Water balance assessment for stable water management in island region

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Water Balance Assessment for Stable Water Management in Island Region

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ABSTRACT

Korea repeatedly experiences floods and droughts that cause traumatic environmental conditions with huge economic impact. With an approach and solution such as Smart Water Grid these problems can be alleviated. Tapping into the retention ponds behind dams, rainfall harvest facilities in urban areas and any other structures installed to store rainfall water during flood events will mitigate the damage of flooding and provide a new source of national water resources. Similarly, purified waste water, ground water and desalinated sea water can also be feasible to use as alternative water resources.

In this study, the water balance assessment model is being developed as a Smart Water Grid research. In fact, large proportions of water resources in Korea rely on river fresh water. Also in the Youngjongdo island, tap water from water purification plant which use original source from the Han river. However the water supply system in the island is quite dangerous since the water purification plant is located in Incheon city and the water comes to island through the sea and no other source is used in the island. Therefore, once the accident at main water pipe in the sea, no water is available in this island.

Information on water availability and water needs are crucial to identify hot spots of quantitative pressures on water resources. In this study, all available alternative water sources are calculated by the model developed through this study. Several physical and stochastic models on hydraulic and hydrological approaches are nominated to investigate physical characteristics of catchments.

Through this study, following results were concluded; a) To preserve the water balance in the study area, this study assessed the water balance within consideration of scenarios and suggested smart water management system which can cover potential risks on current water distribution system.; b) Within the scenario of accident on water supply system, all potential water resources in the island have been calculated through the model developed through this study. As well as, designed capacity of WWTP and desalination plant could also add self-supply water resources.; c) The water balance in the study area was analyzed through estimation of water demand and available water resources in the study area. Although the study area is an island which the major water sources such as dams or national managed rivers are not connected to, water resources from rainfall-runoff through small streams, reservoirs and retention ponds were sufficient to cover water demand.; and d) This study suggested simple and fundamental directions to apply smart water management technologies for the island region which can cover the water for non-drinking purposes at ordinary state. And the smart water management system was analyzed as being able to counter potential problems on water supply system which causes short-term water cutting off.

Keywords: Smart water grid, Water balance, Water in island region, Climate change

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Chapter 1 Introduction

1.1. Research Background

Korea repeatedly experiences floods and droughts that cause traumatic environmental conditions with huge economic impact. With an approach and solution such as Smart Water Grid these problems can be alleviated. Korean water resources environment is rapidly changing because of the Climate Change. For example, Rainfall pattern changed and its term became more and more concentrated. So water resources environment of Korea becomes that the rainfall of central district is increasing and southland part is decreasing. Also, some areas have problems such as water shortage and water distribution. By the way, needless to say, those who are facing the problems described above are not only Korean but it is seriously circulated as global issues.

Globally, there still are more than 1.5 billion people who don't have access to safe water and also 2.6 million people under the lack of sanitation facilities which provide clean water. Especially in the developing countries, unreliable water from poor treatment facilities causes several health problems and this problem can occasionally be linked to serious disease. There also is a problem on water itself which gradually gets polluted since the lack of treatment facilities. This is the problem coming from the unequal of water welfare.

The resources of water supply can be the water from dams, reservoirs, rivers, lakes, rainfall harvest, ground water, desalination plant, waste water treatment plant and so on and it is needless to say a lot. One more idea is making a platform to mix the water from different sources. However, only few of those sources are being used within present state although the water resources are occasionally located at outside supplying city. This is the problem of efficiency of water supply.

In order to figure the problem out exactly, it is firstly necessary to understand the water cycle. The water is continuously moving as definition of the hydrologic cycle which shows movements of water throughout the earth. The hydrologic cycle which can be represented as common feature of Fig. 1.1 involves the exchange of energy, heat and the states of water [1].

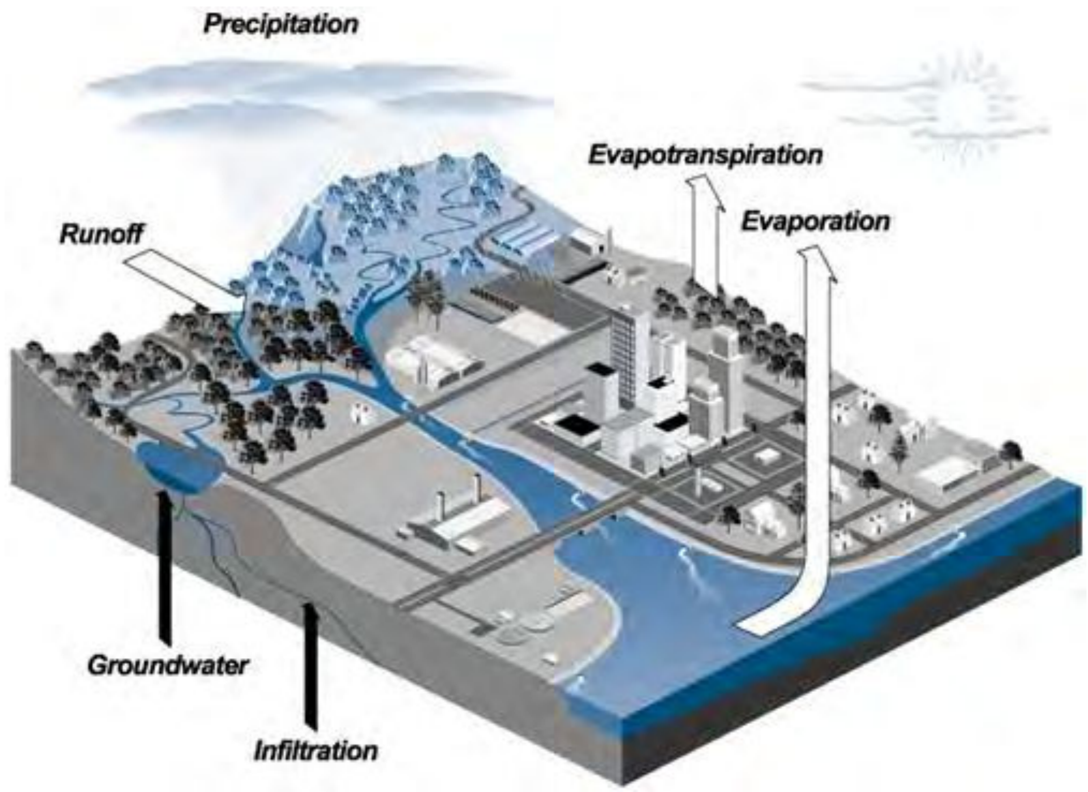


Fig. 1.1 Common view of hydrologic cycle (Gourbesville, 2014)

According to the water movement through the hydrologic cycle, the total quantity of water is always constant and unlimited. Nevertheless the quantity of water as essential resource is quite limited since it is difficult to meet the quality of water for the necessary purpose within natural status. Therefore there are many activities to preserve the essential water resources and the huge domain of Integrated Water Resources Management (IWRM) concept has been developed [2]. The approach from this concept aims the maximized economic and social welfare in the equitable manners without compromising the sustainability of vital ecosystems including human by promoting the well-coordinated development and management of water resources. IWRM approaches involve applying knowledge from various disciplines as well as the insights from diverse stakeholders to devise and implement efficient, equitable and sustainable solutions to water and development problems. As such, IWRM is a comprehensive, participatory planning and implementation tool for managing and developing water resources in a way that balances social and economic needs, and that ensures the protection of ecosystems for future generations. In such approach, ICT solutions can play a key role but focus has to be given to the most demanding and relevant domains of the water cycle. In order to identify which and how ICT solutions can be implemented, it is necessary to look at the water cycle through an approach based on functional domains and business processes. This methodology allows considering each action involved into the resource management and identifying the potential needs of ICT.

Within the concept above, the water cycle can be divided within three specific activities which are associated to activity and business domains as Fig. 1.2. The first domain is natural environment which covers conservation of water-related or aquatic ecosystem. And the second domain is natural hazards which consist of flood, water-borne disease, droughts and landslide (including avalanche events). Water disasters related to meteorological, hydrological and climate hazards repeatedly cause huge loss of life and economy. As well as, the third domain is water uses. The last domain (Water uses) covers the added influence of human activity on the water cycle. Generally, 'water uses' refers to the use of water by agriculture, industry, energy production and households, including in-stream uses such as fishing, recreation, transportation and waste disposal. All of those uses are directly linked to specific activities and processes which are potential targets for deployment of ICT solutions. In order to stick to the reality of the water management operated by entities in charge of water services, the traditional classification can be reviewed. The main water uses appear then as: agriculture, aquaculture, industry, recreation, transport/navigation, and urban.

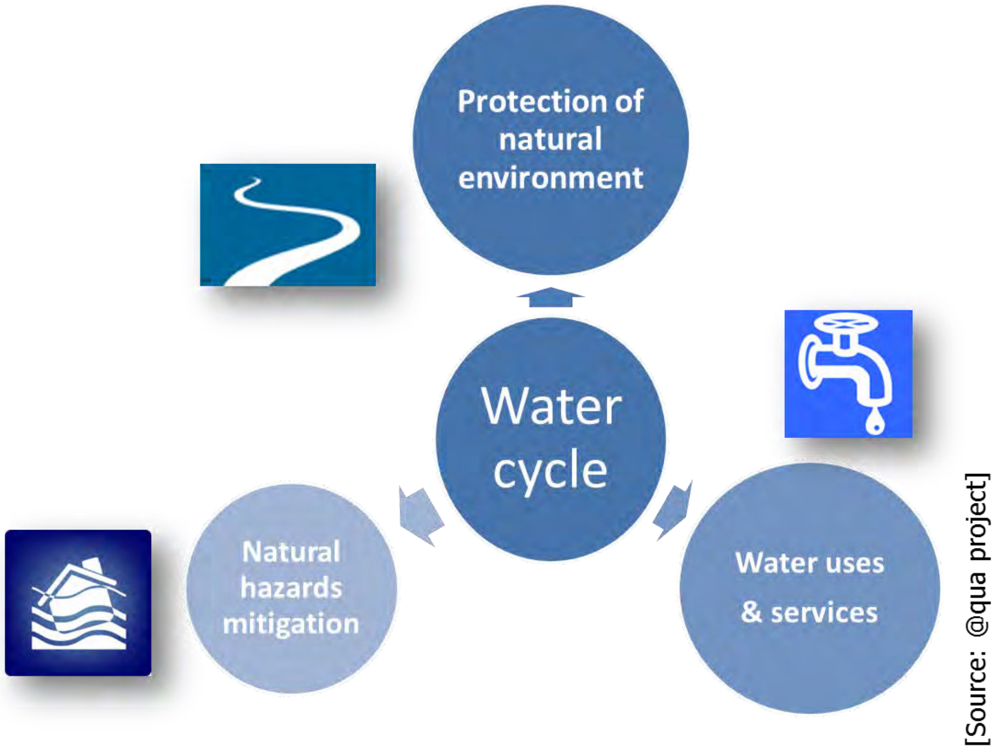


Fig. 1.2 Major domains of water cycle (Gourbesville, 2014)

The detailed description about major domains of water cycle is following;

Natural environment encompasses all living and non-living things, including natural forces occurring naturally on Earth or some region thereof, providing conditions for development and growth as well as of danger and damage. It is an environment that includes the interaction of all living species. Referring specifically to water environment, there are different biotopes than can be distinguished in continental waters (rivers, lakes, reservoirs...), coastal and maritime environments. A biotope is an area of uniform environmental conditions providing a living place for a specific assemblage of plants and animals. The subject of a biotope is a biological community.

Natural Hazards mean unexpected or uncontrollable natural event of unusual intensity that will have a negative effect on the environment or people by threatening their lives or activities. Atmospheric hazards are weather-related events, whereas geologic hazards happen on or within the Earth's surface. However, it is important to underline that atmospheric hazards can trigger geologic hazards, and geologic hazards can trigger atmospheric hazards. In the water domain, natural hazards are related to floods, droughts, tsunamis, limnic eruptions, seiche.

Water Uses are composed of the water cycle with the added influence of human activity. Dams, reservoirs, canals, aqueducts, intakes in rivers, and groundwater wells all reveal that humans have a major impact on the water cycle. According to the defined water domains, the water uses represent the largest field where ICT solutions can be developed and implemented. All in all, the Water uses considered in this framework are:

- Agriculture: Irrigation water use is water artificially applied to farm, orchard, pasture, and horticultural crops, as well as water used to irrigate pastures, for frost and freeze protection, chemical application, crop cooling, harvesting, and for the leaching of salts from the crop root zone. In fact, irrigation is the largest category of water use worldwide.
- Aquaculture: also known as aquafarming, is the farming of aquatic organisms such as fish, crustaceans, mollusks and aquatic plants. Aquaculture involves cultivating freshwater and saltwater populations under controlled conditions, and can be contrasted with commercial fishing, which is the harvesting of wild fish. This implies some sort of intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators and so forth. It also implies individual or corporate ownership of the stock being cultivated. Similar to agriculture, aquaculture can take place in the natural environment or in a manmade environment. This activity uses part of the water bodies in order to develop activities. Aquaculture can be more environmentally damaging than exploiting wild fisheries on a local area basis but has considerably less impact on the global environment on a per kg of production basis.

Industry: This water use is a valuable resource for such purposes as processing, cleaning, transportation, dilution, and cooling in manufacturing facilities. Major water-using industries include steel, chemical, paper, and petroleum refining. Industries often reuse the same water over and over for more than one purpose.

- Recreation: It often involves some degree of exercise as well as visiting areas that contain bodies of water such as parks, wildlife refuges, wilderness areas, public fishing areas, and water parks. Some of the activities that imply the uses of water for this purpose are: fishing, boating, sailing, canoeing, rafting, and swimming, as well as many other recreational activities that depend on water. Recreational usage is usually non-consumptive; however recreational irrigation such as gardening or irrigation of golf courses belong to this category of water use.
- Energy: Derived from the force or energy of moving water, which may be harnessed for useful purposes, such as Energy production. There are several forms of water power currently in use or development. Some are purely mechanical but many primarily generate electricity. Broad categories include: conventional hydroelectric (hydroelectric dams), run-of-the-river hydroelectricity, pumped-storage hydro-electricity and tidal power. Cooling of thermo-electric plants is another essential use of water in the field of energy.
- Transport/navigation: It refers to the transport of goods or people using water as a means of transportation (on rivers as well as canals). This water use refers only to commercial transport, since recreational transports such as sailing is considered above in Recreation water use.
- Urban: Urban water use is generally determined by population, its geographic location, and the percentage of water used in a community by residences, government, and commercial enterprises. It also includes water that cannot be accounted for because of distribution system losses, fire protection, or unauthorized uses. For the past two decades, urban per capita water use has levelled off, or has been increasing. The implementation of local water conservation programs and current housing development trends, have actually lowered per capita water use. However, gross urban water

demands continue to grow because of significant population increases and the establishment of urban centres. Even with the implementation of aggressive water conservation programs, urban water demand is expected to grow in conjunction with increases in population.

In terms of water cycle defined above, AQUA (@qua ICT for water efficiency) (2013) has described five activities for all domains of water cycle as Fig. 1.3 [3].

