and the river to create green rivers

Figure I shows the parks and nature reserves as expected in 2010 and the agricultural area adjacent to water. The parks and nature reserves need to be connected to create an ecological structure, while the agricultural fields provide opportunities to connect a green river to the flow of the Pearl River. The proposed green structure is indicated with the dotted lines. The northern line proposes the main ecological zone that connects all major green areas. The southern line is a proposition for a green river over mostly agricultural fields alongside existing water. Both are oriented ‘down stream’ parallel to the river. The connections (branches) between the two zones create a more robust structure.

Next these zones are combined with the present infrastructure to minimize the intersections of infrastructure and ecological zone as can be seen in figure J where the additional red lines indicate major roads and the dashed lines represent the rail infrastructure.
Refining location ecological zone with the present infrastructure

It can be seen that some small relocations of the two branches aligns them with the major infrastructure rather than crossing them. The combination also reveals an additional advantage of the spatial orientation of the southern green river: an overlap with the rail track for most of its route. The presence of the rail already defines the route, requires part of the surrounding infrastructure to use split level intersections, and makes the area less suitable for habitation. A green river also requires some bridges or tunnels to connect the two sides in case the river is flooded and most off all needs space. Therefore this combination is very favourable. Many other aspects could be included to refine the exact location of the green rivers and to improve the actual functionality and fit within its surroundings.

The fish ponds are identified by combining urbanized area with agricultural area. The fish ponds should preferably be located directly adjacent to urbanized area to profit from the runoff of the buildings. Therefore figure K indicates all areas where agricultural fields are situated next to urbanization.
Figure K: Preferred location fish ponds

Opportunities to place fish ponds directly adjacent to urbanization

A detailed planning should ensure that every 14 m$^2$ of urbanized area is combined with 1 m$^2$ of fish pond and define the infrastructure required to transport the runoff water to the ponds and over flow from the ponds to the river.

The fish ponds can respond to urban growth in three ways depending on the specific type of growth. Limited growth could be met by decreasing the space for the dikes, thus increasing the space for water. This reduces the agricultural yield, but maintains all other functions. Stronger growth could be facilitated by moving the fish ponds and aligning them with the new city boundaries. The most likely development in the Pearl River Delta is scattered growth. Therefore the initial change from field agriculture to fish ponds could be repeated with the same advantages of increased agricultural yield and water storage for new areas of urbanization.

The geographical analysis of Guangzhou demonstrates that both green rivers and fish ponds can be well integrated to their environment and match the cities spatial planning objectives.
5 CONCLUSIONS AND RECOMMENDATIONS

A sustainable coexistence of densely populated areas and flood prone regions can only be achieved by integrating water management within the urbanized area. Especially growing cities will need to incorporate space for water within their boundaries to avoid an ever increasing load on their surroundings.

The combination of the analysis of the entire Pearl River Delta with Guangzhou showed that for a sustainable future the city would need to be able to grow both economical and in population; it would have to reduce the threat of flooding by the river and the consequences of excessive rain; it should improve the water quality for drinking water intake; it should maintain food production; the solution should match the culture and history of Guangzhou and strengthen the green image of the city.

This has resulted in a spatial development objective for the expansion of Guangzhou: expansions should be structured by the ecological zone that doubles as green river. For the projected south bound expansion two ecological zones are defined that are connected to the present ecological zone and parallel to the river. They consist of nature reserves, parks and agricultural fields and are connected to the river at several places. The width is sufficient to reduce flooding to once every 20 years (official statistics) instead of once every 5 years at present.

The long stretch of green will strengthen the green image of the city and will most likely have a positive effect on the prices of the adjacent houses and offices. The reduced flood risk will also help to promote long term investments and can give Guangzhou a competitive edge in the Pearl River Delta.

The second spatial measurement is the introduction of fish ponds to manage the rainfall. A fish pond combines fish farming with agriculture on the surrounding dikes and has a high agricultural yield. Connected to the runoff water of their surroundings each m$^2$ of fishpond can store the water of 14m$^2$ of urbanized area. Therefore they should preferably be situated adjacent to urbanization to limit the transportation effort.

