On the Water Environment System in Water Sensitive Area —Building of Sponge Airport Stormwater System in Beijing New Airport

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Abstract. This paper intends to study the water environmental system within water sensitive area of Beijing New Airport, further to research how it realizes the objectives of effectively controlling urban drainage and flood, scientifically utilizing and managing stormwater resource and efficiently reducing the total runoff volume and pollution, then building the stormwater system of "sponge airport". Through analyzing the problems in the water sensitive area and some limiting factors of airport building, this paper will emphasize the system of stormwater drainage and storage, the system of controlling runoff volume and pollution, the system of recycling stormwater and the system of digitalized stormwater management. The design philosophy and construction method of "sponge airport" as far as functional division of airport and mutual connection of various systems are concerned, and the construction goal of "sponge airport" is put forward. Based on these researches, this paper will state how the construction objectives of new airport are realized and how the different systems provide guarantee to its goal of being an advanced international aviation hinge.

Key words: Beijing New Airport; Sponge city; Digital model; Stormwater management system

1. Overview of Beijing New Airport

1.1. Site and positioning

Beijing New Airport is situated at the junction among Daxing District, Beijing and Langfang City, Hebei Province. The airport is about 50km away from the center of Beijing, which is south to Yongding River, north to Tiantang River, and across both Beijing and Hebei administrative regions (Figure 1) [1]. It is oriented to a large international airport hub, which will provide a critical guarantee for the sustainable development of regional economy in Beijing area, secure sustainable high-speed and safe development of civil aviation industry, international aviation hub construction and integrate Beijing-Tianjin-Hebei construction after completed. It is scheduled to construct and run by phases. In the current phase (in 2020), the planned land area is about 27.5km^2 and the annual passenger throughput is about 45 million. In the recent phase (2025) and the long-term phase (in 2040), the planned land area will be about 28.8km^2 and 45.8km^2, the annual passenger throughput will be about 72 million and 100 million.

Figure 1. Sketch map of the airport

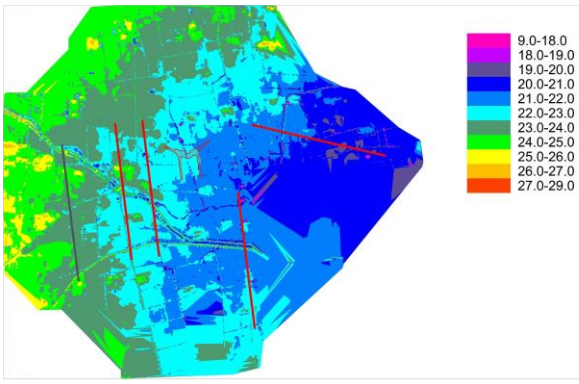

Figure 2. Sketch map of terrain

1.2. Terrain feature
The existing l terrain within the planned land in the airport is dipping from west to east and from north to south with about 3m of height difference from east to west and about 1m of height difference from north to south. Within the site, the original gradient is about 0.3 ‰, the original elevation is about 20.0~25.0m, and the top elevation of sand dunes and sand ridge is 27.0 ~ 29.0m (Figure 2) [2].

The location, weather, terrain, flood control and other multiple factors are taken into accounts for decision of the airport site. Based on the existing terrain conditions of the new airport, a variety of new airport terrain design solutions were proposed, such as the earth self-balancing solution, flood control solution and gravity drainage solution. In addition to the earth self-balancing solution, the other solutions require a large volume of earthwork, however there is no suitabl3 source of earthwork near the geographical location of the site. If a large volume of earthwork is excavated, the vegetation and the ecological environment in the earthwork source area will be destroyed, a large amount of energy will be consumed, the pollution will be imposed on the ecological environment along the way, a huge amount of investment will be yielded and the project is thus not feasible. So, the earth self-balancing solution is selected for the terrain solution.

