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Structure and Functions of Urban Surface Water System in Coastal Areas: The Case of Almere

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Abstract**—**In the context of global climate change, flooding and sea level rise is increasingly threatening coastal urban areas, in which large population is continuously concentrated. Dutch experiences in urban water system management provide high reference value for sustainable coastal urban development projects. Preliminary studies shows the urban water system in Almere, a typical Dutch polder city, have three kinds of operational modes, achieving functions as: (1) coastline control – strong multiple damming system prevents from storm surges and maintains sufficient capacity upon risks; (2) high flexibility – large area and widely scattered open water system greatly reduce local runoff and water level fluctuation; (3) internal water maintenance – weir and sluice system maintains relatively stable water level, providing excellent boating and landscaping service, coupling with water circulating model maintaining better water quality. Almere has provided plenty of hints and experiences for ongoing development of coastal cities in emerging economies.

Keywords**—**Coastal area, resilience, sustainable urban water system, water circulation.

I. Research Background

A. Population Concentration in Coastal Areas

Coastal areas are some of the most productive land on earth and are good locations for global trade. These belt-like regions were continuously concentrating large number of population in the past decades, and now turned into the most intense urban development area in the planet. According to 2003 data, 2,385 million people live within the coastal limit, which represents 41% of world global population. More than 50% of the coastal countries have from 80 to 100% of their total population within 100 km of the coastline. Twenty-one of the 33 world's megacities are found on the coast [1]. If the trends observed between 1990 (2 billion people living within 100 km of the coast) and 2000 (2.3 billion) continue, the UN Population Division estimates that the number of people living on and around coastlines will increase to 3.1 billion people by 2025 (an approximately 34% increase in population) [2].

There are more than 3,000 cities in the low elevation coastal zones around the world. Of these cities, almost 65 percent are in developing countries. Many experts argue that cities will have to cope with almost all of the population growth to come in the next two decades, and much of this increase will occur in coastal urban centers [3]. Close to 60% of China's population live in 12 coastal provinces, along the Yangtze River valley, and in coastal megacities. Along China's 18,000 kilometers of continental coastline, population densities average between 110 and 1,600 per square kilometer [4].

B. Challenges to Urban Development in Coastal Areas

Coastal zones are highly vulnerable to sea levels rise when considering global climate change. Stronger and higher frequency of storm surges poses an increasing threat to coastal urban area, and especially to the infrastructure system. The main issues are flooding, water resources, land loss and many others as well. Coastal population growth increases demand for a continuing supply of clean water, waste disposal, public health, food and protection from natural disasters. There are also increased pressures on ecosystems from recreation and tourism, and from the infrastructure needed to accommodate these in the form of roads, bridges, parking lots and sewers [5]. Human settlements located in coastal regions are very vulnerable to extreme weather events. An increase of such events as a result of global climate change is likely to cause significant damage related costs. In recent years, large number of new commercial and residential development in China also concentrates in coastal areas. Especially in megacities like Shanghai and Tianjin, or city clusters located around them, dozens of new-towns with a planned population from 100,000 to 500,000 emerges along coastal low-lying belts, among which Sino-Singapore Tianjin Eco-city is one of the most known projects.

Sea level rise may cause immense economic loss due to the direct or indirect damage to the urban areas, sewers, ports and other infrastructure. Simultaneously the quality of water is likely to decrease, with the fluctuation of runoff that either increased sediments and pollutants or decreased flushing that leads to higher salinity levels. In north China coastal cities, increased salinity is vastly threatening water quality for residential users and affecting crops as well. Many coastal lowlands, especially in the developing world, have limited or no human-built protection against impacts from sea level rise or storms.

How to deal with the challenges of achieving sustainable development in the coastal zones is a key issue for future global sustainable vision. In this respect, the urban development of low-lying coastal zone in the Netherlands provides significant value as a reference.

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II. Urban Development and Water System Functions in the Netherlands

A. Reclamation History of the Netherlands

The word "Netherlands" in Dutch means the lowland. Historically, the Netherlands is known as the "low-lying country" because almost 1/4 of the land is below sea level. Considering the dense population, expanding the land area has been an important task of the country.