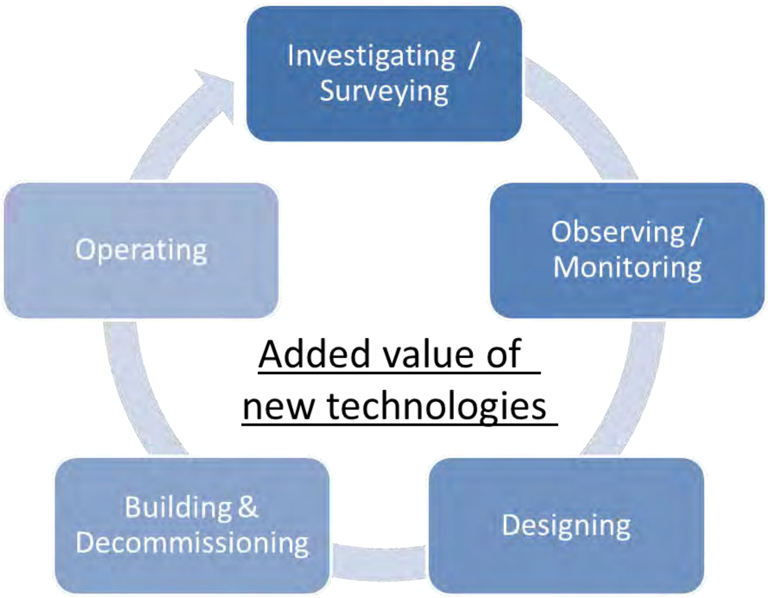


Fig. 1.3 Activities taking place in the various domains and water uses (Gourbesville, 2014)

The first activity is investigation and survey which consist of gathering of information and data for past or present state within study domain. This assembly of information can be done either by a systematic collection of field data (survey) or a collection of information or data from a methodical research of available documents and/or the production of new ones in order to understand or to improve the actual state of the domain. The second activity is observation and monitoring. This activity, in terms of general point of view, means the awareness of the state of a system. It describes the processes and activities that need to take place to characterize and monitor the quality and/or state of the domain in study. All monitoring strategies and programmes have reasons and justifications which are often designed to establish the current status of the domain or to establish trends in its parameters. In all cases the results of monitoring will be reviewed and analysed. The design of a monitoring programme must therefore have regard to the final use of the data before monitoring starts. The third activity is designing (or sometimes planning) which includes risk assessment. It refers the activities to meet desired needs and the process of devising a system, components and processes is mainly included. It is a decision-making process (often iterative) in which the basic sciences, risk assessment and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation. In order to obtain a design that achieves the desired needs for the domain in study, the two previous steps should have been accomplished and taken into account.

And the forth activity is building and decommissioning which include all activities to carry out the plans, designs or solutions proposed through the designing or planning and this activity must be carried out within consideration of risk assessment which is also proposed through the designing or planning (i.e. the third activity) to not meet the threshold of environmental impact. As well as, the fifth activity is operation which makes all designed and built system keep working as their proposed function. This activity should follow the rules designed and it may be protected and surveyed through monitoring.

We faced some points that need to make reasonable correspondence considering Climate Change within the activities and cycle above. Moreover, to secure additional headspring, mainly expand facilities were utilized, and didn't consider the Climate Change but just simply focused on the water supply system and unity water treatment system. Therefore, we need one integrated and effective water management with low-energy and high-efficiency. Smart Water Grid can make use of local IT skill with global level to solve this problem, and it can lead new generation with high green water industry which is come to the fore at water industry.

For overcoming the limitation of existing water resources management system, Smart Water Grid(SWG) appeared, which is an intelligent water management system, combined with most up-to-date technology of information and communications (ICT: Information Communication Technology). As a figure 1, through high-efficient and next generational water controlling infrastructures system, water, reused water, and seawater etc. all kinds of water sources were applied and efficiently distributed, controlled and transported. SWG is by definition the technology that water resource of regional and temporal imbalance can be effectively solved.

SWG project is to be a technology development organization that aimed at combining with Water Business (Water), Information Business (Smart) and Infrastructures Business (Grid), assuring water resources and solving the gap of water resources. It does not only assure the water quality and water safety of supplying, low energy and achieving high-efficiency, but also deal with the Climate Change. For this, the technology of assuring and distributing regional and temporal safe water resources, considering Climate Change, through the water balance assessment and automation of water supply in the area (Grid), applying the technology of water supply assessment and management, infrastructures related to ICT, assuring two ways(importing and exporting data) - real time optimal operation technology, and realizing and developing the essential technology combining with ICT integrated water resources technology.

Furthermore, the applied technology can compare well with the actual place according to its own specificity, and this kind of package is expected to develop. Look into the near future, the package will be applied in the developing countries by Micro unit (Complex, Building etc.)

Innovation in the Information and Communication Technology (ICT) is driven by unbroken progress in hardware performance for processing number, storing data and growing network capabilities, wired and wireless. New member in this story is the sensor for physical, chemical and biological quantities and qualities which, integrated in communication and networking, opens the door to the vision about the Internet of Things [4].

Internet of Things, in terms of original definition, refers to uniquely identifiable objects and their virtual representations in an Internet-like structure. The term Internet of Things was proposed by Kevin Ashtonin 1999. The concept of the Internet of Things first became popular through the Auto-ID Center at MIT and related market analysts publications. Radio-frequency identification (RFID) is often seen as a prerequisite for the Internet of Things. If all objects and people in daily life were equipped with identifiers, they could be managed and inventoried by computers. Tagging of things may be achieved through such technologies as near field communication, barcodes, QR codes and digital watermarking. Equipping all objects in the world with minuscule identifying devices could be transformative of daily life. For instance, business may no longer run out of stock or generate waste products, as involved parties would know which products are required and consumed. One's ability to interact with objects could be altered remotely based on immediate or present needs, in accordance with existing end-user agreements [5]. The Fig. 1.4. shows the concept of water management with internet of things.

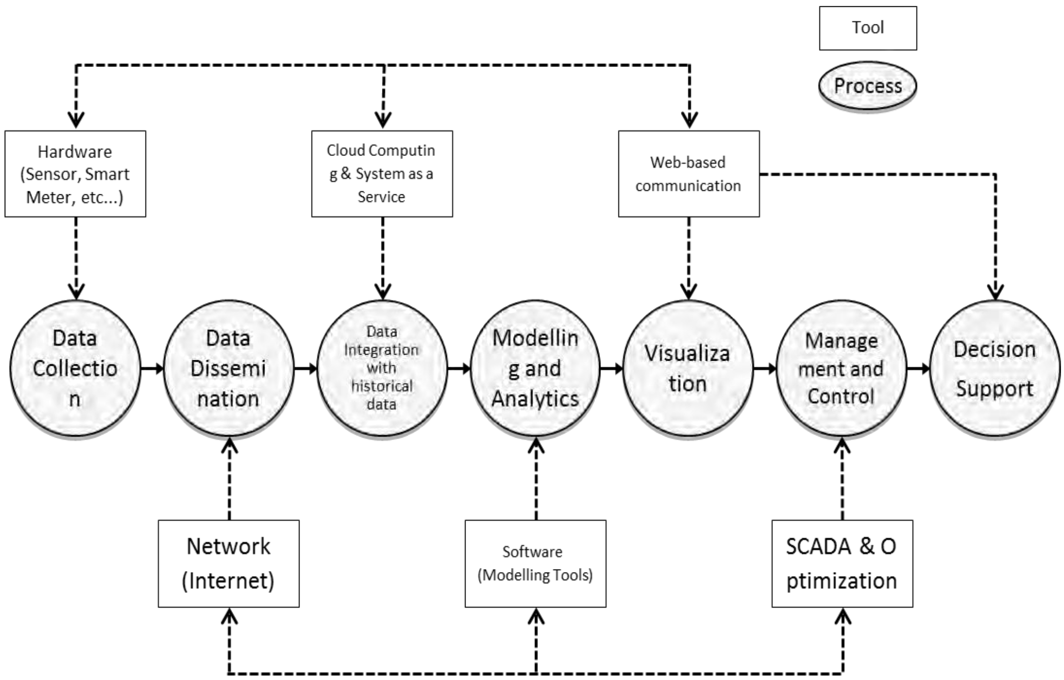


Fig. 1.4 Concept of water management based on internet of things

This is seen as an integrated part of the Future Internet and might be defined as a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual "things" have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network.

Transformation from the vision into some real piece of application is the idea of "Smart Water Grids" (SWG) [2] and their implementation in daily practice. A smart water grid addresses the area environment-water and is a network of fully integrated components, solutions and systems that enable a water utility to remotely and continuously;

- monitor and diagnose problems;
- control and optimize reactions;
- identify and manage maintenance issues; and
- inform its customers about intelligent and cost effective usage using data-driven insight.

In a similar way smart grids might be identified in other areas such as electricity, heat, gas, transportation etc. and all these grids might interact. Sectoral smart grids may interact with grids in other areas. Best known is the "energy-water nexus" as it takes a large amount of energy to extract, treat, store and transport water. Indeed, approximately 15 to 30 percent of typical water utility's operations and maintenance expenses are for energy. At the same time, a large amount of water is used in the production of energy - particularly as cooling water for power plants and for hydraulic fracturing or "fracking" in oil and gas drilling. This nexus will not be deepened in this paper which stays with the water- environment world.

Smart Water Grids are applications of Information Communication Technology (ICT) with the 3 main components;

- Technology: smart devices, data transmission, embedded systems, data management, online services, monitoring & control, distributed systems;

- Application: support of operation and management of systems, services for the public, service to the clients, stakeholders and citizens; and
- Market: people needs in daily life, paid & for free service.

Their development obviously must be a joint effort of specialists from different disciplines - from electronics (sensors, nets) to informatics (databases, communication), from application engineering (water-environment) to joint software system developments (information engineering), from geo- and social science to business and market with the involvement of citizens, customers, stakeholders, decision makers and politicians. Aspects of application are in the domain of “HydroInformatics” (HI) [7] which “comprehends all information technologies, methods, models, processes and systems applied in the "water-sector" and water-issues related neighbouring fields. Information is understood in an abstract sense; it may be about physics, environment, economy, social issues, organization, law, regulations and more. Models and processes concern physics, business, workflow, communication, management and more again. Thus HydroInformatics applies, generates, models, manages, transforms, condenses and archives information concerning the water-sector". So, the HydroInformatics domain, activity or movement embraces the full range of what is commonly called “business models” from public open-source developments through to private commercial developments.

In this context the role of spatial data and spatial analysis is to be mentioned as in most applications in the water-sector the basic information is related to geography, to geospatial definition of it, to its geo-localization. This means that nearly all “objects of information” are “somewhere”, and thus, benefit from very strong “Implicit Geographic Relationships” such as continuity, contiguity, inclusion, graph, neighborhood, proximity, etc. This means that the geographic approach, in a “GIS” or in a database using “geographic objects” should be the hub of the organization of HI Information Systems.

Smart Water Grids are based on the Vision about the Internet of Things. For the water-sector it is driven by eventual scarcity, growing earth population, climate change and commercial interest. Rationally people accept this, however, smart grids by technology will change daily life of people. Do they want? Must we do everything which is be possible? This discussion starts, answers may be differently because of local traditions and cultures as what holds globally must not necessarily hold nationwide or for the region. While Korea builds its digital metropolis of smart homes in Songdo other countries are afraid of security of the nets (US). Some countries slow down implementations and Germany even says about the energy grid "it probably won't follow smart-meter guidance from the European Union (80% of meters up to 2020) because such a move would be too costly for consumers" [8]. Nevertheless smart grid development will continue "selectively and in line with the energy switch" from nuclear to green. This puts the energy-water nexus to priority.

This market environment is an inhibitor for Large Scale Roll-out of smart water grids on the market as;

- opportunities of smart grids not known;
- the water market is conservative;
- there are numerous small companies with special solutions (standards needed);
- it is not clear which business partner will survive;
- it is not clear which solution will prevail;
- long-term of benefit of smart solutions is not clear; and
- the risk of new technologies is not clearly addressed.

In conclusion, there is a business problem, not a technology problem.

HydroInformatics has a long tradition in the development of computational simulation software in the water-environment sector. Many of the software models are available as code for research and as packages for application on the market. These models, the expertise acquired and knowledge are available for use and platform of development towards the smart water systems. Simulation models have to be redesigned for real-time use in networks with thousands of sensors interacting. This challenge raises many technological questions about online operation, security and reliability in water distribution networks. Smart-Online Water Distribution Network (WND) research project might serve as an example.

- Hydraulic state / flow and water quality simulation model must be extended to;
- incorporate measurement, data treatment and assimilation from sensor network in real-time to guarantee the compliance of the models with the observations. The consistency of the measurements is to be checked, methods might be Neural Networks.
- The performance of the models as well as the software design (object, agent, process oriented) have to be critically analyzed in view of high performance computing and final integration in a smart grid system. Standards have to be defined for coupling models and data.

Models have to be calibrated which for networks with thousands of sensors and transient processes cannot be done manually any more. Calibration of models must be supported by an automatic calibration framework which interacts with sensor data automatically. This task however demands knowledge about the optimal sensor distribution in a network, the sensitivity of which sensors at which location to which signal. This is also prerequisite for early warning about failure of pressure (leakage) or contamination detection. The problem of optimal sensor distribution has been covered by quite some papers during last decade, the problem mostly treated as multi-objective optimization problem.

Approaches to water quality and transport are more complicated due to physics than water quantity modeling. So the development of an online contaminant source identification toolkit would be very useful. Deterministic and probabilistic methods that were developed for offline models should be extended correspondingly.

Research on useful techniques, methods and models for this kind of research and development started many years ago in different application sectors of the water business (warning, calibration, control). Today’s methods are much advanced and technologically there is no doubt about the feasibility of smart grids. Here HydroInformatics can help to the story a success.

Within the facing situation in several regions and solution technologies, it is needless to say that the necessary and the first element to secure water for human being is to know the water situation in the region how short it is and how to secure more water. And this study would more focus on the island region since islands easily are isolated especially in terms of water supply unless they have their own stable water source and water distribution system. A few islands which have bridges connected to inland can take water from inland but the proportion of those islands is too little. Although there are alternative water resources such as ground water, harvested rain water, desalinated sea water and so on, this type of water supply accompanies side effects with big noise pollution, high power consumption, low water quality, salt water intrusion and so on. Thus island regions occasionally face difficult to secure sufficient water and need certain assessment data to make their decision to secure water.

According to the Korean Statistical Information Service, there are more than 3,200 islands in Korea and approximately 400,000 persons are living in 470 islands [9]. This study would provide basic data to secure water for one pilot island as study area.

1.2. Objectives of the Study

This study aims the overall framework in terms of water balance assessment in the island region from the methodologies to the solutions to resolve physical and potential water shortage problems. In order to understand the definition and the application of this framework proposed through this study, it is simultaneously necessary to know about the concept of Smart Water Grid and the Hydroinformatics in terms of their theoretical approach and solution built on the basis of them. The idea in simple language, this study conducted within a part of developing Smart Water Grid and it bases on the concept of Hydroinformatics.

Then, it is necessary to make accurate assessment about water supply and demand of grid for water provision for essential market in right time and right amount. For the long term perspective, an assessment system will be developed, which can evaluate and solve water shortage of city including industrial water, agricultural water by automation technique as shown in Fig.1.5.