In the earth-building self-balancing solution, the relevant factors are taken into accounts. In addition to the areas other than such areas as runways, airport platforms, taxiways, terminal, etc., which are highly demanded, the site terrain tendency is the same kept as the original one within the site as far as possible. To meet the use requirement and relevant criteria, the cut and fill of the land shall be reduced. As the new airport is south to the Yongding River, and north to the Tiantang River, the designed terrains shall be lower than the outer flood level so that the new airport area becomes a water-sensitive area in addition to the areas of terminal and runway, etc.

2. Analysis on Water Environment in the airport

2.1. Water sensitivity analysis

2.1.1. Analysis on outer flood . The airport is north to the new Tiantang River, and south to the Yongding River. Because the construction land occupies a part of the new Tiantang River, it is an important basis for the safe operation of new airport to coordinate the relationship between water level and terrain among the Yongding River, new Tiantang River and the new airport. In order to protect the new airport from external floods, the new embankment against the 1-in-100-years floods will be built on the north side of Yongding River and the south side of the new Tiantang River. By then, the new airport will be lower than the external terrain elevation so that it will form an independent on-site drainage system, and the airport will be less subject to the external floods.

2.1.2. Analysis on floods. As a large number of hardened areas, such as runway and terminals, will be built, the total runoff coefficient will be greatly increased in the whole site, and the total amount of stormwater runoff volume and the peak runoff volume will increase and the peak runoff time will be shortened, and other sensitive factors will yield after the development of the new airport. As the floods occurred before have caused great loss,[3] the new airport will form an independent internal drainage system, the stormwater cannot be discharged into the downstream by gravity. The factors, such as accidents in pumping station, non-timely pumping, incapable pumping, etc., will cause the stagnant water inside the new airport and form the waterlogging disasters in the rainstorms after the embankments of Yongding River and the New Tiantang River are built.

2.1.3. Analysis on runoff pollution. The villages, houses, ditches and roads are mainly distributed on the existing land type in the new airport without large industrial and mining enterprises and tall buildings. The existing overall runoff coefficient is low, and there is no excessive pollution source. The stormwater runoff can be received and purified through the soil and tunnels and have a good water environment self-purification capacity. A large number of complexes, roads and other non-point source pollution will appear after the completion of the new airport. Relevant researches [4] have shown that the roads and building roofs are the main source of non-point source pollution in cities and towns, where SS and COD values are higher. For this purpose, the airport will inevitably bring the runoff pollution to an extent.

2.2. Analysis on limiting factors

2.2.1. Limiting factors for drainage peak runoff volume. The diverted New Tiantang River will be used as the drainage outlet in the new airport according to the overall plan of the airport, the provincial and municipal agreements, the riverbed and water level elevation in the New Tiantai River, transformation solution of Tiantang River, the flood evaluation report of the airport and external water systems. According to the flood control in the Yongding River basin, the permitted external drainage flow rate is merely 30 m^3/s in the new airport when the drainage flow rate of the New Tiantang River and the Yongding River meets the design standards. The new airport only uses the land area about $27.5km^2$ in the current phase and will fail to meet the drainage and flood control requirement by merely relying on the external drainage flow rate of 30 m^3/s in the traditional way in storms.

2.2.2. Requirement for utilization of non-traditional water. Beijing is a city with serious water shortage, where the sewage that is treated in-depth and made as a renewable resource is an important mean to relieve the shortage of water resources, and it is an inevitable requirement for the construction of new airport (green airport). For this purpose, in the construction of the airport, all sewage and partial stormwater stored in the primary and secondary water retention facilities are made as a reclaimed water source for extensive treatment. The treated water meets the quality standards of the renewable water and is used to sprinkle green land, wash vehicles, clean roads, make up the landscape water and circulating and cooling water for air-conditioners. The surplus of reclaimed water will be discharged into the inner landscape lake within the site.

These factors shall be taken into accounts, such as the water system evaporation, leakage, rainfall, water quality maintenance and other factors for the make-up water in the landscaping river and lake within the airport. The main factors include water evaporation, leakage loss, exchanged and circulated water amount for maintaining the water quality. In the new airport, the surface area of water system is about 110 hectares, the annual average daily evaporation rate is about $3000m^3/d$ in the current phase; as the summer temperature is high, if the water quality requirement is to be met, the water must be exchanged once every 10 days with a large make-up water volume. Therefore, in addition to recycled water, the stormwater will be the main source of water for the water system in the new airport, and the necessary stormwater collecting facilities must be applied.