The Netherlands has a long history of reclamation. Between 800 and 1250 the largest part of the peat areas, situated behind the coast, was reclaimed. But then flooding and land loss became the main thread to the country due to dike collapse and land subsidence in the next centuries. 17^{th} and 18^{th} centuries were characterized by intense dynamics in the struggle against water, during which great masses of water had been turned into productive agricultural areas. Then greater extent of land reclamation was achieved in 19^{th} and 20^{th} centuries. In 1932, the enclosure of Zuiderzee has been completed and gradually followed by the reclamation of land over 1,660 km^2 and related development as agriculture, urban development, recreation and nature conservation. From 1956 to 1986, the Delta Works was also implemented. As a result, threat from the sea was substantially reduced [6]. And currently, the reclamation area of the Netherlands has reached 5,200 km^2.

B. Water System in the Netherlands

The Netherlands could be considered as a gateway for water. All the water that is carried across its borders by streams and rivers, and with rainwater, must be discharged into the sea overland or underground. Water in the low-lying areas that lie below sea level needs artificially discharged. Pumping stations, locks, dams, dikes and weirs are extending over the Netherlands. This has resulted in a mosaic of rivers, canals, lakes and (dammed) estuaries, interlaced with a system of ditches, town canals and channels. Netherlanders direct water from the Rhine and Meuse to planned locations. A substantial amount is stored in Lake IJsselmeer, so that it can be used later on for the production of drinking water, irrigation purposes and much more. Furthermore, making sure that there is sufficient water in the canals to allow shipping to continue and people use it to combat saline intrusion of groundwater. A water system of the Netherlands comprises various components which interconnect to a high degree, such as highland, streams, polder, inter-region ditches and installation facilities connecting each other. They influence each other, they are co-dependent and moreover they play a predominant role in controlling water quality and quantity.

Polder here shall be specially mentioned. A polder is an area that is protected from external water by a dike and that has a controlled water level on the inside of the diked area. Any water entering the polder (rain, seepage water) that is not used or stored has to be pumped out. The water is first pumped into the polder outlet [7].

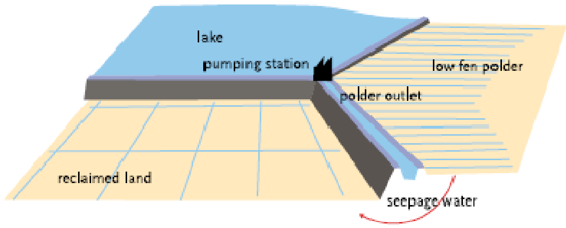

Fig. 1 Diagram of 'polders' and 'reclaimed land' [7]

There is constant interchange between the different components: the polder drains water into the lake by ditches and canal, as well as absorbing it through the same system in summer. Water level in the lake influences the seepage water which then will affect the groundwater flows in ditches and canals. This interconnectedness is the basis for management of main water system. Under normal circumstances, it's obvious that water in every component is at the present level and that it flows where it is needed. However, in periods of excess rainfall or drought, people have to constantly control and manipulate the system to meet demand and prevent problems [7].

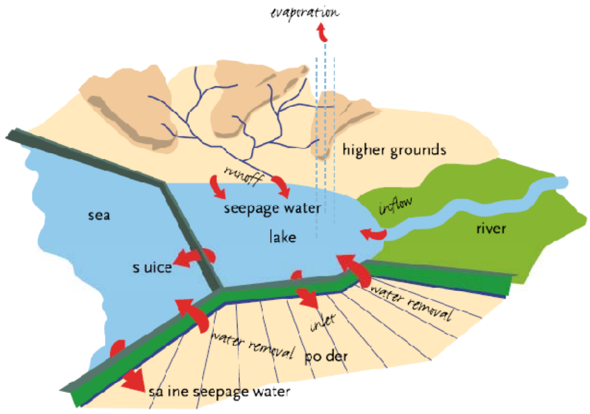

Fig. 2 The interconnectedness of the water system components [7]

III. Development History of Almere

Almere, initially built as a satellite town of the capital Amsterdam, is located in Flevoland of the Netherlands, 20km away from Amsterdam. The city covers 248.77 km^2 in total, including water area of 118.29 km^2. As the largest city of Flevoland, Almere has become the seventh largest city in the Netherlands with the population over 180,000 by July 2008. Owing to the expansion plan of Almere, its population is expected to reach 350,000 by 2030.