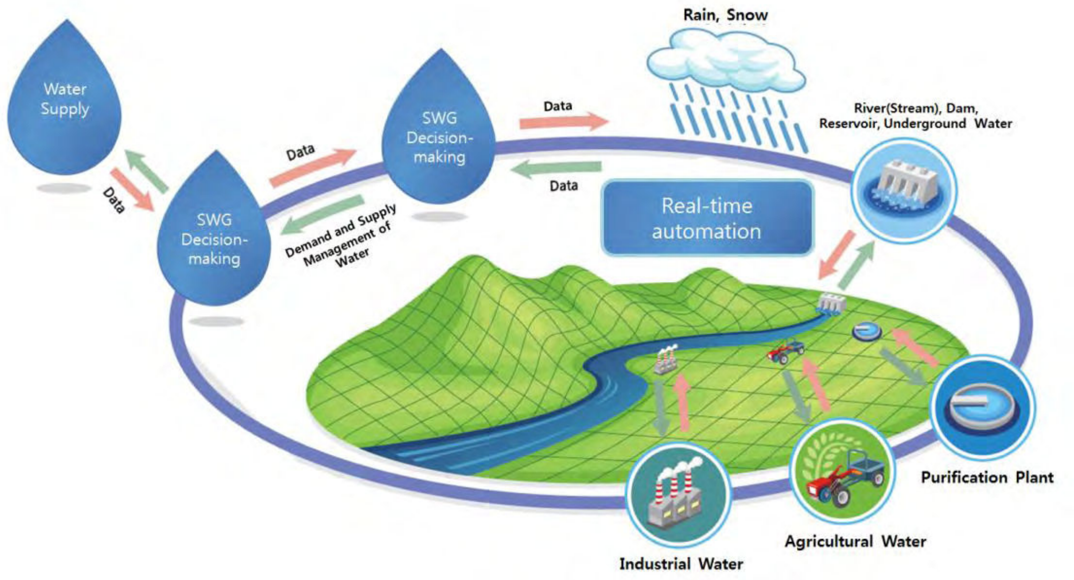


Fig. 1.5 Concept of Water supply and demand evaluation system

Tapping into the retention ponds behind dams, rainfall harvest facilities in urban areas and any other structures installed to store rainfall water during flood events will mitigate the damage of flooding and provide a new source of national water resources. Similarly, purified waste water, ground water and desalinated sea water can also be feasible to use as alternative water resources.

1.3. Literature Review

1.3.1 Review on modeling

In modelling practice there is a well-established 'good practice' principle within four stages [10]:

- Instantiation or set-up or 'construction'. This consists in defining such features and parameters as discretization, computational grid, limits and boundary conditions; an introduction of topography, soil occupation, structures, initially assessed values of roughness coefficients, etc.
- Calibration, which consists in executing a number of simulations of past observed events and in varying the parameters of the model until an acceptable (to the modeller) coincidence between observations and computations is obtained.
- Validation, which consists in executing with a calibrated model a number of simulations of past observed events (different from those used for calibration) and checking to see if the simulated results are sufficiently close to observation.
- Exploitation runs (studies) with the model recognised as a validated tool.

These four stages historically come from hydrological correlative or black box modelling practice. They are a natural and indisputable approach when data-driven 'models' are concerned. This approach is the very essence of such 'models', parameters of which in most cases have no physical meaning. Such 'models' cannot explain what is going on within the ‘modelled’ system: they do not describe the interaction of processes within the system. What counts is the ‘training’, i.e. the calibration of these parameters in such a way that, for given inputs, computed outputs correspond to observed ones.

Many true models are in reality composed of both deterministic and data-driven or black box correlative parts. Some of the processes within the model or modelling tool may well be described by physical laws and equations but others, within the same model, may not. The MIKE SHE modelling tool provides a deterministic approach for all processes of water transfer through a catchment, but it allows the user to replace some of the deterministic components by others that are of a datadriven type. This option is often used when there is no need for some components to be predictive. A similar situation arises for other applications:

- Modelling river floods often involves a model that is a combination of a deterministic component of river flow simulation and of a data-driven rainfall/runoff component (e.g. MIKE11 and NAM).
- Modelling pollutant fate in groundwater flow often involves deterministic components, such as the water flow itself and the advection–diffusion of the pollutant, but also data-driven ones, such as the adsorption of the pollutant in unsaturated zones.
- etc.

Clearly, in all such cases the data-driven components have to be calibrated (‘trained’) as explained above. And it is important to realize that they must be calibrated separately from the overall tool and, hence, there is the need for data that concerns only these components, as well as the methodology to calibrate them as specific components. It is not easy to calibrate some components as data-driven models and then consider others as deterministic ones! However, we still have to do so with a model in the sense that we can always trace an expressive property or meaning to the productions of the tool concerned.

When we consider, however, deterministic modelling (based on physical laws describing simulated processes and their interactions), this four-stage paradigm is not only illusory as a way of increasing accuracy but it may also lead to dubious and unreliable results. Hence it should be abandoned and a modified paradigm is to be applied when physically based deterministic models are concerned. More precisely, the calibration stage should be eliminated from the paradigm while the validation stage, as compared to current practice, should be carried out in a different way and in a different spirit. We shall illustrate this position in the following and by examples of current practice.

When the calibration of deterministic models (or deterministic components of models) is considered, one may ask oneself: what is to be calibrated? What is modified during the calibration procedure? An obvious principle (often violated in practice) is that the calibration must be limited to the model parameters that are invariant between the instantiation and exploitation stages, unless the purpose is to study the sensitivity of the model to modifications in its parameters. To calibrate parameters that will subsequently be modified during the exploitation runs used for simulating the impact of future projects is most often a useless, as well as costly, exercise. It is better by far to let a model be truly deterministic, i.e. a model without 'inner black boxes' describing physical processes, the only parameters of which are empirical or experimental coefficients related to physical characteristics. For example, in open channel flows in rivers, such parameters are roughness Manning/Strickler/Chezy coefficients, singular head-loss coefficients and discharge coefficients of structures (weirs, gates, culverts, etc.). But certainly not topography, dyke elevations, operations rules for structures, etc. Roughness coefficients are invariant parameters between calibration and exploitation stages, unless the exploitation concerns projects that could modify them.

Cleaning up and dredging a badly maintained river stretch invaded by vegetation will necessitate the modification of the roughness coefficients. In this situation, roughness coefficients cannot be invariant. In order to study the impact of cleaning, one may wish to calibrate the current coefficients (before cleaning) in order to ascertain that the model reproduces the present conditions accurately. But to assess the impact of the change one has to modify the coefficients for the future situation and there is no way to calibrate these new values:

they are defined through an engineering assessment. Any calibration of ‘global’ head-loss coefficients along a stretch including features, the characteristics of which vary between a calibrated situation and exploitation runs (structures, sills, narrowing or widening of the river bed, etc.), may lead to a nonpredictive black box model.

Another question to be asked and considered: in practice, is a meaningful calibration possible? It should be clear that the answer is negative, at least for most cases, because of the lack of appropriate data, or the cost of their acquisition. It can be shown in examples how ‘obvious’ applications of a paradigm including calibration may well lead to serious errors because of the belief that calibration is meaningful or because of a wrong choice of calibrated parameter. One problem area is that of open (sea) boundary conditions for two-dimensional tidal estuarine models, as introduced earlier. There are still modelers who impose tidal free-surface elevations at open boundaries and ‘calibrate’ roughness coefficients within the model using stage hydrographs recorded at a few shore stations. However, as explained earlier in this paper, water elevations within the modelled area, both in reality and in the model, follow the variations of the boundary elevations, which means that even large variations in roughness coefficients of the model have little influence on elevations that are compared with observed values. As mentioned before, the main parameters that are calibrated to make models of this kind reliable are the variation of in-flowing and out-flowing discharge hydrographs and their distribution at the open seaward boundary [11]. Roughness coefficients within the domain must be assessed using the engineering experience of the modeler and then they can only be modified rarely and only locally. It is legitimate to calibrate the discharge distribution at an open sea boundary of a tidal model for the ‘project tide’ because the same distribution and the same ‘project tide’ would be applied to exploitation runs: this distribution is invariant for the model. It is futile to do so if projects proposed for the estuary could influence the discharge distribution at the boundary.

Another classic example concerns one-dimensional river modelling. One-dimensional models of rivers have a typical resolution of computational grids between 100–1,000 m, with distances between gauging stations where the water stages are recorded being of the order of 10

000 m. Thus along a 50 km channel there might be four calibration sections (boundary conditions excluded). In open channel flow engineers can evaluate values of roughness and head-loss coefficients by inspection, within a narrow range of error. If a visual inspection of the river stretch suggests a Manning coefficient of 0.03, it is easy to accept that the actual value of the coefficient may vary between, say, 0.025 and 0.035. If, however, the calibration of roughness (coincidence between computed and observed water stages at gauges at a distance of some 10 000 m) leads for this reach to values such as 0.04 or 0.05, this is unacceptable. Indeed, such a river bed would be, according to the Strickler formula, covered with equivalent roughness elements of diameters 0.78 or 3.00 m high! The only possible conclusion in such a case is that the model does not reproduce reality and that the calibration is meaningless. Obviously, when instantiating the model for this case, something has been forgotten: a bridge, a singular head loss, river shape-induced head losses, the appropriate representation of an inundated plain, etc. Another possibility is that the river geometric characteristics are not correct in the model and calibration gives absurd values because it compensates for narrows or for sills that influence more the surface elevations than does the roughness. Or, worst of all, the model is based on equations that do not describe adequately the physical process, such as fixed-bed equations applied to alluvial bed rivers, or a diffusive wave equation model applied to downstream-influenced or inertia-dominated flows. At any rate, from the point of view of prediction and future exploitation, the calibration effort is futile and useless.

Other typical examples of meaningless 'calibration' (should we say mindless 'fitting'?) of parameters until a coincidence between computed and observed free-surface elevations is reached are:

- Two-dimensional modelling of inundated plains. Indeed, the only past-observed data concerning the unsteady evolution of water stages that can be found on inundated plains are those rare marks of the highest elevations attained during historical floods. The only one known to the author, and a never repeated historical case, where the records were adequate for calibration purposes of such a situation was in the case of the Mekong Delta Model [12][13]. There were 350 computational points and three consecutive floods (1963, 1964 and 1965) were recorded at 300 gauges located over the modelled area. The cost of the modelling and measurement campaigns was over US$1 million (at 1963 values: this would be ten times more in 2002). This number alone shows that this approach would not be repeated today.

- Two-dimensional modelling of tidal coastal areas, for the same reason: the records are available at only a very few stations, generally located at the coast where conditions are specific and the tide is deformed. Thus the calibration of large areas through fitting computed and observed results may well be meaningless because the calibration criteria for large domains are really dependent upon the local effects of features located near stations.
- Groundwater flow modelling provides several flagrant examples, of which there is only space here for one. Following the current 'good practice' paradigm the permeability coefficients are systematically calibrated to obtain a coincidence between observed and computed evolutions of piezometric levels. In practice, the resolution of the network of piezometric recording wells, as compared to the resolution of computational points over the modelled domain, is always very small. It is rarely dense enough to make it certain that it 'captures' the possible main variations of geological conditions and of permeability parameters over the domain. Consider, on the other hand, the duration of the measurement period (at best 10 years) as compared to the time needed for the flow to cross the modelled area (often 50-100 years). The chances are great indeed that the modeler, by calibrating the parameters on the basis of 10 year records, 'twists the arm' of reality, and that the resulting 'calibrated' model is not a reliable image of reality at all. Once more the calibration is meaningless.

Why then, in the current paradigm, is calibration considered as a necessary step?

There are several reasons, such as:

- The end user’s or client’s measure of satisfaction. How does she or he know that the model is correct? Answering that the calibration reproduced past-observed results accurately makes him or her happy because, in the absence of any understanding of the inner mechanisms of the modelling he or she is reassured by the image of two coinciding curves.
- The end user (or client) might have spent a lot of money on collecting data, carrying out measurements, etc., and does not like the idea that this money was spent for nothing. It makes him or her happy to show that this data is being proved useful for the project: ‘these data were essential for a calibration that in turn is essential for proving the accuracy of the model . . .’.
- Suppose problems arise with a project built on the basis of modelling studies where nature did not behave as the model predicted. Then a modeler has arguments in his favour if he followed ‘good practice’ and if the calibration was carried out which led to the coincidence of past-observed and computed results.

In most specific cases, as developed above, it can be shown that these reasons are fallacious. To take a very crude intellectual shortcut, one may attempt to say that the calibration is still a common practice because it makes both sides happy: the modeler (who may estimate his or her intellectual effort as finished when the model is ‘calibrated’) and the end-user/client who feels that his or her duty of control and supervising has been done. Neither realizes that their satisfaction is so often related to a formal coincidence and not to any understanding of the physical problems, with this last criterion as the most important point for projects and future developments, and the very reason for commissioning the model at all. This is to say that the technology in such a case is not directed to an understanding of the underlying phenomena, but only to persuading an end-user or client that something of value has been done. It thus corresponds to the technologies of persuasion in their most negative sense [14].

The modified paradigm identifies the following stages in the modelling process:

- Instantiation or set-up or 'construction' of the model; definition of the methodology necessary to define the range of uncertainty in the results of the computations.
- Validation, which consists of executing a number of simulations of past-observed events with the model, computing or otherwise finding the range of uncertainty for the results and analyzing and finding physically logical reasons for differences between the simulated and observed results. After this, analyzing the impact of the differences as well as of the uncertainties upon the exploitation results.
- Exploitation runs (studies): supplying the results and impacts and their range of uncertainty to the end-user or client in a comprehensible form.

The modified paradigm for deterministic modelling as proposed above eliminates the calibration stage as such. The validation stage is not only maintained, but reinforced. In a way it incorporates the calibration stage. The past measured data will, of course, be as useful and as necessary as for calibration under the currently admitted paradigm but they will be used for a validation analysis of the computed results. It is claimed that a deterministic model, with values of parameters defined by inspection on the basis of engineering practice, should simulate reality correctly and its results should be close to past observed results without calibration in its irrational sense. 'Close' does not mean an immediately satisfactory coincidence. But making computed results nearer and nearer the observed ones must not be carried out through a calibration process as it is currently understood and applied. Indeed:

- If the differences between the computed and the observed lie within an acceptable interval of uncertainty, or can be explained by physical reasons, and if the consequences of differences upon exploiting the model as it is are analyzed and acceptable, then there is no reason to go any further with the modification of parameters.
- If the differences are greater than the uncertainty interval, than they must be explained. The reasons must be found and analyzed, taking into account, once more, the

consequence of using the model as it is or amending it. Most often the findings lead to modifications of originally erroneous data, such as topography, hydraulics characteristics or boundary conditions, and have not much to do with parameters. Sometimes there are factually important errors in values of parameters assessed during a visual inspection. But, sometimes, one may find that the modelling tool is not adequate: such often occurs when using 1D models where only 2D can simulate the real flows.