2.2.3. Requirement of water environment policies. As the water problems, such as water shortages, water pollution, and flooding, are becoming increasingly prominent,[5] Chinese government has always attached importance to the protection of the water environment. Relevant documents, norms and standards have been issued by the state and various regions in view of the major water environment problems brought about by the intensified urbanization in recent years. The water environment construction has been strictly enforced during the regional development. In the water environment construction of the airport, we should plan and design the supporting stormwater infrastructures based on the runoff control requirement as described under General Office of the State Council's Guidance on the Recommended Sponge City Construction *(State Office [2015] No.75),* Technical Guidance for Sponge City Construction-Low-Impact Development of Stormwater System Construction *(Hereinafter referred to as the "Guide")issued by the Ministry of Housing and Urban Construction, Beijing municipal specification DB11/685-2013:* Code for Stormwater Control and Utilization Engineering Design.

2.3. Analysis on countermeasures

Conclusively, the main problem facing the construction of water environment system in the airport is to meet the regional flood control requirements, to avoid the waterlogging due to the unsmooth internal independent drainage, to achieve the effective control of the total stormwater runoff volume, and to maintain the water quality in the new airport. Stormwater control and the facilities should be used to regulate the peak runoff, the total storage and retention volume of runoff water, etc. Thanks to the limited external drainage capacity, drainage and waterlogging demand large water supply and make-up water storage capacity.

The core to construct the sponge city is to realize the overall target of pollution control, disaster prevention, stormwater resources and urban ecological restoration, etc. With the mechanism building, planning control, design implementation, construction operation and management, multi-professional coordination and control, protection and utilization of urban green space and water system, it's priority to use green infrastructure scientifically combining gray stormwater infrastructure, and a flexible stormwater infrastructure is built jointly to achieve the goal of "infiltration, retention, storage, purification, use, drainage" for the stormwater runoff water. It's necessary to cope with the extreme storm and climate change, restore the urban benign hydrological cycles, protect or restore the urban ecosystems [6]. The coincidence of existing conditions, challenges and concept of building the sponge city just necessitates the building the sponge airport.

3. Overall frame of sponge airport

3.1. Overall objective

The determined overall control objectives are as followed: total runoff volume, runoff pollution, drainage and waterlogging, stormwater resource management and water environment protection according to the objectives of drainage, flood prevention and sponge airport construction, as well as characteristics of water system in the airport (Figure 3).

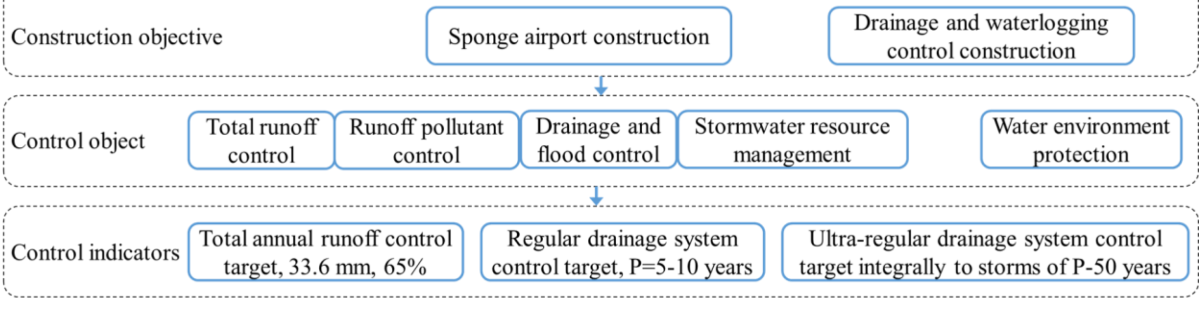

Figure 3. Major control objectives of the sponge airport

3 major control indicators are determined to fulfill the above control objectives for the water environment in the airport.