Almere is a typical polder city. The sea reclamation project in Flevoland is initially planned for agricultural purpose. In the end of World War II, two new polder cities were planned because of the rapid population growth and the increasing house demand. The one is Lelystad, the other one is Almere. As one of the latest built cities in the Netherlands, with the first building emerged in 1976, Almere was formally established as a municipality until 1984.

Almere is planned with several semi-independent core areas with own blocks, public facilities and location markers. These core areas are connected to the urban center through the public infrastructures. The ditches and lakes intersect in the six urban areas of Almere. The water system of polder city is protecting the land from damage, and maintaining the social and economic development in this region.

IV. Structure of Almere Surface Water System

The surface water system of Almere mainly comprises lakes, drain/ditches, weirs/sluices, dikes and pumping stations.

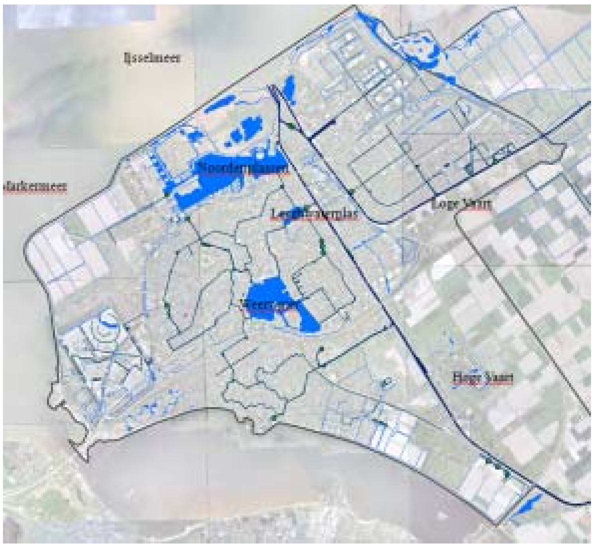

Fig. 3 Open water bodies and canals in Almere

A. Lakes

Almere is surrounded by water in three sides. The lake Markermeer in the north is the twin lake of IJsselmeer built in the early Zuiderzee Works. The Markermeer covering 700 km² is 3 m to 5 m in depth. Due economic and ecological concerns, the area that initially planned to build polder turns to form a lake after building a dam. Nowadays, the Markermeer functions as fresh water reservoir, buffering for drought and flood control, and ecological conservation as well. IJmeer in the west converges with the Markermeer; lake in the south is Gooimeer. The three external lakes' water level is very close to sea level.

The entire Almere is below the sea level, and the road elevation is -6.2 m to -3.15 m N.A.P. The overall terrain of the planning area is relatively flat; most high-lying areas are located in the southwest; low-lying areas are located in the north. Lake Weerwater in the central part covers 1.5 km^2; Lake North (Noorderplassen) covering 2 km^2 is a Wetland Protection Park.

B. Drain and Ditches

The polder in which Almere located carries dense river network that are mainly function as drain and ditches, including high canal, low canal, normal river ways and capillary water net.

High canal, of 50 m in width, collect seepage water and rainwater from higher ground in the south and direct to Ketelmeer in the east. Owing to the large amount of seepage water here, regular flow of high canals is significant to security, ecology and recreation. Low canals, of 45 m in width, collect excess surface water from lower flow rate area in the middle of polder and use it to adjust the water level. The water quantity of canal is under control, and the water quality is ensured by continuous refreshing water. The large part of Almere is located at west of the two canals. The staggered network of water in the region plays a significant role to maintain the quantitative and qualitative balance of local water system.

C. Pumping Stations

Pumping station de Blocq van Kuffeler is one of the largest pumping stations in the world. It is located on the dam where high and low canals meet in the northeast of Almere. The huge structure is put into use in 1967, which is diesel-powered. It maintains the polder's water elevation with other three pumping stations in Flevolands.

The pumping station comprises four pump units. It works at 85 rpm under normal conditions, with processing capacity of 850 m³/min to 700 m³/min. The pump unit can work for 600 to 900 hours during the dry season, and 1200 hours during the rainy season.

D. Weirs and Sluices

Weirs are mainly used to adjust the water level. Movable weirs are adopted to better control the height of the regulated water. This kind of weir, with a movable flap valve, allows excess rainwater passing through the weir in the condition of heavy rainfall, and then the water surface elevation gets back to the present level. Most of the weirs are automatic or semi-automatic. Water is directly discharged into the canal through the weirs.