The new paradigm insists on the fact that this modified approach is not a calibration under a new name. The new ‘good practice’ asks for the collection and analysis of data for the purpose of validation, and validation is not just a check that computed values are not very far from observed ones: it is a study of the reasons why there is a difference between the two! Also it must, of course, be substantiated by a report leading to an understanding how such an analysis was carried out and how the conclusions were reached.

Paramount to the successful acceptance of this modified paradigm by the engineering profession as ‘good practice’ are the following conditions:

- A broad understanding of the difference, with respect to calibration, between deterministic and data-driven or black box models. A clear understanding of the difference, within a model, between an empirical parameter and a black box replacing a process.
- An acceptance that the simulation results of past events do not reproduce exactly the on-site measurements. A requirement for an engineering analysis of the differences.
- An acceptance, and even a requirement, that the results of models should be presented as uncertain and with a sound evaluation of the uncertainty range or interval.

The need for this new approach, and for this modified paradigm, is not fully recognized and not yet instituted as good practice, but the first descriptions of and information on applications and studies that follow these ideas are beginning to become available. One such study is the modelling of flood propagation across an inundated plain in South-Western France [15]. Interested readers are encouraged to read this reference. The case is interesting precisely because a calibration, in the usual sense, would be meaningless. The link between the requirements put on the reliability of the results, on the one hand, and the means necessary to analyze and ensure an accessible degree of reliability, on the other hand, is described. It is worth noting that, even in this case the authors thought it useful to insert one paragraph titled 'Model calibration', although there was no calibration in the traditional sense [10][16].

1.3.2 Review on computation of distributed water resource

The water is seen the premier constitutive factor of human being. Thus, it always plays an important role to the development of human society. However, water distribution is not equal due to time and space. These unbalances conduct many negative impacts to the human. Annually, natural disaster related on water issue such as flood, drought, storm…bring out lots of severe damages. These are not only on the property but also on the life. According to IPCC (2007) in recent years, under the impact of climate change, the consequences of flood, drought catastrophes are more serious [17]. Getting the deep knowledge on the hydrological factors in a catchment is an essential objective of hydrologist community to be able to transform disadvantages to advantages or mitigate the natural catastrophic damage to people. Nowadays, with the development of mathematics and computer science, the simulating the hydrological cycle for catchment becomes easier and more accurate. These progressions help hydrologists might have concrete and truthful insights about what happens in hydrology to make good decisions for reducing natural hazards on the catchment [10].

Up to date, many hydrological models have been developed with different theories to simulated catchment's hydrological phenomenon. They may be classified according to the description of physical process as conceptual and physical based, and according to the spatial description of catchment processes as lumped and distributed [18]. Each of them has advantages and inconveniences for simulating the hydrological process. Lumped models are one of simple hydrological model which assume that all characteristics are constant across the catchment such as HBV model, MIKE11/ NAM Model, Tank, Topmodel, Xinanjiang [19]. Lumped parameter models are much simpler in their treatment of spatial variation, which each model parameter described by a value that is uniform for the whole catchment so these could not be determined directly from physical characteristics of the catchment under consideration. These parameters are generally determined via calibration [19][20]. In contrast, distributed model is constructed on dividing catchment into sub units which each unit represents all physical characteristics for a real area. These kinds of models maintain the physical details at a given grid size and consider the distributed nature of hydrological properties such as soil type, slope and land use [21][22]. In principle, parameters of distributed model could be gotten from the catchment data. For this reason, distributed model is evaluated to be able to translate more accurately and concretely the hydrologic process in a catchment. One more advantage of distributed model is that the outputs such as water level, discharge, hydrological factors could be perfectly extracted at anywhere in the catchment. These efficiencies help to overcome difficulties in lack of observed data, which have a great significance for simulating the hydrological process at a large catchment or in developing countries. However, which model is the best to simulate hydrological process? Until now this question has not been clearly answered yet. There are some arguments on the advantage and limitation of this both kind of model. Even if distributed model have drawbacks on computation time, initial parameter definition or lack of spatial data for set up model as well as validation, most of modelers estimate highly the capacity of distributed model than lumped model [23][24]. The lumped models, in many case, perform just as well as distributed models with regard to rainfall runoff simulation when sufficient calibration data exist [25][26]. Conversely, the distributed model could not prove completely its performance in simulating the hydrological factor. Because the spatial input data such as topography, soil type, land use nowadays might be available to build the model, but it is really not easy to find the spatial data for calibration or validation. This leads to quality estimation of the model in the whole catchment is mostly unable, the calibration and validation are generally carried out against the data at several gauging stations. One more weak point of distributed models is that this model type commonly consists of more parameters than lumped models so the calibrated process is more complicated and difficult to achieve the acceptable values [27]. However, Refsgaard noted that more detailed physically base and spatially distributed models are assumed to give a detailed and potentially more correct description of the hydrological process in the catchment whereby might provide more accurate predictions [21]. From these preeminence, many distributed models have been developed and applied in recent years such as MIKE SHE, SWAT, SWIM, LISFLOOD and WETSPA.

In many current hydrological models, deterministic distributed model is likely to have more advantages. The main interest of a deterministic distributed hydrological model is to be able to provide hydrological data at any locations within the catchment. This possibility allows to investigate, in depth the hydrological dynamic. Several tools are today available and could be used for such analysis. The typical model is MIKE SHE developed and extended by DHI Water & Environment since the last decades of the 20^{st} century. MIKE SHE covers the major processes in hydrologic cycle and includes process models for evapotranspiration, overland flow, unsaturated flow, groundwater flow, channel flow, and their interactions. Each of these processes can be represented at different levels of spatial distribution and complexity, according to goals of the modeling study, the availability of field data and the modeler's choices [28]. The representation of catchment characteristics and input data is provided through the discretization of the catchment horizontally into an orthogonal network of grid squares. In this way spatial variability in parameters such as elevation, soil type (soil hydraulic parameters), land cover, precipitation and potential evapotranspiration can be represented. Within each grid square, the vertical variations in soil and hydro geological characteristics are described in a number of horizontal layers with variable depths. Lateral flow between grid squares occurs as either overland flow or subsurface saturated zone flow. The one-dimensional Richards' equation employed for the unsaturated zone assumes that horizontal flow is negligible compared to vertical flow [29].

Researches on the spatial and temporal distribution of water flows through the land are needless to say important for sustainability of water resources and for mitigation of water-related natural disasters such as flooding. Hydraulic and hydrological analyzing tools serve as important tools for providing compulsory information in advance. Several models on water control through the knowledge about hydrology and hydraulics have been developed through various studies in the past time with various levels of processes on water movement represented within accordance of the characteristics and availability of data [30]. Especially the hydrological models have been divided into conceptual or physically-based in terms of their computation type [18][31][32]. Conceptual models treat the real situations such as complexity of domain, variation of spatial basement and complicated processes on water movement as simple mathematical expressions without consideration of explicit treatment of the underlying physics or inter basin heterogeneity [33][34]. Physically-based hydrological models, which occasionally refers to as distributed model, mathematically represent each of the important components of the hydrological cycle based on their physical governing equations [18][35]. The potential strengths of distributed hydrological models are:

- The ability to account for the intra-basin variability of runoff-producing mechanisms;
- The ability to infer model parameter values from geospatial data (e.g. geology, topography, soils, and land cover). A hybrid modelling strategy that maintains a balance between the degree of physical realism and data requirements, so as to provide reliable simulations under a variety of settings, seems to be advantageous.

Nevertheless, the application of spatially distributed, physically based models, such as SHETRAN [36], MIKE SHE [18] or CASC2D [37], to large catchments, is restricted by the vast amount of high quality and fine resolution data needed, in order to reliably model the physical processes taking place in the catchment [38]. Alternative approaches to the rainfall-runoff modeling have, therefore, been developed, which represent physical processes with far less detail but still give a spatial distributed representation of the catchment. These models were developed to simplify the simulations of practical case studies where a detailed representation of the processes involved in the catchment is not necessary. They are distributed models where some (or all) of the hydrological processes are modelled using conceptual schemes. Examples of these alternative models include the SLURP (Simple LUmped Reservoir Parametric) model [39], which subdivides the catchment into units of different land cover and other sub-units (Grouped Response Units). It is a distributed conceptual model, which has been primarily designed in order to make use of remotely sensed data. It has been applied in climate change studies. Another alternative model, TACD [40], is an example of a raster based conceptual model. The core of the model is a process-oriented runoff generation routine based on experimental findings, including tracer studies [41]. Further attempts to simplify the rainfall-runoff modelling approach while maintaining a spatial description of the catchment have produced a class of semi-distributed models that make use of a distribution function to represent the spatial variability of runoff generation [42]. TOPMODEL [43] is one such model. It predicts the dynamics of the contributing areas based on the pattern of the soil topographic index. It has been applied in many practical hydrological studies such as estimation of flood frequency distribution, by continuous simulation, in ungauged catchments [44][45][46]. The HBV model of Lindstrom et al. (1997) [47], whose early applications date back to the 1970s [48], belongs to the class of semi-lumped models. The authors tried to develop a model that covered the most important runoff generating processes by using the most simple and robust structure possible [33]. The HBV model has been applied, in several countries, for studies concerning real time forecasting, climate change impact assessment and simulations in ungauged basins. One of the most widely used rainfall-runoff models in Australia is the Australian Water Balance Model (AWBM) [49][50]. It consists of a conceptual model that simulates the spatial variability of the saturation overland flow by means of the conceptual basis of the Antecedent Precipitation Index (API) model. In detail, a bucket with a particular storage capacity is assigned to each portion of the catchment with different storage capacity. The rainfall is abstracted until the bucket is filled, and then all rainfall becomes runoff.

1.3.3 Review on water balance

A water balance, applied to a particular spatial unit is an application of the law of conservation of mass which states that mass can neither be created nor destroyed. Balancing the availability and the demand in a spatial scale will be the best way to cope up with the present trend. To achieve this balance, the rate of change of storage of water within the spatial unit must be equal to the difference between its rates of inflow and outflow across the unit. Calculation of water balance is a basic approach for determining stocks of water in different components (air, soil, water bodies) of the hydrologic cycle and fluxes between these components. The water balance model will be able to assess the water resources, in finding out the moisture deficit and moisture surplus with different temporal and spatial resolutions. Knowledge of the quantity of water in different components of the water cycle serves in (a) Sustainable management of water resources and the protection against over exploitation and contamination (b) Cropping pattern – irrigation and drainage practices (c) Analysis of the effect of land use changes on water availability (d) Analysis of the effect of climate changes on water availability (e) Identification of recharge zones, (f) Rainwater harvesting, etc.

In the last few decades, changes in land use and land cover, changes in climatic conditions, population explosion, enhanced industrialization and urbanization has deteriorated the conditions of the Amaravathi watershed a semiarid region of Tamil Nadu, India. As a result, the effect of these changes on the water balance components is unknown. A serious problem recognized is that sufficient water is not available during the dry season. The water sector is very sensitive and is strongly influenced by the changes in climate and land use. Hence, it has the potential to impose additional pressures on water availability, water accessibility and water demand in the Amaravathi river basin. Even in the absence of climatic change, present population trends and patterns of water use indicate that the basin will exceed the limits of the economically usable, land based water resources before 2025 [51]. It is important to bridge the gap either by reducing the demand or by increasing the supply level to match the growing demand in future. Mechanisms must be developed for allocating the scarce water resources between the competing demand such as irrigation, rapidly expanding domestic and industrial needs, hydropower and environmental requirements [52].

A central support for decision making in sustainable water resources management arises from water balance modeling, which provides scientifically sound information of the current water resources and fluxes. Traditional approach of calculating the water balance using a spatially and temporally lumped scale does not give an accurate estimate of the water volume in a hydrologic component. Therefore there is a need to develop a methodology to model the distribution of the available and necessary water in the basin. A set of representative water balance models that have been used worldwide, their assumptions and limitations were considered. This eventually leads to the guidelines for the model selection. It is, however, not the intention of this paper to discuss all the models that have appeared in the literature.

Thornthwaite and Mather (1957) worked with the water balance approach to assess water needs for irrigation and other water related issues [53]. Water balance methodology has been used in a lumped water shed scale in order to develop climate classifications. Savanije (1997) developed a monthly time scale water balance model for the Mali sub catchment of the Niger River Basin, to determine the total evaporation from the earth's surface using the relation between transpiration and soil moisture storage [54]. A semi distributed conceptual model that simulates selected components of the water balance on a sub catchment scale, has been developed at a much finer spatial resolution and has mainly focused in the accurate estimation of the semi distributed model parameters [55]. The BROOK90 model, a lumped hydrologic simulation model, has been calibrated and used for the water balance analysis to determine the model performance and the fractions of precipitation that become stream flow, evapotranspiration, and ground water flow [56]. A semi distributed groundwater recharge model based on the concept of the tank model has been proposed to quantify the temporal changes of water table and water balance variables [57]. Tilahun and Merkel (2009) has used a spatially distributed water balance model WetSpass to simulate long-term average recharge using land use, soil texture, topography, and hydro meteorological parameters in a semiarid region of Ethiopia [58]. Jasrotia et. al. (2009) has performed a water balance study using the model developed by Thornthwaite and Mather [53] by using the remote sensing and GIS for figuring out the moisture deficit and moisture surplus of a watershed [52][59].

Water balance assessment modeling helps planning, designing and operating water systems [60][61]. Such models use user-defined operating and allocation rules to predict flow and storage of water throughout the water resource node-link network over time [62][63]. They help predict how different management rules and infrastructure configurations react to adverse conditions such as droughts, flooding or long-term change. Simulation models are frequently used in integrated assessments [64] and can be embedded in decision support systems or linked to optimization models [65][66].

Two main computational approaches exist for simulating water resource management: ‘rule-based’ and ‘optimization-driven’ simulation. Rule-based models use procedural or object-oriented computer code where programming instructions sequentially define how water is managed using object-oriented constructions (‘loops’). Iterative solution procedures are used to represent the interconnections between water requirements and management rules at different locations, often moving from upstream to downstream to route flows and track storage throughout the system. Such ‘ad hoc’ algorithms are challenging to build but have the potential to reproduce management mechanisms with high fidelity. Examples of generalized rule-based models available with user-interfaces include RIBASIM [67], WRAP [68], HEC-ResSim [69], WaterWare [70], AQUATOR [71] and WARGI-SIM [72]. IRAS-2010 and AQUATOR, the models considered rule-based simulation models [73]. Table 1.1 summarizes selected defining features of a representative set of rule-based simulators including whether they allow scripting and whether their time-steps are fixed or user-selected. Scripting allows customizing actions of particular nodes or links in a network using a generalized programming language rather than modifying source code. Scripting increases flexibility but requires more skillful users.