- According to the requirement under the "Guide", as the control rate of total annual runoff volume is 80%~85% in Bejing, the control rate of total annual runoff volume is 85% in the airport, namely, the designed rainfall is 33.6mm; these will meet the requirements for the storage volume equipped with less than 30 m^3 stormwater storage facilities per 1000m^2 hardening area under Beijing municipal specification DB11/685-2013: *Code for Stormwater Control and Utilization Engineering Design*.
- In the stormwater planning in the master plan of the airport, the designed recurring period of stormwater for the regional stormwater pipe in general area is P=5 years, the independent stormwater system is used in the terminal area and the stormwater recurring period of the stormwater pipe is P=10 years.
- In addition, with the integrated function of water environment system control measures, the airport should have a comprehensive capability of response to 1-in-50-years extreme rainfall.

3.2. Total runoff volume and pollution control solution

The "sponge airport" will be constructed involving a diversity of land types, such as construction area, roads, rivers and lakes. Regional drainage system planning, water system planning, vertical planning, etc. should be combined, and linking relationship between the areas and system should also be considered. To implement the overall goal of "sponge airport", the sponge airport stormwater system consists of three parts: source, midway and end controls (Figure 4). Among them, the source control mainly means that the total runoff is controlled and the runoff drained downwards is reduced by using the biological retention facilities and stormwater detention tank and other facilities in the area around the hardened area within the airport building area, roads, etc; the midway control measures mainly means that the runoff peak is adjusted and the runoff is purified by configuring the retention tank, grassing tunnel, etc in the small drainage system; the end control measures mainly mean that the requirements for total runoff, runoff peak and runoff quality control are met by using the landscape water, ecological embankment and other measures based on the source and midway control measures. With the organic combination of 3 parts, the airport city construction is promoted, the safety at the airport flood season is ensured, the quality of the new airport water environment is increased and the regional heat island effect is improved.

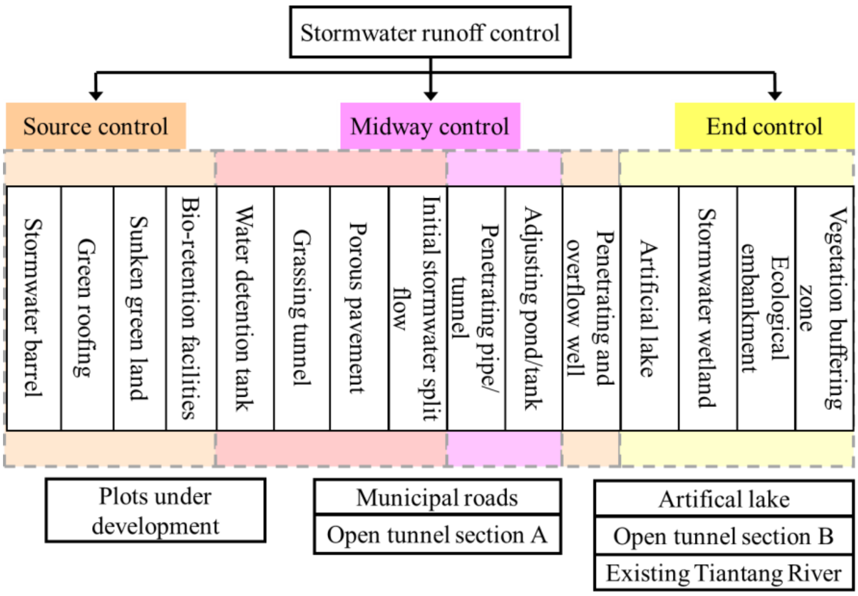

Figure 4. Sketch of stormwater management system in the airport

The airport is divided into five zones: flight, terminal, work, freight and maintenance according to the function of land use (Figure 5). According to its land use characteristics in the different areas, the different patterns and measures for stormwater runoff control are used to determine different stormwater runoff control solutions. The work, freight and maintenance zones are hereinafter referred to as the work zone to discuss as they have the similar conditions.