V. Operational Modes and Function Analysis

As a typical polder city, the basic goal for Almere is to maintain a long-term stability of surface water level in the polder. This is essential not only to ensure safety of the city with an expected population of 350,000 in the future, but to exert the functions of urban water system in ecology, recreation and transportation. Water quality must be kept in good conditions to fully achieve these functions.

A key climate feature of the region is the relatively even distributed rainfall all the year round, with a significant difference of evaporation between winter and summer. Therefore, "flood in winter and drought in summer" emerges regularly, and the urban water system can be roughly defined as two "operational modes": "winter mode" and "summer mode". In colder seasons, excess surface water is discharged from the polder to the outside water body, so as to prevent flooding from occurring in reclaimed land for urban construction and agricultural use; in warmer seasons of the year, external water is introduced to the polder to ensure stability of regional hydrological system, and to meet agricultural water demand and protect dams from damage as well. In different management regions, the internal water level control in winter and summer are mostly the same, with some slight difference in certain area. Throughout the year, "winter mode" is generally longer because the average annual rainfall (755 mm) is exceeding the total evaporation (563 mm) up to 192 mm [8]. In addition, when rainstorm comes, the water system in the polder will turn to "flood relief mode" which will pose greater challenge to the system's draining efficiency.

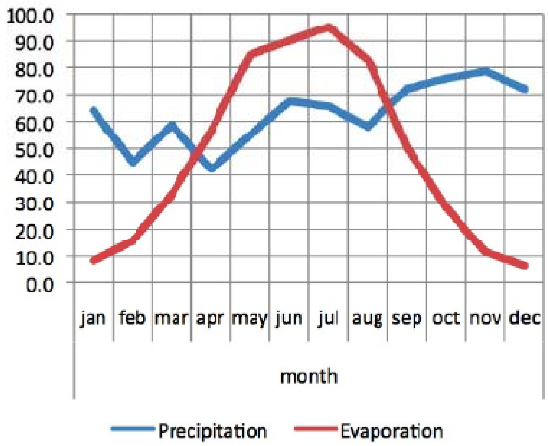

Fig. 4 Averaged monthly rainfall and precipitation in millimeters (1971 – 2000) over the period of one year in the Netherlands. Well visible is that the evaporation is exceeding the precipitation during the summer months [9]

Almere and the polder's water system implements three important functions in these operating modes, which show great hints for future urban development of coastal areas.

A. Damming System: Defense Seawater Intrusion

Almere is under the protection of three dams, including the Ijsselmeer formed in the early Zuiderzee Works, the Markermeer formed in the Markermeer project, and the south Flevoland polder project. These dams have completely prevented seawater intrusion.

The standards on hydraulic engineering design and construction in the Netherlands are extremely high. The 32km-long Afsluitdijk was completed in 1932 under the design standard of flood with recurrence interval of ten thousand years. It is 3.5m higher than the given highest tide, and 90m wide at the sea level, equipped with strict impermeable measures. The dam is still intact even it has experienced maritime storm surges for many times [10].

The Markermeer project has not been fully completed, but the 28km-long Houtribdijk dam becomes the second line of defense. Markermeer is also a key buffer and protection element for this region. In 2003, the Netherlands suffered a severe drought and many dams were threatened. Water was transferred from Markermeer to surrounding polders imminently, which effectively kept the soil moist and ensured the dam safe.

The multi-layer dam system under scientific and strict management is quite sufficient to handle the storm surges that may increase in the future, and to deal with coastal problems caused by land subsidence and sea level rise.

B. Highly Expanded Open Water System: Higher Resilience Dealing with Floods

The standard drainage capacity of the Netherlands can be converted as 14 mm rainfall drainage per day, and the designed drainage capacity of Flevoland polder is 11mm to 18 mm per day [11]. This drainage standard is very high, but still difficult to resist occasional heavy rain. For example, 24 hours rainfall in parts of the Netherlands had reached 130mm in September 1998, which exceeded the drainage capacity and resulted in flooding in extensive agricultural and urban areas. Over the past few years, such situations made the Netherlands lose billions of euros [12].