Table 1.1 Characteristics of existing water balance modeling tools

Model	Characteristics
AQUATOR	Flexible generalized scripting at nodes and links using the VBA language; Simplified modeling of groundwater flow or storage not included; Time-step is daily
RIBASIM	Wide variety of features (lay-out, demand and control nodes) and several link types; Links to DELWAQ water quality model and HYMOS hydrological model; Geographic interface; Many international case-studies; Time-step is user-selected between monthly and daily
WRAP	Represents priority-based water allocation; Calculates supply reliability performance measures; Time-step is user-selected between monthly and daily
HEC-ResSim	Includes generalized scripting using the Jython language for reservoir rules allowing complex rules including flood control operations; Operational focus rather than long-term planning; Multiple routing methods; Geographic interface; Incorporates time-series generated by sister hydrologic model HEC-HMS; Public domain (free); Time-step is user-selected between daily and 15-mimute intervals
WaterWare	Includes native rainfall runoff, water quality, and irrigation demand models; Web-interface with user-management which allows running models on servers and clusters; Link to heuristic optimization procedures for calibration and management; Time-step is daily
WARGI-SIM	Links with WARGI-OPT, an optimization model; Time-step is user-selected between seasons and hours
IRAS-2010	Free and open-source; Computationally efficient; Multi-reservoir operating rules; Flow routing; Geographic interface implemented in a separate customizable open-source model platform named 'HydroPlatform'; Time-step is user-selected between 1 and 365 days

Optimization-driven simulation models solve a distinct optimization model at each simulated time-step to route flows, track storages and allocate water through the network. This method is popular because of its relative ease of use and flexibility; optimization-driven allocation takes some of the burden off the programmer whose code no longer has to consider every conceivable system state or outcome. However, some complex rules may be difficult to represent using optimization and model results may not be easy to replicate in practice. Examples of such models with user-interfaces include WATHNET [74], AQUATOOL [75],

OASIS [76], MISER [77], MODSIM [78], RIVERWARE [79], MIKE BASIN [80], CALSIM [81], REALM [82] and WEAP [83]. Further information on the optimization-driven simulation approach is given by Labadie (2004) and descriptions of modeling systems that use it can be found in Wurbs (2005) [84][85].

Since each approach has advantages and limitations, the institutional and water management context often determines which modeling type is most suitable for a particular application. For example a model seeking to predict water trading will benefit from an optimization engine, whereas rule-based models are well-suited for modeling actual system operating procedures (e.g. reservoir release tables) and predicting their performance under certain conditions.

1.3.4 Review on smart technologies for water management

The phrase "Smart Grid" is currently used in the context of energy, especially to explain how ICT tools could help the real-time integration of disseminated micro energy sources (solar, biomass, etc.) in a national/regional energy grid, and how ICT could provide tools to the subtle balance between production and consumption of a physical phenomenon which is not easy to store. Naturally, the concept of "Smart Grid" was extended to Water, but the comparison is not so simple because water and energy are fundamentally in the completely different natures.

Let's give just two examples:

1 - it is no so difficult to decide if you can inject locally-produced power = you just have to check if the frequency and tension of the produced current are within the specified boundaries of the grid (and this can be done in real-time). In the case of locally-produced water (let's say by rain harvesting), you have to check water "quality" (which is not so easy in real-time) and increase the pressure sufficiently to be able to inject your produced volume in the network (at a pressure of several bars, which is rather energy-consuming).

2 - time-steps are quite different: in a power grid you have to react in milliseconds, while in water networks it is a question of minutes (or even tens of minutes), because water is a heavy material, with an appreciable inertia, and which can be stored easily.

For all these reasons, the "model" of Energy Smart Grid cannot be easily translated to the domain of water management.

Nevertheless, the technological novelties that emerged in the last years, such as AMR (Automated Meter Reading), low-cost sensors, real-time hydraulic models, Internet 2.0, etc.) induced a real change in the possibilities of ICT towards a better efficiency in water management, and must be taken into account in the evolution of ICT Systems for Water.

The "classical" ICT model for Water Efficiency

The question of "how can ICT help improving the efficiency of water management" has been addressed for more than 30 years and a lot of ICT progresses have already been done in the domain of Water since that time. Since the early 80s, several tools have been developed and widely implemented, e.g.: SCADA systems, for real-time monitoring, especially in plants, and pumping stations, Hydraulic models, both for pressured networks and open channel flows, GIS (even if the phrase "geographic information system" was "officialized" just at the end of the 80s.)

In the late 90s was solved the question of "Enterprise Architecture" and a model of a completely integrated Information System for the Water Industry was proposed, which was, at the same time, compliant with the objectives of the business, internally consistent (mostly thanks to the uniqueness of data) and open to technological evolutions.

This model, based on the analysis of the business processes, and the concept of "business invariants", insists on the necessity of providing tools to the "added-value" business processes, such as "Asset Management", "Field Work Management", and others (which can be summarized in "Efficiency of Operations"). This model has been used for the last 3 year as a basis of the @qua project (European Project of Thematic Network on ICT for Water Efficiency), and the discussion focused on the several still missing components of the ideal Water Information System:

- Overall consistency of the information system (convergence of applications, and uniqueness of data) : this very technical aspect of ICT has a huge influence on the overall efficiency, interoperability (and cost) of Information Systems
- Need for Ontologies, that could be shared by all the actors of the Water Industry, with a special focus on Asset Descriptor
- Real Time Modelling and Decision Support System (including the systems taking into account all the "new" real-time measurements such as AMR, and new water-quality μ-sensors)
- Management of Geographic Information: Towards Geographic Intelligence (advanced concept of GIS)
- Asset Management Tools and Field Work Management Tools (this is a real gap = the tools that exist on the market are not really consistent with the niches of added-value of the water industry, and are not easy to integrate in a consistent IS)
- Clearly "Smart Water" (or Smart Water Grid) starts with the implementation of those missing tools solving the question of "ICT for Water Efficiency".

What do new technologies bring to the "classical" ICT model for Water Efficiency?

The recent evolutions of the context of the water industry bring both new questions and new solutions that are of a second order of magnitude compared to the urgent needs of the previous paragraph. There are 3 typical examples of "new" questions that are in fact related to permanent questions of the "classical" ICT themes: Real Time Monitoring, Cities of Tomorrow, Water-Energy Nexus.

1.4. Scopes of the Study

As per analyzed in the sections above, this study is to calculate the water resources available in the domain and to predict the water demand in various purposes. Thus, this study consists of following scopes to make conclusions.

A. Theoretical background

B. Development of water balance assessment model

C. Application of water balance assessment in real region as study area

The theoretical background on movement of water in various scales of watersheds would be summarized to be a basis of modeling and discussion. This summary consists of the theories on a rainfall-runoff, an overland flow with channelized open channel and pipe drainage as representatives of water flow which can be considered as available water resources and the theories on prediction of water demand within several purposes such as domestic, industrial and agricultural water consumption.

Within the theoretical background of models, modules which represent each water cycle domain are developed. The developments consist of planning and designing the model, making codes for each modules and simple test of model. The final model is the form of integrated several modules as component and the integration would be implemented through the flow control component which manages the water management scenario and connectivity of modules so that the model can provide integrated modelling of water resources and water demand at once in the target study area.

For summarizing from the theoretical approach on the concept above, it starts from making software tool to assess water balance within overall movement of water from the precipitation to the outflow to the sea in the study area. The result from the model would be validated within comparison with preliminarily observed data.

Chapter 2 Methodology and Theoretical Background

2.1. Methodology

In order to assess water balance of target area, it is necessary to determine the water resources available for each purpose of water use and the water demand. These variables such as water resources and water demand can sometimes be calculated through simple equation or modeling. However, it should sometimes follow the plans of development if there is certain project to secure water. The basic philosophy of methodology is producing certain results from proved or officially planned input data.

2.2. Theory for Rainfall Runoff

Rainfall runoff is compulsory procedure to calculate the basic quantity of water resources for water balance control. And it is continuously varied spatially and temporally. Therefore it is necessary to investigate runoff from precipitation event within consideration of physical condition of water and spatial-temporal variation, i.e. distributed or fully distributed runoff modeling system. And it is surely the first step of water balance management.

A physically based and distributed runoff model also can be useful for any use of prediction, impact assessment, and source variation on water. Nevertheless, it is difficult to development or application of this type of model due to the complexity of input data set which must consist of time varied and spatially varied data set for a whole domain, physical capacity of simulation hardware such as CPU, RAM and GPU as well as complexity of model itself which is difficult to handle. However, those difficulties could be resolved and be easier by the increasing availability of computation engine to counter hardware limitation and complexity of model and geographic information systems and advanced metering infrastructure, which are helpful to handle complicated data set as model input.

A distributed conceptual (or mixed conceptual physically based) models can be a useful tool for the solution of several practical problems related to water resources, since hydrological analyses can be performed that would not be possible by using ‘‘pure’’ lumped models. Lumped models are not capable of evaluating the effects of local land use changes (such the reduction of the permeability of urbanized areas, or the deforestation of skiing resorts) and cannot simulate river flows in internal river sections. Distributed models have the advantage, once they are calibrated by using river flow data observed at a selected site, of being able to simulate the flows in any location of the river network. Moreover, the use of conceptual schemes allows simulations that would be demanding, in terms of data requirement and computational resources, if fully physically based models were utilized. The following requirements were determined:

- The model simulations should be reliable in making predictions for ungauged or scarcely gauged catchments or where little information about the contributing area is available;
- The model should allow a spatially distributed description of the geomorphological characteristics of the catchment in order to generate river flow data at any cross-section of the river network;
- The model should perform reliable simulations of the river flows even when only short records of historical data are available;
- The model should have some physical basis in order to constrain the range of values of some parameters by means of in situ measurements or physical reasoning and in order to decrease parameter uncertainty;
- The model should be computationally inexpensive in such a way that long simulation runs could be performed at short time steps in a reasonably limited time, even for medium size basins.

The proposed rainfall-runoff model belongs to the class of distributed conceptual models because it allows a spatially distributed description of the catchment combined with the use of conceptual and physically based schemes for modelling hydrological processes at the grid scale. As the listed requirements show, the model has been conceived to be used for practical purposes and to be applicable to a wide spectrum of real world case studies. The description of the model is given in the following section together with the description of the data needed to perform rainfall-runoff simulations. The third section of the paper describes the parameters of the model and how they can be calibrated. The last section shows the application of the model to three different catchments, proving its robustness and efficiency even when limited historical information is available.

2.2.1 Input Data Management

The model can run for any spatial resolution and for any time resolution (typically, hourly or shorter intervals). The input meteorological data consist of both observed precipitation (rainfall depths) and air temperature, at the same time step. The input topography data are required as a grid based Digital Elevation Model (DEM), which is given in raster format by means of a m _ n rectangular matrix, placed in an ASCII text file. Each element of the matrix represents the mean elevation of the corresponding DEM cell, whereas cells located outside of the catchment are assigned an elevation less than zero. To characterize the spatial pattern of the infiltration capacity, a second matrix has to be provided in a separate ASCII file containing the Curve Number (CN) parameters associated to each DEM cell. The value of the CN parameter depends on soil type and land use and can be estimated by using the tables provided by the USDA [86][87]. The soil type and land use can be found from maps, or estimated by means of in situ surveys and/or prior knowledge of the catchment. The ArcCN-Runoff tool is a useful Arc- GIS extension that could be used for generating the Curve Number map when the maps of soil type and land use are available as shape files [88]. If soil type and land use data are not available at fine spatial resolution, one possible option is to lump the available data at a sub-catchment (or even catchment) scale, by assigning each sub-catchment group of cells with the same CN number [89]. Finally, a matrix placed in an ASCII text file is used to represent the spatial variability of the roughness on the hill slope for the overland flow. According to land use, different classes of roughness may be determined and a value for the Strickler coefficient is assigned to each class. The Strickler coefficient may be estimated from the scientific literature according to the land use type [90].

2.2.2 Flow Identification and DEM Process

The model discretizes the drainage area in square cells coinciding with the pixels of the DEM. Initially, the river network is generated from the DEM by using an existing computer code which applies the D-8 method [91][92][93]. This approach estimates the river flow paths and the contributing area to each pixel as shown in the Fig. 2.1.

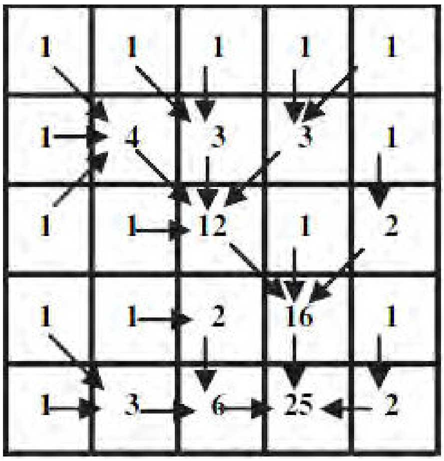


Fig. 2.1 Concept of D-8 Flow grid [79-affdef 논문]

In detail, the flow network is determined by assigning a maximum slope pointer to each DEM pixel and then processing the DEM in order to organize the river network according to the Strahler’s stream ordering system [94]. The values of the maximum slope pointer, according to the flow direction, are shown in Fig. 2.2.

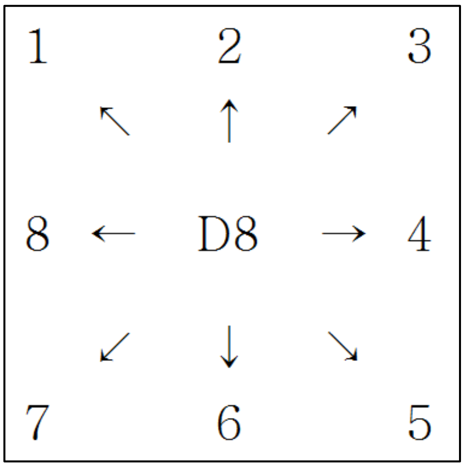


Fig. 2.2 Value of flow direction indicator

Digital pits are filled in a pre-processing step. When pits are not located in correspondence of lakes (in this circumstance they are not eliminated), they are the result of approximations made in the discretization of the topography from the DEM. The procedure for removing pits is generally efficient in steep basins, but may give errors in flat areas. The code stops trying to remove a pit when attempts are made to raise the original elevation of a cell above the maximum elevation of the catchment. In this case, the coordinates of the particular cell are shown on the screen and a manual adjustment of the DEM is necessary.

2.2.3 Precipitation Data Control

The distributed approach of the model allows for spatial variation of climate input within the drainage area. Precipitation data are in the form of observed rainfall depths, linked to raingauges located within or close to the catchment. Precipitation is input to SWG-RUNOFF via an ASCII text file, listing observed precipitation in each site as well as the coordinates of each raingauge. The precipitation routine estimates rainfall, $P_l[t,(i,j)]$ (mm), as a function of time t at cell coordinates (i,j) either using Thiessen polygons or the inverse squared distance interpolation method. The Thiessen polygon method assigns to a particular cell the rainfall depth that has been recorded at the nearest raingauge at the same time step. In the second case

$P_l[t,(i,j)]$ is given by the interpolation of the observed rainfall depths $Pl[t,k]$ (mm), $k = 1, \ldots., N_R$ 1,.,NR, measured at each one of the N_R (dimensionless) rain gauges, which can be formulized as Eq. (1).

$$P_l[t,(i,j)] = \sum_{k=1}^{N_R} \lambda_k(i,j) P_l[t,k] \quad (1)$$

Where, the weights λ_k(dimensionless) are expressed as Eq. (2).

$$\lambda_k(i,j) = \frac{1/d_k^2(i,j)}{\sum_{m=1}^{N_R} 1/d_m^2(i,j)} \quad (2)$$

Where, $d_k(i,j)$ (m) is the distance between the (i,j) cell and the k-th raingauge. If a raingauge does not have data recorded at a particular time step, then only available measurements are taken into account by the model. The Thiessen polygons are then recalculated or the weights λ_k updated, according to the interpolation technique chosen.