The fish ponds can reduce the consequences of excessive rain or drought, intensify food production and they have a strong historical value for the region. The combination of mulberry trees with silk worms on the dikes with fish could become a land mark for the city, since silk worms are sensitive to air pollution their very existence would prove the ‘greenness’ of the city.

The geographical design approach made it possible to identify opportunities for interaction between functions and design solutions that fit well in their environment. It would yield very different results for another location. Therefore the design method is suitable for other deltas, but the solutions that were found are specific to Guangzhou and will not have the same effect in other circumstances.
Prof. van den Akker and H. Savenije, *Hydrology I*, TU Delft Press

Citizens’ party 1999, *Improving water quality in the Pearl River Delta, opportunities & challenges, Role for Hong Kong.*

Anthony Gar-on-yeh and Xia Li 1999, *Economic development and agricultural land loss in the pearl river delta, China*, Habitat international vol. 23 no 3 pp373-390, Elsevier Science, ISSN 0197-3975, 1999


W. Seabrooke, C.W. Yeung, M.F. Ma, Y. Li 2004, *Implementing sustainable urban development at the operational level (with special reference to Hong Kong and Guangzhou)* Habitat international vol 28 pp 443-466, Elsevier Science, ISSN 0197-3975, 2004


US Consulate General Guangzhou 2000 ‘*Guangdong environment: Some progress, but many problems remain*’

Qihao Weng, ‘*Modelling urban growth effects on surface runoff with the integration of remote sensing and GIS*’, Department of geography and geology, Indiana state university.
APPENDIX A: COMPUTER MODEL OF THE FISHPOND

Starting points

- Control of the water level in the fishpond in a simple way.
- A constant flow of water is taken from the pond during the whole year. This can be used for agricultural purposes, a grey water circuit or (most likely after purification) drinking water.

Basic formula

The water level is calculated by:

\[ h(x) = h(x-1) + \varphi_{\text{input}}(x) - \varphi_{\text{evap}} - \varphi_{\text{control}}(x) - \varphi_{\text{constRAIN}} \]

with:

- \( h(x) \) the water level at day \( x \),
- \( h(x-1) \) the water level at day \( x-1 \),
- \( \varphi_{\text{input}}(x) \) the input flow per squared meter pond (units [m/day]) at day \( x \),
- \( \varphi_{\text{evap}} \) is the flow per squared meter pond that evaporates (units [m/day]),
- \( \varphi_{\text{control}}(x) \) is the flow per squared meter pond that is discharged by the controller,
- \( \varphi_{\text{constRAIN}} \) is the flow per squared meter pond that is constantly removed from the pond (units [m/day]).

Note that it is assumed that no water exits the pond through the sides and bottom of the pond. This assumption can only be justified if the ponds are constructed from, or lined with a material that is barely water permeable or even water impermeable, like clay and concrete.

Boundary conditions

For the maximum allowable level in the pond a typical value of 3.5 m is used. This value is used for the simplified static calculation in the main text of the paper as well.

The lower level is chosen as a level that is deemed sufficient to sustain fish life in the pond. The value of 1.5 m is the same as used in the main text of the paper.

Input by precipitation

Three different scenario’s for precipitation (see table A.1) are used to calculate whether the control is sufficient to not exceed the boundaries or not. The input by precipitation in days is the average precipitation per day based on the precipitation per month. This is due to the limited availability of precipitation on daily basis. That this assumption is not entirely valid can be seen in the last column of table A.1. The input to the pond is calculated using a run-off coefficient of 0.5 for the city. The rain that falls on the dikes around the pond is conservatively assumed to end up in the pond, which means that a coefficient of 1 is used for the dikes. The level in the pond is however not very sensitive on the coefficient used for the dikes. Obviously all rain directly into the pond is stored in the pond.
The ratio of build-area-to-water and the ratio of dike and water is chosen in accordance with the static calculation from the main text, i.e. build-area to water 14:1 and dike to water ratio=1:1. the input into the pond can be calculated as:

\[
\varphi_{\text{input}}(x) = h_{\text{rain}}(x) \cdot r_{\text{city}} \cdot \left( \frac{A_{\text{build}}}{A_{\text{pond}}} - \frac{A_{\text{pond}}}{A_{\text{water}}} \right) + h_{\text{rain}}(x) \cdot C_{\text{dike}} \cdot \left( \frac{A_{\text{dike}}}{A_{\text{water}}} \right) + h_{\text{rain}}(x)
\]