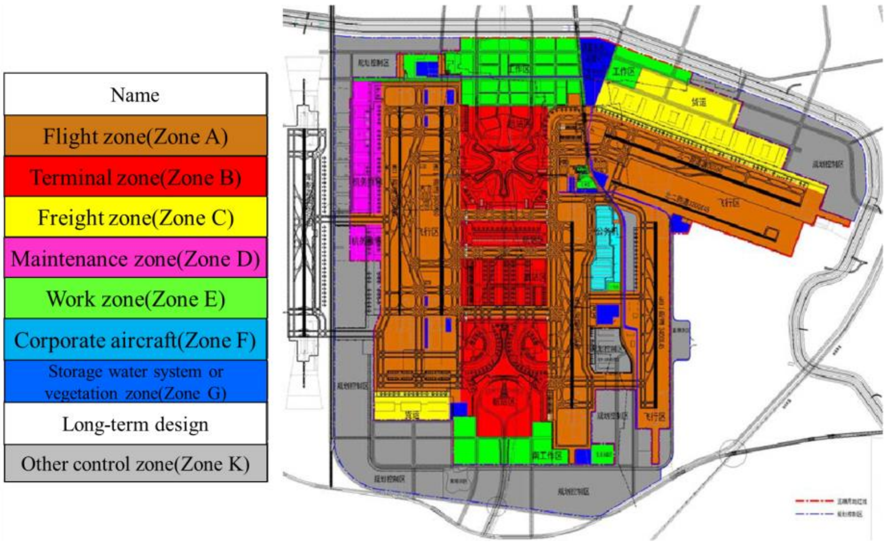

Figure 5. Sketch of the forward land division in the airport

The work zone is one of the core areas in the new airport. Its site conditions include the construction area, roads, green space, water, etc. Among them, the site construction area is the main land use type of the work zone. The area should be given full play to the storage capacity within the stormwater runoff area, and control the total runoff and clean runoff water quality by combining the land conditions and using the sunken green space, stormwater garden and other facilities. During the stormwater transfer, the runoff water quality is purified through the environment-friendly stormwater outlet, initial stormwater pool, etc. and the large public green space is used to regulate the rainfall runoff. Finally, the total runoff volume and peak runoff volume are stored with the end water detention tank. In the freight and other local zones, the rainfall coefficient is higher, and there is no adequate space to build the large-scale or distributed water storage facilities, the large-scale ecological stormwater detention tank must be built in the drainage downstream to centrally infiltrate and purify the runoff water through the infiltration area at the pool bottom, control the total runoff volume and adjust the peak runoff with the start and shutdown of pumping station in addition to the usage of the inner green land, the usage of the infiltration pavement, local stormwater detention tanks, etc. so as to reduce the rainfall runoff coefficient and receive the stormwater runoff.

The flight zone is based on runway and green space for the site conditions. Around the runway and the roads, there is a large number of green space and a good control condition of source stormwater runoff. A large number of source green spaces directly regulate the total amount of stormwater runoff volume, purify the runoff water quality, indirectly reduce the rainfall runoff coefficient and peak runoff volume in the flight zone by the sunken form. Meanwhile, the stormwater runoff in the flight zone is mainly drained through the open channel and regulated through the detention tank inside the flight zone. During the transfer of stormwater runoff, some stormwater runoff seeps into underground and makes up the groundwater and the runoff water can be purified. The stormwater runoff finally drains into the lower reaches of rivers after regulated through the large-scale detention tank and some stormwater runoff is received by seeping into the underground, evaporating and making up the landscape water and so forth.

The terminal zone is mainly based on the terminal building in the north side. In addition to the independent stormwater drainage system with the rainfall recurrence period of P=10 years, according to the stormwater runoff control principle in the work zone, the source control requirements are fully implemented in other areas, the water converges into the downstream detention tank at the end before draining into the landscape lake. The terminal zone is mainly based on the north terminal building. The terminal zone is mainly based on the air side area in the south side. The site condition is similar to the flight zone. The principle of stormwater runoff control is the same as that of the flight zone.