2.2.4 Energy Balance and Evapotranspiration

For each DEM cell, the potential evapotranspiration is estimated using the radiation method [95], which is based on a simplification of the Penman-Monteith equation. The terms related to the vapour pressure and wind speed are neglected by the radiation method as they are usually not available. Temperature is assigned to each DEM cell using Thiessen polygons, but only considering stations that have measured data at the time step t. Temperature data are input to SWG-RUNOFF by means of an ASCII text file, where the observed temperature, the coordinates of each thermometric station and the parameters of the radiation method are provided. According to the radiation method, the evapotranspiration $E_p[t,(i,j)]$, can be expressed as a linear function of temperature at each time step t and cell of coordinates (i,j), in such a way that it can be aggregated at monthly time steps or disaggregated at short time steps without losing the long term balance. $E_p[t,(i,j)]$ (mm/month) at the monthly step is expressed as Eq. (3).

$$E_p[t,(i,j)] = a + bT[t,(i,j)]N(i)W_{ta}(i) \quad (3)$$

Where, a (mm) and b (mm°C^{-1}) are the regression coefficients of the radiation method; $T[t,(i,j)]$ (℃) is the observed temperature at time t; $N(i)$ (dimensionless) is the monthly mean of the maximum number of daily hours of sunshine referring to the i-th month (tabulated as a function of latitude); and $W_{ta}(i)$ (dimensionless) is a compensation factor dependent upon the monthly average temperature and elevation above the sea level. $N(i)$ and $W_{ta}(i)$ can be derived according to the reference values of Tables 2.1 and 2.2 [95].

Table 2.1 Mean daily duration of maximum possible sunshine hours for different months

Northern Lats	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Southern Lats	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
50	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.6	11.1	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1

Table 2.2 Values of the weighting factor Wta at different altitudes (levels) and temperature

Level [m]	Temperature [°C]																			
	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
0	0.43	0.46	0.49	0.52	0.55	0.58	0.61	0.64	0.66	0.71	0.73	0.75	0.77	0.78	0.85	0.82	0.83	0.84	0.85	0.86
500	0.45	0.48	0.51	0.54	0.57	0.60	0.62	0.65	0.70	0.72	0.74	0.76	0.78	0.79	0.81	0.82	0.84	0.85	0.86	0.87
1000	0.46	0.49	0.52	0.55	0.58	0.61	0.66	0.69	0.71	0.73	0.75	0.77	0.79	0.80	0.82	0.83	0.85	0.86	0.87	0.88
2000	0.49	0.52	0.55	0.58	0.61	0.64	0.66	0.69	0.71	0.73	0.75	0.77	0.79	0.81	0.82	0.84	0.85	0.86	0.87	0.88
3000	0.52	0.55	0.58	0.61	0.64	0.66	0.69	0.71	0.73	0.75	0.77	0.79	0.81	0.82	0.84	0.85	0.86	0.88	0.88	0.89
4000	0.53	0.58	0.61	0.64	0.66	0.69	0.71	0.73	0.76	0.78	0.79	0.81	0.83	0.84	0.85	0.86	0.88	0.89	0.90	0.90

Eq. (3) is therefore suitable for implementation in the model on the basis of the time step of the observed temperature data. For instance, if temperature is observed at an hourly time scale, Eq. (3) has to be divided by $24 \cdot n(i)$ to get $E_p[t,(i,j)]$ in mm h^{-1}, where $n(i)$ (dimensionless) are the number of days of the i-th month.

2.2.5 Basic Runoff Calculation

The schematic of the hill slope hydrology simulated by SWG-RUNOFF is shown in Fig. 2.3 [96]. In particular, the model takes into account the evapotranspiration from the vegetation cover and the soil. The lateral sub-surface runoff and surface runoff from each hill slope cell are routed towards the basin outlet along the river network. In order to perform continuous time simulation of the water fluxes among soil, vegetation and atmosphere, a modification of the Curve Number method is used within SWG-RUNOFF as shown in Fig. 2.4 [96][86]. SWG-RUNOFF accounts for interception of precipitation by vegetation by means of a local 'interception reservoir' at the cell (i,j), in which the rainfall depth accumulates. l number of interception reservoirs are used, where l is the number of DEM cells used to discretise the watershed. The capacity of the interception reservoir is equal to $C_{int}S(i,j)$, where C_{int} (dimensionless) is a parameter, that is assumed to be constant over the basin and time. $S(i,j)$ (mm) is the local CN soil storativity given by Eq.(4) [86][97]

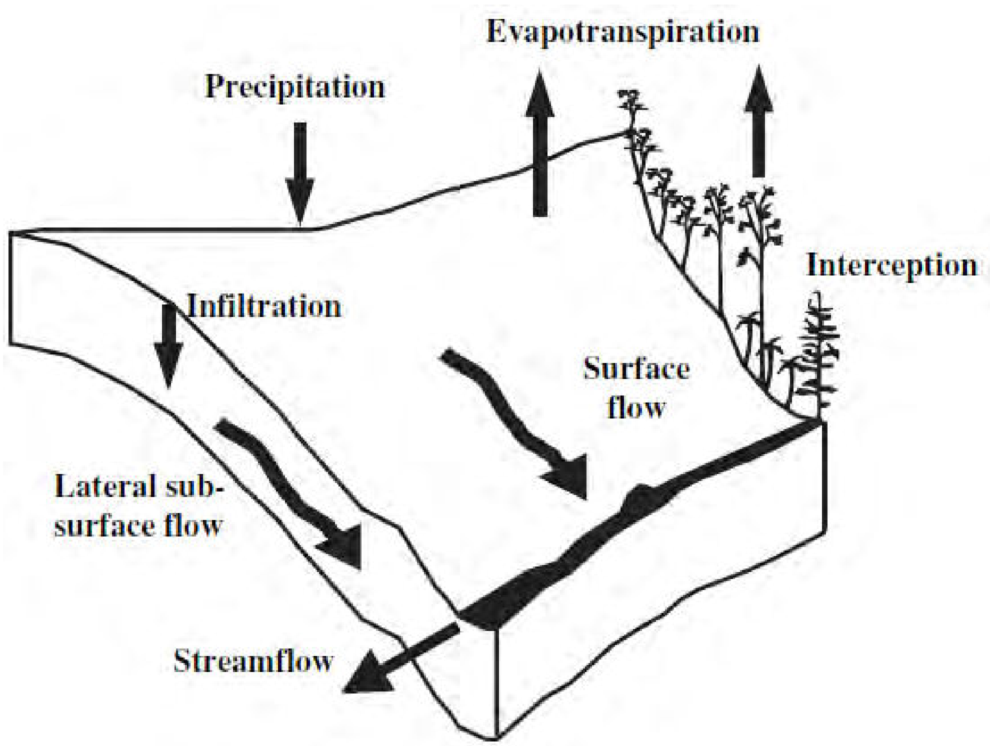


Fig. 2.3 The schematic diagram describing hill slope hydrology (Moretti, 2007)

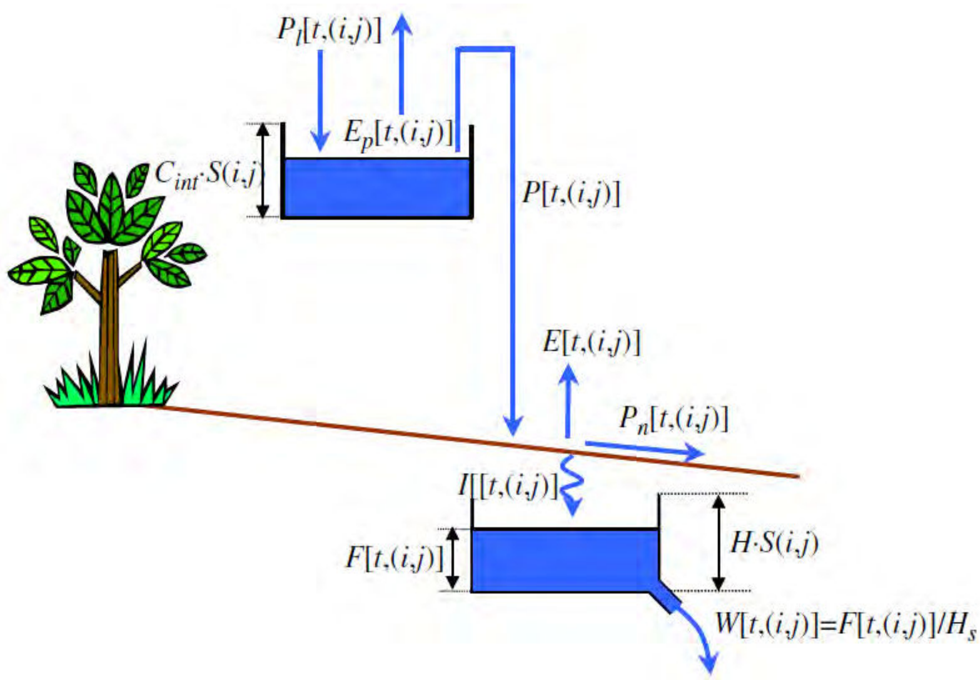


Fig. 2.4 The schematic diagram of soil interaction of water (Moretti, 2007)

$$S(i,j) = 254\left(\frac{100}{CN(i,j)} - 1\right) \tag{4}$$

Where, $CN(i,j)$ (dimensionless) is the Curve Number at the given cell location. Once the interception reservoir is full of water, the exceeding rainfall reaches the ground, where it is split into surface and sub-surface flow. Flow subdivision is done by using an approach derived by modifying the CN equation. In detail, it is assumed that for each cell, a linear reservoir (infiltration reservoir) is located at soil level, where infiltrated water is collected. λ number of infiltration reservoirs are used. The rainfall, $P[t,(i,j)]$ (mm), that reaches the ground at the time t (i.e. overflow from the interception reservoir) is divided between surface runoff $P_n[t,(i,j)]$ (mm) and infiltrated water $I[t,(i,j)]$ (mm) according to the relationship of Eq. (5).

$$\frac{P_n[t,(i,j)]}{P[t,(i,j)]} = \frac{F[t,(i,j)]}{HS(i,j)} \tag{5}$$

Where, $F[t,(i,j)]$ (mm) is the water content of the infiltration reservoir at time t. $HS(i,j)$ (mm) is the capacity of the infiltration reservoir itself, given by the parameter H (dimensionless) multiplied by the soil storability defined in Eq. (4). As mentioned above, the runoff response subroutine uses a modified version of the CN method to distinguish between surface runoff and infiltrated water. Since the CN method is considered as an infiltration excess process approach [98], it is expected that our proposed model is better suited for basins characterized by low permeability and prevalently impervious hill slopes, where the generation of surface runoff is more likely to be well represented by an excess infiltration scheme, instead of excess saturation. It should be noted that, as the capacity of the infiltration reservoir is proportional to the soil storability S, the CN method is used to distinguish between areas having higher and lower infiltration potentials within the catchment. It is then the calibration parameter H that assigns to each cell the effective value of the infiltration storage capacity that can be derived from the hydro-pluviometric data. The infiltrated water at time t is computed as Eq. (6).

$$I[t,(i,j)] = P[t,(i,j)] - P_n[t,(i,j)] \tag{6}$$

Where, each infiltration reservoir releases an outflow $W[t,(i,j)]$ (mm s^{-1}) to the sub-surface river network through a linear bottom discharge, according to the relationship as Eq. (7).

$$W[t,(i,j)] = \frac{F[t,(i,j)]}{H_s} \tag{7}$$

Where, H_s (dimensionless) is a parameter. H and H_s are assumed to be constant with respect to both space and time. When some water is stored in the interception reservoir, the effective evapotranspiration $E[t,(i,j)]$ (mm s$_{-1}$) is considered equal to $E_P[t,(i,j)]$ (mm s^{-1}) and is subtracted from the water content of the interception reservoir itself. When the latter is empty, or is emptied while subtracting the evapotranspiration, the remaining part of $E_P[t,(i,j)]$ is subtracted from the water content of the infiltration reservoir. In this case, it is assumed that $E[t,(i,j)]$ is varying linearly from 0 when $F[t,(i,j)] = 0$, to $E_P[t,(i,j)]$ when $F[t,(i,j)] = HS(i,j)$. Finally, by combining the following continuity equation governing the infiltration reservoir as Eq. (8):

$$I[t,(i,j)] - W[t,(i,j)] = \frac{dF[t,(i,j)]}{dt} \tag{8}$$

With the Eqs. (5)-(7) and taking the effective evapotranspiration into account, one derives the equation governing the mass balance of the infiltration reservoir, i.e.:

$$\frac{dF[t,(i,j)]}{dt} = -\frac{F[t,(i,j)]}{H_s} - E[t,(i,j)] + P[t,(i,j)]\left\{1 - \frac{F[t,(i,j)]}{HS(i,j)}\right\} \tag{9}$$

which is solved with the fourth order Runge-Kutta method.

2.2.6 Flow Path Routing

Surface and sub-surface flow are propagated towards the basin outlet by applying the Muskingum-Cunge model with variable parameters [99]. These latter are determined on the basis of the 'matched diffusivity' concept [100][101]. The subroutine propagates the surface and sub-surface runoff downstream following the network ordering system determined by the slope pointers. Each cell receives water from its upslope neighbors and discharge to its downslope neighbor. For cells of flow convergence, the upstream inflow hydrograph is taken as the sum of the outflows hydrographs of the neighboring upslope cells. Distinction between hill slope rill and network channel is based on the concept of 'constant critical support area' [102]. Rill flow is therefore, assumed to occur in each cell where the upstream drainage area does not exceed the value of the calibration parameter A0 (km^2), otherwise channel flow will occur.

The parameters of the Muskingum-Cunge method vary in space, assuming different values on the hill slope and along the river network, and in time. In the following equations, from (10)-(19), the temporal and spatial dependence of C_1, C_2, C_3, C_4, D_n, D_h, X, c_k, B, and Q^* is omitted to simplify the notation. The inflow and outflow discharges for a given cell of coordinates (i, j) are denoted with the subscripts in and out, respectively, and $t\ , t + \Delta t$ are the time steps at which they occur as Fig. 2.5.