With \( r_{\text{city}} \) the run-off coefficient for the city and \( C_{\text{dike}} \) the coefficient for the dike. \( h_{\text{rain}} \) is the rain per m² terrain (unit [m/day]) A is for area. The areas themselves are not specified, just the ratio of the areas.

Table A.1: Data precipitation

<table>
<thead>
<tr>
<th>Month</th>
<th>Precipitation 2003 [mm/month]¹</th>
<th>Precipitation 1997 [mm/month]²</th>
<th>Average precipitation [mm/month]³</th>
<th>Mean number of precipitation days [mm]³</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>33.1</td>
<td>65.9</td>
<td>43</td>
<td>8</td>
</tr>
<tr>
<td>February</td>
<td>7.6</td>
<td>105.6</td>
<td>65</td>
<td>11</td>
</tr>
<tr>
<td>March</td>
<td>65.1</td>
<td>59.6</td>
<td>85</td>
<td>15</td>
</tr>
<tr>
<td>April</td>
<td>59.7</td>
<td>197.1</td>
<td>182</td>
<td>16</td>
</tr>
<tr>
<td>May</td>
<td>189.4</td>
<td>165.6</td>
<td>284</td>
<td>18</td>
</tr>
<tr>
<td>June</td>
<td>329.8</td>
<td>468.6</td>
<td>258</td>
<td>19</td>
</tr>
<tr>
<td>July</td>
<td>61</td>
<td>248.4</td>
<td>228</td>
<td>16</td>
</tr>
<tr>
<td>August</td>
<td>189</td>
<td>282.4</td>
<td>221</td>
<td>16</td>
</tr>
<tr>
<td>September</td>
<td>367.7</td>
<td>203.6</td>
<td>172</td>
<td>13</td>
</tr>
<tr>
<td>October</td>
<td>3.2</td>
<td>142.6</td>
<td>79</td>
<td>7</td>
</tr>
<tr>
<td>November</td>
<td>30.9</td>
<td>9.7</td>
<td>42</td>
<td>6</td>
</tr>
<tr>
<td>December</td>
<td>1.2</td>
<td>48.8</td>
<td>24</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>1338.2</td>
<td>1997.9</td>
<td>1683</td>
<td>150</td>
</tr>
</tbody>
</table>

³ http://www.worldweather.org/001/c00241.htm
Evaporation

In the Guangzhou area approximately 2/3 of the rainfall evaporates. The evaporation from the pond is assumed to be approximately 2/3 of the average yearly rainfall directly into the pond, which equals 1100 mm. It is assumed that evaporation is constant throughout the year. These are rather bold assumptions. For use of this model for the actual construction of a pond this assumption needs to be verified with local data.

The amount of water evaporating can also be estimated using an energy balance for the pond per m²:

\[ E_{\text{solar}} - E_{\text{reflection}} - E_{\text{radiation}} - E_{\text{convection}} - E_{\text{conduction}} = E_{\text{evaporation}} \]

with \( E_{\text{solar}} \) the energy from the sun, \( E_{\text{reflection}} \) the reflected energy from the sun, \( E_{\text{radiation}} \) the amount of heat radiated by the pond, \( E_{\text{convection}} \) the energy released into the air due to convection, \( E_{\text{conduction}} \) the energy away from the pond due to conduction and finally \( E_{\text{evaporation}} \) is the energy necessary to evaporate the evaporating water.

\( E_{\text{conduction}} \) is approximately zero, because air is a very good isolator.