3.3. Storage and drainage system solution

The airport has a large catchment area, the smooth terrain, and merely 30m^3/s allowable external drainage flow rate is. By considering the impact of stormwater pipe & ditchdesign on the investment, pipeline depth, pipeline layout, drainage safety, etc, the stormwater drainage pipe & ditch and detention facilities shall be planned as a whole [7]. The stormwater system in the airport will use a 2-level drainage system (Figure 6). The runoff from each land block will be diverted into the municipal road stormwater drainage channel or the open drainage tunnel in the flight zone before the runoff water drains into the primary detention facilities in each drainage area. The runoff water drains into the open tunnel and landscape lakes for secondary detention in the field after pumped in the primary pumping station and finally drains into the planned New Tiantang River through the secondary pumping station at the river end. 2-level water storage volume reaches 2 million m^3 above.

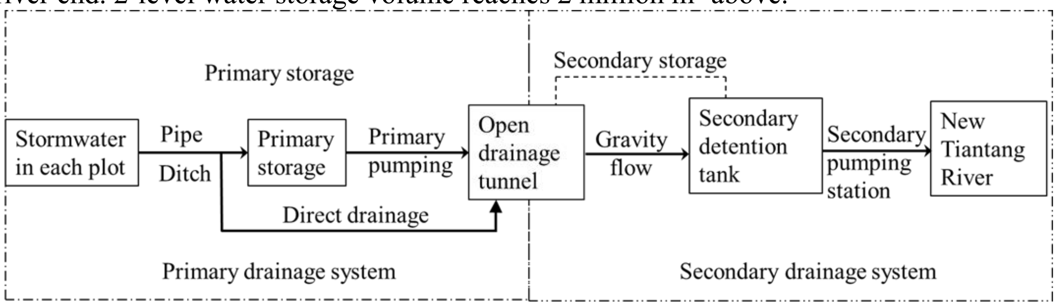

Figure 6. Sketch of simplified 2-level drainage system in the airport

The regional terrain in the airport is lower than the external flood level, and the drainage cannot be achieved through the gravity flow, the rational layout of pumping stations and storage facilities is essential in the airport to build the water storage system. According to the light, medium and heavy rainfall levels, the pumping station implements 3 different operating plans. In the case of light and medium rainfall levels, the pumping station has a relatively high pumping water level and the water storage facilities meet the total runoff control requirements. In the case the forecast heavy rainfall or heavy storms, the water detention tank and the landscape lake will lower the water level, reduce the pumping water level in advanced time, and keep the adequate time for regulating the peak stormwater flow rate.

3.4. Build the digital stormwater management system

3.4.1. Stormwater management system framework. Research has shown that not only the basic infrastructure construction such as monitoring system, drainage facility and demonstration area should be strengthened, but the water management system should be performed.[8] The digital stormwater management system to be built in the new airport is the key technology that the “sponge airport” is distinguished from the other stormwater system in general areas. The digital stormwater management system in the new airport uses digital model to simulate stormwater system, achieves comprehensive control and utilization of stormwater with the intelligent management goal, the model prediction and remote control mean, and has the ability to respond to emergencies rapidly.

The digital stormwater management system framework in the airport is shown in Figure 7, and divided into five layers. The 1st and 2nd layers are mainly used to provide information through the field equipment. In the open drainage channel, stormwater pipe & ditch outlets, etc. the measurement devices for liquid level, flow rate, etc. are set to monitor/control the running state of pumping station,

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water level before and after grates, as well as the water quality; the 3rd layer is to create the digital model to analyze and predict the drainage system operation state in differential precipitations in the new airport; the 4th and 5th layers are for the managerial staff to schedule and control the stormwater system in the new airport through the information feedback in the former 3 layers, integral real-time data and monitoring videos, etc.

With the construction of digital stormwater management system, the airport will integrate the monitoring, operation and management, flood control and scheduling organically, base on the basic data sharing, analysis and exchange platform of database management layer and automated control layer, realize the real-time flood control data collection, storage and optimization processing, visually display the production state, analyze and guide the operation, production and schedule, and timely generate the accurate statistical analysis report. With modeling and analysis, the rainfall scope and extent are derived from the weather report rainfall data or real-time data so as to provide the valuable info for decision-making of the upper management. With the automatic control means, the remote control of pumping station with the control scope is realized so as to overcome the defects of traditional manual tour inspections, such as large workload, low efficiency and slow response.