These make people realize that a climate proof rainwater management method has to ensure a sustainable and flexible rainwater management system in the polder. The system may achieve selective storage in clean rainwater season, and realize rain flood regulation and storage under extreme precipitation. Although maintaining larger open water area may limit urban development and building use, it is almost impossible to result in rainwater infiltration and underground storage because of the higher water table, small drying height and non-permeable soil structure in the polder. Therefore, expanding use of open water to capture and store rainwater is widely recognized. Based on the Netherlands' guidelines for water resources management in the future, local water affairs management institutes keep the following idea: in the new urban development, open water shall account for 10% of the total land area [13]. In the Flevoland polder, the early open water accounts for only 1%, this is currently expanded to 4%. In the region of Almere with concentrative construction, nearly 4 km^2 lakes within the polder in the northern, central and southern parts and the ditches all over the city become important buffer water to deal with storm disaster. Large water storage facilities and extensive open water system greatly reduce surface runoff, as well as construction and operational costs of urban infrastructure.

C. Dynamic Closed Water System: Self-cleaning Internally

Water management system for Netherlands polder is based on considering each polder as an independent water system, which is mainly to control the stability of the groundwater and surface water elevation. Because of climate reason, the stability of the water level within the polder cannot be self-sustaining. In winter with less evaporation, the excess rainwater will be pumped into the canal at higher terrain, and ultimately discharged into the external lake. The process is reverse in summer, water must be introduced from external lakes, so as to add water and prevent the water level lowered. The control process is effective to ensure stable water quantity, maintain boating conditions, coastline landscaping and ecological services. Simultaneously, it is able to separate water within the polder from pollutants out in the external water bodies.

Nevertheless, researchers are still working on the sustainability of water management system. The system is still lacking of sufficient inherent resilience, a large amount of relatively clean rainwater is discharged, but much polluted external lake water is also introduced inward in the opposite case. Thus, there is certain risk of water quality decrease. So there comes a challenge to avoid cleaner internal water being discharged, and to prevent external pollutants from canals and rivers. In order to achieve this goal, expanding the open water is an important way to collect clean rainwater, as much as possible. However, for the purpose of maintaining good inter-seasonal water quality in a closed system, sewage plant should be fully used and its drainage standards should be improved. Besides, hygrophyte around the lake shall be used to purify the water, such as reed in ponds and ditches.

At the same time, the so-called "circulation model" [14] for sub-areas is vastly established in Almere in accordance with the water level control. This method is not only conducive to water quality maintenance at low cost, but also improve the quality of urban landscape.

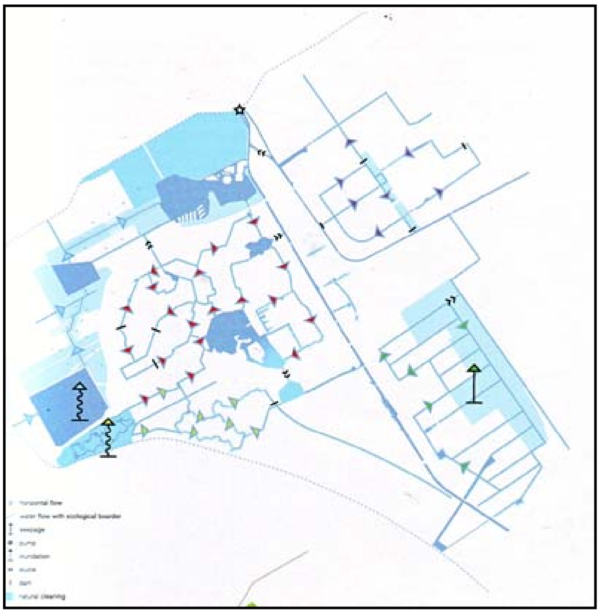

Fig 5 Circulation model applied in open water system in Almere [15]

VI. Conclusion

With higher frequency of extreme climate events, global climate change is challenging the urbanization process and population concentration in coastal zones. Although there are many differences in premises and backgrounds comparing with Asian coastal cities, Dutch polder cities have demonstrated the potential dealing logic and operation methods under extreme cases. Almere with its typical layout of polder city - dispersed settlements, dense river network, large area of open water body, precise control of water level, efficient drainage system, sound damming system, provides us with many experiences in coping with the potential coastal risks in low-lying areas. For the many coastal new town construction projects in emerging economies, more skills must be acquired to prevent seawater intrusion, to maintain internal water balance, and to achieve good water quality, so as to lay a more solid foundation for urban sustainable development locally and globally.

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