\( E_{\text{solar}} \) is for the Guangzhou area on average 3.5 kWh per m² per day^{29}.

\( E_{\text{reflection}} \) is reflectivity times \( E_{\text{solar}} \). The reflectivity is 0.06^{30}. \n
\( E_{\text{radiation}} = \varepsilon \sigma T_{\text{pond}}^4 \). With \( \varepsilon \) the emissivity of the medium which is by approximation 1-reflectivity, \( \sigma \) is the Stefan-Boltzmann constant, which is \( 5.67 \times 10^{-8}\ \text{W/(m}^2\text{K}^4) \)

\( E_{\text{convection}} \) is linked to \( E_{\text{evaporation}} \) by:

\[
\frac{E_{\text{evaporation}}}{p_{v,\text{air}} - p_{v,\text{pond}}} = \frac{0.0035 \cdot (T_{\text{pond}} - T_{\text{air}})}{P} 1.013 \times 10^5
\]

Source of this formula is Wikipedia, but it is rewritten to SI-units, with \( T \) temperature in Kelvin (or Celsius) and \( P \) total pressure in Pascal, and \( p_{v,\text{pond}} \) and \( p_{v,\text{air}} \) the vapour pressure at the surface of the pond and actual vapour pressure in the air far away from the pond.

With \( T_{\text{pond}} \) 30°C and \( T_{\text{air}} \) 25°C and 90% humidity (estimated values) it can be calculated that 0.8 meter of water evaporates per year. This means that the assumption of 1.1 m evaporation seems fair.

Control of the water level in the fishpond

A drain with certain dimensions at a certain height is the simplest way of a control of the water level. The flow per area at moment \( t \) is related to the water height by:

\[
\phi_{\text{control}}(t) = \sqrt{K \cdot \left(h(t) - h_{\text{ref}}\right)} \quad \text{for} \quad h(t) > h_{\text{ref}}
\]

Formula III

K is the control parameter. The larger K the larger the response on the exceedance of the reference height and the quicker the discrepancy between the actual level and the reference level is reduced. Note that in the actual discharge over a day is dependant of the average water level over the period
under consideration. At this moment the water level of one time step earlier is taken as the average water level, this induces a small error.

The reference height and control parameter $K$ can be chosen freely (within the physical possibilities to fit the water level between the lower and upper boundary. For further use of the reference height see constant flow of water from the pond.

Formula III and the factor $K$, that were boldly introduced above have got a physical background, which is explained below.

For a tank (or in this case a pond) with a drain an energy balance over a streamline can be made:

$$\frac{p_{\text{pond}}}{\rho} + \frac{\alpha_{\text{pond}} V_{\text{pond}}^2}{2} + g z_{\text{pond}} = \frac{p_{\text{drain}}}{\rho} + \frac{\alpha_{\text{drain}} V_{\text{drain}}^2}{2} + g z_{\text{drain}} + \left(\dot{u}_{\text{drain}} - \dot{u}_{\text{pond}} - q\right) + w_s + w_v$$

$w_v$ is the viscous work, $w_s$ the shaft work, $q$ heat transport. $\alpha$ is a loss factor due to friction, $V$ is for velocity, $u$ internal energy, $g$ the gravitational constant, $\rho$ the density of the medium and $z$ the height, which may be chosen (if chosen consistently) as absolute or relative.

This formula can be simplified considerably assuming:
1. Steady flow
2. Incompressible flow
3. Frictionless flow
4. Flow along a single streamline
5. No shaft work between pond and drain
6. No heat transfer between pond and drain
7. $p_{\text{pond}} = p_{\text{drain}}$, i.e. no backpressure on the drain

Assumptions 1 to 6 reduce the formula to the Bernoulli equation. With assumption 7 this leads to the rather simple formula:

$$V_{\text{drain}}^2 - V_{\text{pond}}^2 = 2 g \left(z_{\text{pond}} - z_{\text{drain}}\right)$$