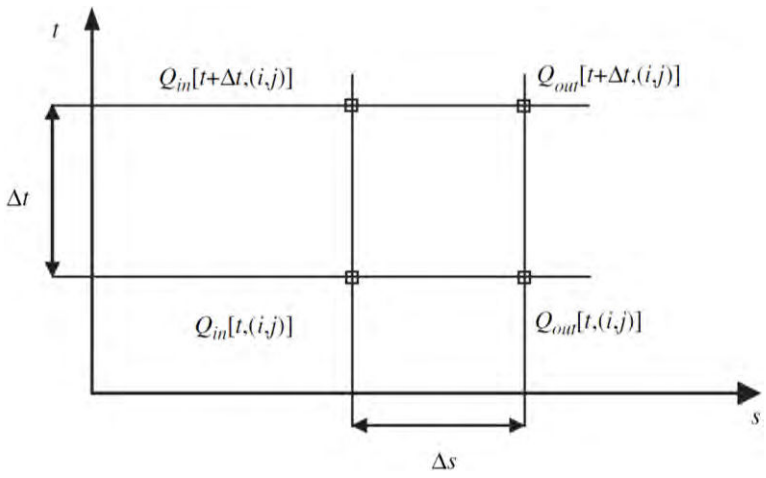


Fig. 2.5 Time and Space grid for numerical solution

The outflow hydrograph $Q_{out}[t+\Delta t]$ (m^3/s) from the cell is given as Eq. (10):

$$Q_{out}[t+\Delta t,(i,j)] = C_1 Q_{in}[t+\Delta t,(i,j)] + C_2 Q_{in}[t,(i,j)] + C_3 Q_{out}[t,(i,j)] + C_4 q_{L\,out}[t+\Delta t,(i,j)] \quad (10)$$

Where, $Q_{in}[t+\Delta t,(i,j)]$, $Q_{in}[t,(i,j)]$ and $Q_{out}[t,(i,j)]$ are expressed in m^3/s. $q_{out}[t+\Delta t,(i,j)]$ ($m^3/s/m$) is the lateral inflow rate can be calculated as Eq. (11):

$$q_{L\,out}[t+\Delta t,(i,j)] = P_n[t,(i,j)] \frac{\Delta x \Delta y}{\Delta s} \frac{1}{1000} \quad (11)$$

Where, $P_n[t,(i,j)]$ (mm) is the surface runoff (local net rainfall that reaches the ground, see Section 2.5), Δx (m) and Δy (m) are the dimension of the cell in the horizontal and vertical direction, respectively, Δs (m) is the channel length within the cell. C_1 (dimensionless), C_2 (dimensionless), C_3 (dimensionless) and C_4 (m) are the time and space variable routing coefficients expressed by the following relationships:

$$C_1 = \frac{c_k\left(\frac{\Delta t}{\Delta s}\right) - 2X}{2(1-X) + c_k\left(\frac{\Delta t}{\Delta s}\right)} \quad (12)$$

$$C_2 = \frac{c_k\left(\frac{\Delta t}{\Delta s}\right) + 2X}{2(1-X) + c_k\left(\frac{\Delta t}{\Delta s}\right)} \quad (13)$$

$$C_3 = \frac{2(1-X) - c_k\left(\frac{\Delta t}{\Delta s}\right)}{2(1-X) + c_k\left(\frac{\Delta t}{\Delta s}\right)} \quad (14)$$

$$C_4 = \frac{2 c_k \Delta t}{2(1-X) + c_k\left(\frac{\Delta t}{\Delta s}\right)} \quad (15)$$

Where, Δt (s) is the time interval and c_k (m/s) is the kinematic celerity. X (dimensionless) is a weighting factor, which is introduced to match the numerical diffusion coefficient of the Muskingum model, $D_n = c_k \Delta s(0.5 - X)$ (m^2/s) and the hydraulic diffusivity of the convection- diffusion flow equation, $D_h = Q^*/2Bi_f$ (m^2/s) [99]. X can be expressed as Eq. (16):

$$X = \frac{1}{2}\left(1 - \frac{Q^*}{Bc_k i_f \Delta s}\right) \tag{16}$$

While c_k is computed from the Gauckler-Strickler formula assuming rectangular river cross-section as Eq. (17):

$$c_k = k_s i_f^{\frac{1}{2}} B^{\frac{2}{3}} (w+2)^{-\frac{5}{3}} (\frac{5}{3} w + 2) \tag{17}$$

Where, k_s (m^3/s) is the Gauckler-Strickler roughness, i_f (dimensionless) is the friction slope and w (dimensionless) is the width/depth ratio of the water surface. The assumption of a rectangular river cross-section is frequently adopted in spatially distributed models and can be considered reasonable for river sections where the width of the surface water is much greater than the water depth [101]. In the case of rill flow, which typically occurs on the hill slopes, the assumption of a rectangular section is a conceptual approximation. Here the width/depth ratio of the water surface and roughness of the hill slopes are considered calibration parameters. When the Muskingum-Cunge model is applied to hill slopes, the literature reports much higher values for w and lower values for k_s with respect to river network applications.

The width of the water surface B (m) can be estimated by applying the Gauckler-Strickler equation as shown in Eq. (18):

$$B = \left[\frac{Q^*(w+2)^{\frac{2}{3}} w}{k_s i_f^{\frac{1}{2}}}\right]^{3/8} \tag{18}$$

Where Q^* (m^3/s) a first order estimation of the river flow, given by the relationship described as Eq. (19) [103]:

$$Q^* = \frac{1}{3}\{Q_{in}[t,(i,j)] + Q_{in}[t+\Delta t,(i,j)] + Q_{out}[t,(i,j)]\} \quad (19)$$

As X varies in space and time with flow, the numerical diffusivity simulates the hydraulic diffusivity of the actual flood wave. The diffusion wave model is unconditionally stable since numerical instabilities, which may arises when $D_n < 0$ ($X > 0.5$), are prevented by matching the numerical and hydraulic diffusivities. On the hill slope, w has a constant value with respect to both space and time, whereas the Strickler roughness (which is constant in time) is evaluated for each cell on the basis of land use. Along the river network, w is assumed constant in space and time, but assumes a different value with respect to the hillslope; the channel roughness is allowed to vary from a minimum to a maximum value depending on the elevation according to Eq. (20):

$$k_s = k_{sr}^1 \exp\left[\frac{log\left(\frac{k_{sr}^0}{k_{sr}^1}\right)}{z_{top}-z_{outlet}}(z(i,j)-z_{outlet})\right] \quad (20)$$

Where, k_{sr}^0 ($m^{1/3}/s$) and k_{sr}^1 ($m^{1/3}/s$) are the maximum and minimum Strickler roughness for the channel network, $z(i,j)$ (m) is the elevation of the cell (i,j), z_{top} (m) and z_{outlet} (m) are the maximum elevation of the catchment and the elevation of the outlet, respectively.

The outflow from the infiltration reservoir $W[t,(i,j)]$ locally feeds the flow along the sub-surface river network. Let us suppose that the sub-surface flow Q_s' (m^3/s) reaches a cell of the channel network of coordinates (i',j') at time t'. Q_s' is then joined to the surface flow of the cell of coordinates (i',j') at time t'.

Again, the propagation of the sub-surface flow, is modelled with the spatially distributed model according to the following Eq. (21):

$$\mathrm{Q}_{\mathrm{out}}^{sub}[t+\Delta t,(i,j)] = C_1^{sub} Q_{in}^{sub}[t+\Delta t,(i,j)] + C_2^{sub} Q_{in}^{sub}[t,(i,j)] + C_3^{sub} Q_{out}^{sub}[t,(i,j)] + C_4^{sub}\left(\frac{W[t,(i,j)\Delta x \Delta y}{1000\Delta s}\right) \quad (21)$$

where Q_{in}^{sub} (m^3/s) and $\mathrm{Q}_{\mathrm{out}}^{sub}$ (m^3/s) are the inflow and outflow discharges for a given cell, and $W[t,(i,j)$ (mm/s) is the outflow from the infiltration reservoir. The routing parameters for the sub-surface flow C_1^{sub} (dimensionless), C_2^{sub} (dimensionless), C_3^{sub} (dimensionless) and C_4^{sub} (m) are expressed as the following (note that the temporal and spatial dependence of C_1^{sub} , C_2^{sub}, C_3^{sub} and C_4^{sub}, X^{sub}, c_k^{sub}, Q^{*sub} and D_h^{sub} is omitted to simplify the notation):

$$C_1^{sub} = \frac{c_k^{sub}\left(\frac{\Delta t}{\Delta s}\right) - 2X^{sub}}{2\left(1-X^{sub}\right) + c_k^{sub}\left(\frac{\Delta t}{\Delta s}\right)} \quad (22)$$

$$C_2^{sub} = \frac{c_k^{sub}\left(\frac{\Delta t}{\Delta s}\right) + 2X^{sub}}{2\left(1-X^{sub}\right) + c_k^{sub}\left(\frac{\Delta t}{\Delta s}\right)} \quad (23)$$

$$C_3^{sub} = \frac{2\left(1-X^{sub}\right) - c_k^{sub}\left(\frac{\Delta t}{\Delta s}\right)}{2\left(1-X^{sub}\right) + c_k^{sub}\left(\frac{\Delta t}{\Delta s}\right)} \quad (24)$$

$$C_4^{sub} = \frac{2c_k^{\mathrm{sub}}\Delta t}{2\left(1-X^{sub}\right) + c_k^{sub}\left(\frac{\Delta t}{\Delta s}\right)} \quad (25)$$

c_k^{sub} (m/s) and X^{sub} (dimensionless) are the kinematic celerity and the weighting factor for the sub-surface flow. c_k^{sub} and X^{sub} have different formulae with respect to the corresponding variables introduced for surface flow [104]. In particular, the sub-surface kinematic celerity c_k^{sub}, which varies spatially, is given by Darcy's law as Eq. (26):

$$c_k^{sub} = K_{sat} i_s \qquad (26)$$

In Eq. (26), K_{sat} (m/s) is the saturated conductivity of the soil and i_s (dimensionless) is the slope of the sub-surface river network, which is assumed to be equal to the surface river network. This is the first major simplification used in the model. K_{sat} defines the velocity of the sub-surface flow and can be estimated based on the characteristics of the soil or, alternatively, can be treated as a calibration parameter constant in space and time. The weighting factor X^{sub} varies in space and time and is computed according to Eq. (27):

$$\mathrm{X_{sub}} = \frac{1}{2} - \frac{Q^{*sub}}{i_s B_P^{sub} c_k^{sub} \Delta s} \qquad (27)$$

where Q^{*sub} (m^3/s) is a reference sub-surface flow, analogous to Q^* for the surface network and computed in the same manner (see Eq. (19)). B_P^{sub} (m) is the width of the water surface, which can be treated as a calibration parameter constant in space and time, assuming a rectangular cross-section for the sub-surface river network. Eq. (27) is again derived by matching the numerical diffusion coefficient of the Muskingum-Cunge method, D_n^{sub} (m^2/s), with the hydraulic diffusivity of the sub-surface flow D_h^{sub} (m^2/s), expressed by Eq. (28):

$$\mathrm{D_h^{sub}} = Q^{*sub}/(i_s B_p^{sub}) \qquad (28)$$

$\mathrm{D_h^{sub}}$ varies in space and time. As one may note, the subsurface flow is modelled as a unique entity, without any distinction between near surface and deep water flow. This simplified description has the advantage of reducing the number of the model parameters and, consequently, also the amount of historical data required for calibration. However, a significant approximation in simulations of low discharges is expected, especially in highly permeable basins.

2.3. Urban Drainage Model

In order to calculate the urban drainage through the collection system, SWG-UDS as an urban drainage modeling module for this study has been developed. This numerical model for urban drainage system, will be used as a tool to propagation of urban runoff which can be count as a part of water resource abundance [105]. Basic data about land features in the form of a digital map in various GIS format and topographic maps will be used to develop a DEM for the study area. The simple diagram for urban drainage modeling is shown in the Fig. 2.6.

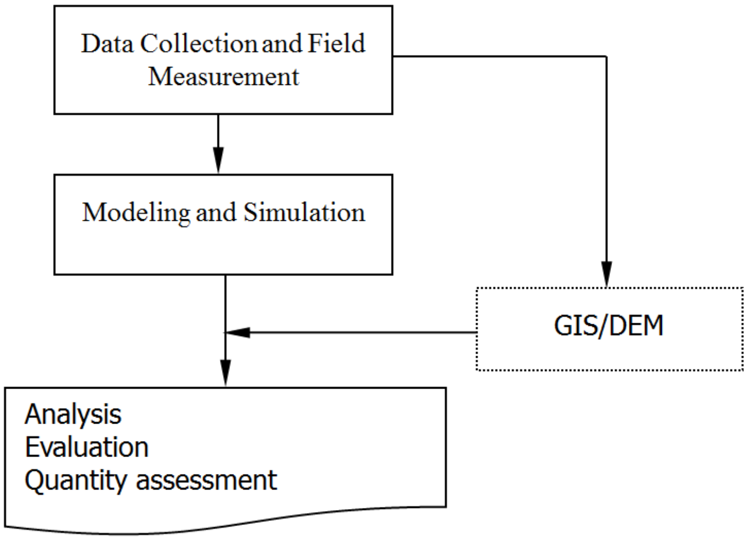


Fig. 2.6 General procedure on urban water modeling

2.3.1 Data Collection

Essentially, the computer model consists of three components: input, the computer program, and output. Input usually includes meteorological data as common data for all models in this study, land/catchment data, and conveyance and storage data. Land data are the surface and subsurface characteristics that may affect the amounts and rates of runoff such as area, land slope, soil/cover type, imperviousness, concentration time, roughness coefficients, and hydrological losses. Conveyance and storage data involve the channels, storm sewers, reservoirs as detention ponds or lakes. For the purposes of this study, data on land use, population, dry weather flow, spot-elevation data on streets, and runoff data are also needed.

2.3.2 Modeling of Urban Drainage

SWG-UDS module is a software system for computer-aided analysis of urban sewer systems. It has computational modules for runoff and pipe flow modeling, as well as a pollution model and graphical presentation of input and output data. The pipe flow model can accurately simulate surcharge conditions and backwater effects.

Using secondary data, the model is set up. Model calibration is performed after schematization, which involves a trial-and-error adjustment of parameters to fit simulated to observed data. Verification is done to check the quality of the calibrated model. When the model is found to be acceptable, it is used to simulate different scenarios—the results of which are used for analysis and formulation of recommendations.

2.3.3 Surface/Overland flow model

There are several ways of determining the amount of surface runoff. This model employed 2 of them such as Time-Area Method and Non-Linear Reservoir Method.

A. Time-Area Method

This model computes for the surface runoff using the time/area method. The volume of runoff is controlled by the initial loss, size of the contributing area, and by a continuous hydrological loss. The shape of the runoff hydrograph is dictated by the time of concentration and by the chosen time-area (T-A) curve, which represent the catchment reaction speed and the shape of the catchment.

The runoff process is divided into time steps, Δt in the computation. Assuming that the runoff velocity is constant, the catchment is then spatially discretized into cells forming concentric circles with a center at the point of outflow. The number of cells is equal to Eq. (29):

$$n = \frac{t_c}{\Delta t} \tag{29}$$

Where, n (dimensionless) is the number of cells, t_c (s) is time of concentration and Δt = simulation time step. For correct description of the catchment layout, a time-area curve, which characterizes the shape of the catchment, can be specified. There are three types of curves, each corresponding to a particular shape as defined in the Fig. 2.7.