<table>
<tr><th colspan="3">Main contents</th></tr>
<tr><td>ODSS Intellectual decision</td><td>Risk simulation and evaluation /decision-making expert system</td><td rowspan="2">Command and coordinating layer</td></tr>
<tr><td>COLLABORATION command and scheduling</td><td>Real time data integration/ 3D trend display/ video monitor integration/Rainstorm analysis system/flood prediction system/flood control material management/flood command &scheduling/ video conference system/geological info system/mobile flood control command/flood emergency plan/flood info release/flood season traffic evacuation</td></tr>
<tr><td>SIMULATION system simulation</td><td>Regional drainage model/stormwater prediction</td><td>Analysis and prediction layer</td></tr>
<tr><td>SCADA real-time monitoring</td><td>Network communication/ data collection/real time monitoring</td><td rowspan="2">Sensing and executing layer</td></tr>
<tr><td>DCS/PLC equipment & meters</td><td>Onsite equipment/monitoring meters/electric applauses</td></tr>
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Figure 7. Sketch of conceptualization for digital stormwater management system in the airport

3.4.2. Effects of stormwater management system. The construction of the digital model is one of the core construction contents in the digital stormwater management system for the airport. The modeling and simulation results, if the stormwater pipe& ditch system in the new airport that meets the design criteria is verified, the flood risk and effect of extreme rainfall is evaluated on the new airport flood, the capacity of the stormwater system solutions is optimized in response to the flood risk, the countermeasure against flood risk and emergency plans against flood are proposed and the scientific and rational stormwater system guideline is determined based on the rational formula computing.

The airport is modeled based on the data, such as stormwater ditches, pumping station, landscape lakes, detention tank, planned terrain elevation and other data all together. Beijing 24-hour rainfall pattern and Chicago rainfall pattern are respectively used for modeling. The modeling results need to meet the pipe's non-pressure flow state for 1-in-5-years rainfall and no-stagnant water state on the surface in the flood control design standard for 1-in-50-years rainfall. It is found from the modeling that the stormwater pipe & ditches meet the drainage requirements for 1-in-5-years rainfall basically except for pressure flow in a partial of pipes & ditches; the manhole overflows the water in local areas for 1-in-50-years rainfall. We propose the following correction plans after the reasons are analyzed:

- Adjust the riverbed water level, reduce the flood pipe & ditch flooded outflow level, and avoid the raising of water level in stormwater pipe & ditches;
- Increase the stormwater pipe & ditch design standards, discharge the water of high water-level at high speed and avoid the extraneous water inflow;

- Increase the number of stormwater outlets at the indented road section and improve the capacity of pumping station;
- Optimize the road elevation design.

The drainage system of Beijing New Airport is remodeled to see whether it meets the above criteria after the stormwater system solution is adjusted. After the completion of the new airport, with a period of monitoring the condition of runoff generation and convergence, the model is calibrated and verified, the running solution of drainage system in the airport is proposed against different rainfalls so as to ensure the safe operation of drainage system in the new airport.

4. Conclusion

The “sponge airport” will be constructed by combining the traditional stormwater pipe& ditch system planning, drainage and flood control planning and water system planning, etc. The source control system, small and large drainage systems will be coordinated scientifically and reasonably. Through analyzing problems in the water sensitive area and some limiting factors in face of airport building, as well as the different land characteristics, the construction of “sponge airport” of New Beijing Airport is discussed respectively from the systems of controlling the total runoff volume, the system of pollution control, the system of stormwater drainage and storage, the system of recycling stormwater and the system of digitalized stormwater management. With mutual supplementing forms between the source and end, surface and underground, green and gray spaces, the 3-character policy of "infiltration, retention, storage, purification, use, drainage" is fully implemented. With the construction of optimal digital stormwater management solution, we can improve the capacity of operation and management, improve the ability of decision and analysis, ensure the safety and stability of production, and achieve the goals of total runoff volume control, runoff peak control, runoff water quality control, stormwater utilization, etc. for the construction of sponge city.

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