This formula can be translated to the height relative to the bottom of the pond:

$$V_{\text{drain}}^2 - V_{\text{pond}}^2 = 2 g \left(h(x) - h_{\text{ref}}\right)$$

If we use a mass-balance and assume no heat transfer and no compression (already assumed) the mass balance equals a volume balance.

$$Q = A_{\text{pond}} V_{\text{pond}} = A_{\text{drain}} V_{\text{drain}}$$

With $A$ the surface and $V$ velocity through the surface. Note that $V_{\text{pond}}$ equals the decrease in height in the pond per second, or in other words, if we define $\phi_{\text{control}}$ in m/day, $\phi_{\text{control}} = V_{\text{pond}} \times 3600 \times 24$. 

\[\text{Formula I}\]

\[\text{Formula II}\]
Combination of formula I and II leads to formula IV.

\[ V_{\text{pond}} = \frac{A_{\text{drain}}}{A_{\text{pond}}} \left[\frac{2g(h(x) - h_{\text{ref}})}{1 - \left(\frac{A_{\text{drain}}}{A_{\text{pond}}}\right)^2}\right] \]

Note that mostly \( \left(\frac{A_{\text{drain}}}{A_{\text{pond}}}\right) \ll 1 \) and formula IV is often simplified as:

\[ V_{\text{pond}} = \frac{A_{\text{drain}}}{A_{\text{pond}}} \cdot 2g(h(x) - h_{\text{ref}}) \]

In reality assumption 3 and 4 do not hold. It is common engineering practice to correct formula IV (or formula V) them by introducing a so-called discharge coefficient \( c_d \). The value of this discharge coefficient varies between 0.6 en 1.

\[ V_{\text{pond}} = c_d \cdot \frac{A_{\text{drain}}}{A_{\text{pond}}} \cdot 2g(h(x) - h_{\text{ref}}) \]

Hence the control parameter \( K \) is defined as:

\[ K = \left( c_f \cdot c_d \cdot \frac{A_{\text{drain}}}{A_{\text{pond}}} \right)^2 \cdot \frac{2g}{1 - \left(\frac{A_{\text{drain}}}{A_{\text{pond}}}\right)^2} \]

with \( c_f \) the conversion factor to get from seconds to the time unit used in the simulation.

**Constant flow of water from the pond**

The water level in the pond cannot exceed the lower boundary of 1.5 m. Therefore the constant flow from the pond is automatically calculated assuming that the flow can be ensured during 6 totally dry months (see formula below).

\[ \varphi_{\text{constrain}} = \frac{h_{\text{ref}} - h_{\text{min}}}{N_{\text{drymonths}} \cdot N_{\text{dayspermonth}}} \]

Note that this formula does not incorporate the removal of water by evaporation, which is incorporated in the model. The assumption of 6 totally dry months is a very conservative assumption however, and the formula is valid up to a minimal reference level of 1.6 m.

**Processing**

As the starting level for the calculation the minimum level was taken. Two consecutive years have been calculated, because due to the initial level the first year is not representative.
Results
The conservative assumption for the constant drain resulted in a water level that was never below the lower limit for the three scenarios and the chosen reference water levels. The exceedance of the upper level is strongly related to the precipitation and the value of control parameter K. A higher value of K results in no exceedance of the upper limit, but results in a stronger response on precipitation (or in other words a higher run-off coefficient from the pond).

5 different sets of parameters are shown in table A.2 that fulfill the boundary conditions. Set 1 gives the minimum reference level. It is not equal to the minimum level due to evaporation of water.

Table A.2

<table>
<thead>
<tr>
<th>Set</th>
<th>Set 1</th>
<th>Set 2</th>
<th>Set 3</th>
<th>Set 4</th>
<th>Set 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{\text{ref}}$ [m]</td>
<td>1.57</td>
<td>1.7</td>
<td>2.1</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>K [m/(day$^2$)]</td>
<td>0.025</td>
<td>0.03</td>
<td>0.04</td>
<td>0.06</td>
<td>0.12</td>
</tr>
<tr>
<td>$\phi_{\text{const drain}}$ [m/day]</td>
<td>0*</td>
<td>0.011</td>
<td>0.033</td>
<td>0.0055</td>
<td>0.0082</td>
</tr>
<tr>
<td>ratio constant drain to drinking water consumption* [%]</td>
<td>0</td>
<td>134</td>
<td>403</td>
<td>671</td>
<td>1006</td>
</tr>
</tbody>
</table>

* Manually set to zero

# To put the constant drain into perspective. Based on value drinking water quality consumption in Guangzhou, discussed in the main body of the paper and assuming whole Guangzhou was Area of Guangzhou of 7400 km$^2$. Source: www.blikopnieuws.nl and www.cnhomestay.com/city/cityguids/guangzhou.

The most desirable dataset can be chosen, depending on whether a slow response or a large constant flow is preferred.
**Output**
Examples of output of the program with dataset 2 and the scenario with precipitation in 2003.

![Input rainfall](image1.png)

![Variation waterlevel in pond starting first of January](image2.png)

The black striped line represents the minimum level in the pond. The upper level is indicated by a same line, but is not visible due to the relative small amount of rain in this scenario.
Run-off coefficient is in this case defined as drain from the pond divided by the rainfall. In dry moments the drain exceeds the rainfall, which results in values larger than 1.
Conclusion and recommendations appendix A

It is shown that a fish pond can indeed mitigate run-off peaks due to excessive rainfall at the calculated ratio in the paper of 14 m² city to 1 m² fish pond. This ratio is too small for the fish pond to act as a storage of rainfall during long periods, but this was not the aim of this design. It is also shown that a fish pond can be used as a source for constant water withdrawal. It is possible to modify the behaviour of the fish pond to favour a higher constant water withdrawal or to favour more smoothening of the run-off peaks by modifying vertical position and dimensions of the drain. The water level can be controlled with more advanced controls, but a drain at a certain height fulfills all the requirements.

For actual dimensioning of the drain it is strongly recommended to use rainfall data on a daily but preferably hourly basis. This means that the calculation needs to be repeated with smaller timesteps. It is recommended to use data on evaporation in Guangzhou with a higher time resolution.
NOTES

1 Based on the definition for sustainable development of the Brundtlandt Commission (1987)
2 Ciro Najle 2004; Hydrotypes, water processing devices, Research Studio 2004-2005; Berlage Institute
4 A.W.M Wong and M.H. Wong, 2003, Recent socio-economic changes in relation to environmental quality of the Pearl River delta
6 http://www.china.org.cn/e-china/openingup/sez.htm
7 Anthony Gar-on-yeh and Xia Li 1999, Economic development and agricultural land loss in the pearl river delta
9 J.Shen, Z. Feng, KY Wong 2003, Dual track urbanisation in a transitional economy: The case of pearl river delta in South China.
10 Travel China Guide
11 Exact figures: Tropical Storms > 34 knots: 26.7/year, Tropical Cyclones > 63 knots: 16.9/year, Category 3+ Tropical Cyclones > 95 knots: 8.5 times a year.
12 Improving water quality in the Pearl River Delta Citizens Party
13 China Daily
15 De grote Bosatlas 50th edition, 1988, Wolters Noordthoff BV Groningen
16 Asia Environmental Trading Ltd., China Environmental Review, August 1998
17 US Consulate General Guangzhou 2000 ‘Guangdong environment: Some progress, but many problems remain’
18 Zhenguo Huang et al. 2004 ‘Coastal Inundation due to sea level rise in the Pearl River Delta, China, Guangzhou institute of Geograpy.
19 prof van den Akker, hydroloog, CT TU Delft
20 prof. van den Akker, hydroloog, CT TU Delft
21 prof. van den Akker and H. Savenije, Hydrology I
23 Prof. Savenije ‘Modelling urban growth effects on surface runoff with the integration of remote sensing and GIS’, Qihao Weng, Department of Geograph and Geology, Indiana State University.
25 Improving water quality in the Pearl River Delta 1999, opportunities and Challenges.