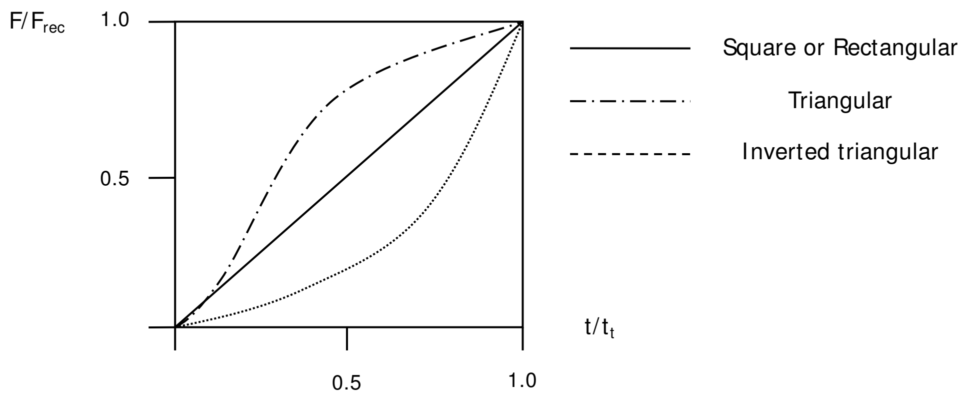


Fig. 2.7 Time and area curve in typical urban catchment

An initial loss is specified for the catchment. Runoff starts when the depth of water on the surface exceeds the initial loss and it stops when the accumulated rain depth on the surface goes below it. At every time step, the accumulated volume from a cell is moved downstream. The values of the resulting hydrograph are the outflows from the last downstream cell.

B. Non-Linear Reservoir (or Kinematic wave) Method)

Surface runoff computation in this model is based on the kinematic wave computation (Manning Equation). The surface runoff is computed as flow in an open channel, considering only gravitational and friction forces. The volume of runoff is controlled by the hydrological losses and the size of the contributing area. The shape of the runoff hydrograph is controlled by the length, slope, and roughness of the catchment.

Initially, the amount of effective rainfall—that is, rain that causes runoff—is determined by subtracting the various losses specified (evaporation, wetting, infiltration, etc.) from the rainfall. Then, hydraulic routing based on the kinematic wave (Manning Equation) and continuity equations are performed.

Runoff starts when the resulting intensity of the effective precipitation is more than zero. The hydraulic process is described with the kinematic wave equations for the entire surface at once. This assumes uniform flow conditions, i.e. equal water depth over the entire surface. The surface runoff is calculated by Eq. (30).

$$Q(t) = MBI^{1/2} y_R(t)^{5/3} \tag{30}$$

Where, $Q(t)$ (m^3/s) is runoff discharge occurred at time t, M (dimensionless) means Manning's roughness factor, B (m) is the width of flow path, I (dimensionless) is slope of flow path or surface and $y_R(t)$ (m) is Runoff depth at time t. The depth $y_R(t)$ could be obtained from the continuity equation as Eq. (31):

$$\mathrm{I}_{eff}(t) \times A - Q(t) = \frac{dy_R}{dt} \times A \tag{31}$$

Where, $I_{eff}(t)$ (m) is effective precipitation at time t, A (m^2) is contributing catchment area, Δt(s) is numerical time step and Δy_R (m) is change in runoff depth

2.3.4 Pipe flow model

The pipe flow model is capable of simulating unsteady flows in pipe networks with alternating free surface and pressurized flow conditions. The computation is based on an implicit, finite difference numerical solution of basic one-dimensional, free surface flow equations. Unsteady flow in the pipes/links of the system are computed by solving the equations of conservation of continuity and momentum (Saint Venant Equations) using the following assumptions:

The flow is one-dimensional such that depth and velocity varies only in the longitudinal direction of the channel. The flow everywhere is considered to be parallel to the bottom, i.e. vertical accelerations can be neglected and hydrostatic pressure variation along the vertical can be assumed (1) The longitudinal axis of the channel is approximated as a straight line; (2) The bottom-slope is small and the channel bed is fixed; (3)Resistance coefficients for steady uniform turbulent flow are applicable so that Manning's equation can be used to describe resistance effects; and (4) The water is incompressible, homogenous such that density variation is negligible. The governing equations are following continuity equation as Eq. (32) and momentum equation as Eq. (33):

$$\frac{\delta Q}{\delta x}+\frac{\delta A}{\delta t}=0 \tag{32}$$

$$\frac{\delta Q}{\delta t}+\frac{\delta(\frac{\alpha Q^2}{A})}{\delta x}+gA\frac{\delta y}{\delta x}-gA(I_o-I_f)=0 \tag{33}$$

Where, Q (m^3/s) is discharge, A (m^2) is flow area, y (m) is flow depth, ∝ is velocity distribution coefficient, I_o (dimensionless) is bottom slope and If (dimensionless) is friction slope.

There are three different hydraulic descriptions—the kinematic wave formulation, the diffusive wave formulation, or the complete dynamic wave formulation—available, from where the most appropriate one may be selected for the system. The different flow descriptions are characterized as follows:

Kinematic wave model: This approximation is appropriate for steep, partially full pipes without backwater effects, wherein flow conditions are mainly established by the balance between gravity and friction forces. The inertia and pressure terms in the momentum equation are less dominant. Flow is considered to be uniform and accelerations are small. The model can only be applied for cases when the flow is not affected by downstream conditions (i.e. supercritical flow). It cannot correctly simulate backwater effects and surcharge phenomena.

Diffusive wave model: This approximation models the bed friction, gravity force, and the hydrostatic gradient terms in the momentum equation. The pressure term is retained in the computation so that downstream boundary conditions can be implemented and backwater effects, considered. The inertia terms are still ignored, thus, it is only suitable for backwater analyses where the bed and resistance forces dominate, and where the change in inertia is negligible.

Dynamic wave model: This uses the full momentum equation. It describes all forces affecting flow conditions and is able to correctly simulate fast transients/changes in flow and backwater profiles. This description of flow should be used where the change in inertia of the water body over time and space is of importance, as when bed slopes and bed resistance forces are small.

Modeling Techniques

There are three different scenarios to describe the urban flood modeling [106]., These are Scenarios A, B, and C, which vary in terms of the drainage elements represented in each model.

Scenario A is a model made up only of the conduits (pipes and canals) and manholes is the traditional means of simulating flow in drainage systems as shown in Fig. 2.8. In this scheme, one hundred percent (100%) of the runoff is assumed to be immediately collected by the pipe system, and when the water level in a manholes reaches ground level, the model generates an artificial reservoir attached on top of the manhole with a surface area one thousand (1000) times that of the manhole, which stores the water temporarily. The water goes back into the manhole when water level in the pipe system recedes.

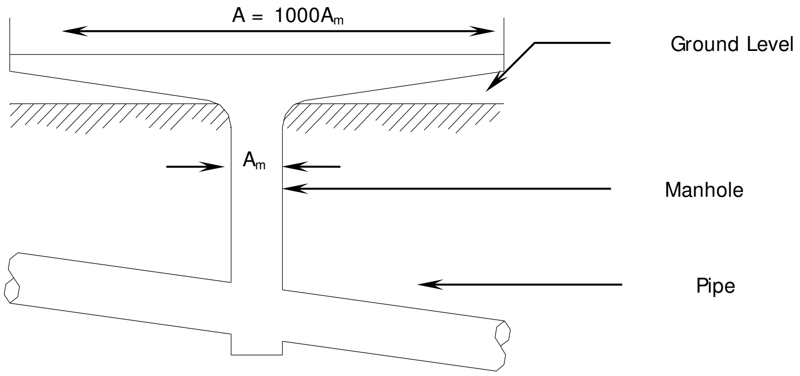


Fig. 2.8 Scenario A Simulation of Surface Flooding [106]

Scenario B (Fig. 2.9) adds a street network layer to the pipe network layer of Scenario A, connecting them through weirs at manhole inlets. Water can therefore be shown to flow along the streets as well as through the pipe network, which more accurately represents flooding. The street flow model simulates unsteady flows on streets with free surface conditions. Flows on streets towards manholes and inlets occur at the onset of rain, and when catch pits and the pipes are overwhelmed, water spills out onto the surface. The computation is the same as for pipe flow, by means of free surface flow equations (Saint Venant equations) and relying on the same assumptions.

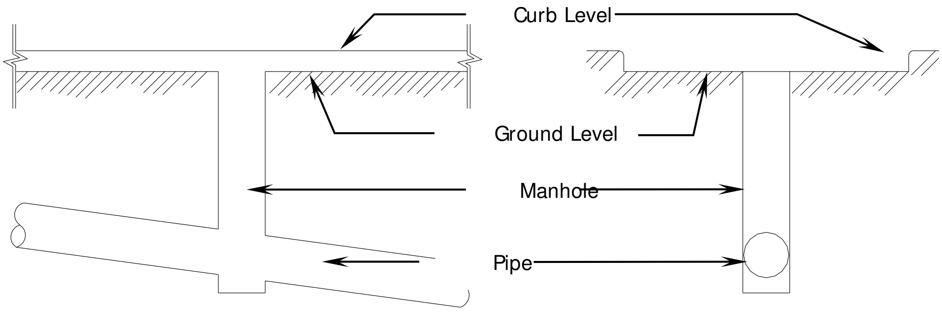


Fig. 2.9 Scenario B Simulation of Surface Flooding [106]

Water levels may also rise higher than the footpath and spill over the curb. Scenario C accounts for this because it further includes topographic information to the double layer of pipe and street networks of Scenario B. (Fig. 2.10) Flood cells capable of holding water spilling over the streets are identified from terrain information. Flooding on the surface is taken as temporary storage in these basins having shapes dictated by topography and connected to the street by weirs, such that water can flow between the basins and the streets.

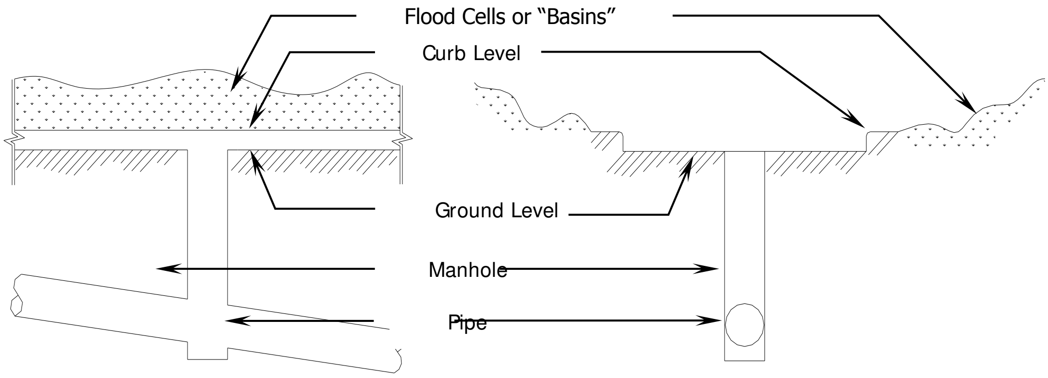


Fig. 2.10 Scenario C Simulation of Surface Flooding [106]

2.4. Rural Drainage Model

If the water propagated by rainfall runoff events flows without urban collection system, it moves through either overland or channel system as flood wave. Most of flow characteristics such as water level and discharge are in fact unsteady and non-uniform flows as the passage of waves of either through channel or storage because flow and its wave keep being modified by variable friction, lateral inflow and outflow, storage and so on.

A flow routing at rural region can be represented as generating a hydrograph at the outlet of a channel or a reservoir by a rainfall runoff calculation at the basin and hydraulic calculation of channel. And there are 2 major procedures such as a reservoir (or lumped) routing and a channel (or distributed) routing.

A reservoir routing, which is also referred to as a lumped routing, is calculation of the effect from runoff water inflowing to a reservoir. According to pre-calculated volume-level relationship of reservoir and outflow-level relationship for outlet, water volume and water level in a reservoir and outflow to connected reservoirs are calculated through the rainfall runoff volume in the connected basin. However a channel routing, which is also referred to as distributed routing and must be considered as rural drainage model in this study, can be described as the time-series flow rate of water within consideration of variable hydrograph as water flows down a channel at target channel section. Thus this type of calculation can show the time-series discharge at various sections of channel. This routing method does not include only hydrologic routing which is similar and as simple as lumped method but also complicated hydraulic routing calculations. Hydrologic routing methods are set of statistical calculations and a continuity equation. But hydraulic routing methods also include momentum equations for unsteady flow which can use the St. Venant Equation representatively of momentum of water.

2.4.1 Governing Equations

The flowing water in the rural drainage is normally a gradually varied unsteady state flow which needs both continuity and momentum equations. A continuity equation can be solved through the time dependent volume change and basic form of continuity equation is shown in Eq. (34):

$$Q_I - Q_O = \frac{dS}{dt} \tag{34}$$

Where, Q_I (m^3/s) is inflow to storage point, Q_O (m^3/s) is outflow from storage point and dS (m^3) is storage volume change. By the way, a calculation of rural drainage flow needs the distributed continuity which must include conservation differential equation as Eq. (35):

$$\frac{dQ}{dx} + \frac{dA}{dt} = 0 \tag{35}$$

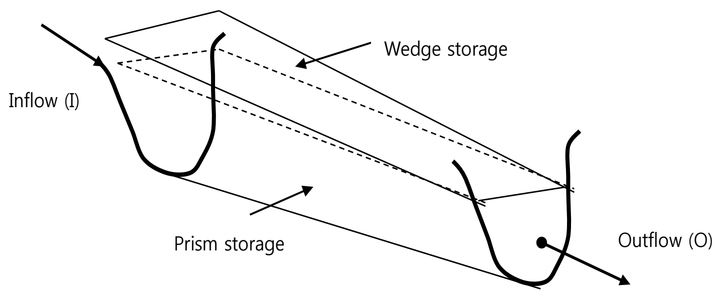
And a St. Venant Equation as a momentum equation is shown in Eq. (36):

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial\left(\frac{Q^2}{A}\right)}{\partial x} + g\frac{\partial y}{\partial x} - g\left(S_0 - S_f\right) = 0 \tag{36}$$

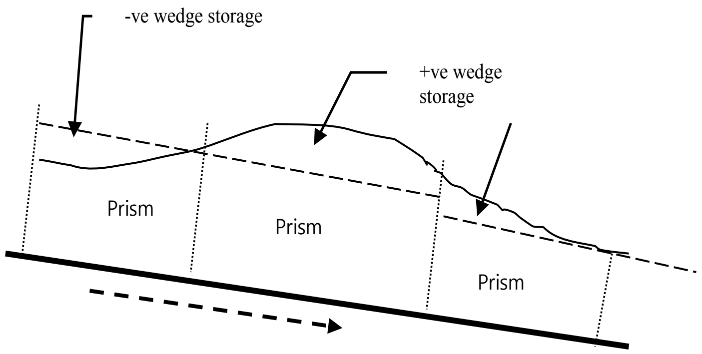
Where, y (m) is water level at given section, S_f (dimensionless) is the slope of total energy line, S_0 (dimensionless) is the slope of channel bed, A (m^2) is a flow section area and Q (m^3/s) is a flow rate at a section. Each term represent the local acceleration, the convective acceleration, the pressure gradient force, the gravitational force and the friction force respectively from 1st to 6th term. The flow is unsteady and non-uniform state if values from all terms are significant figure. And this kind flow commonly is referred to as dynamic wave.

2.4.2 Rural Drainage Modeling Method

The storage in channel in channel routing, the storage is a function of both the inflow and the outflow discharges. Hence, a different routing approach is required. It is important to note that the flow in a river during a flood passage belongs to the category of gradually varied unsteady flow. The water surface is not only unparallel to the channel bottom but also varies with time. Thus, considering a channel reach having a flood flow, the total volume in storage can be considered under two categories such as prism and wedge. Prism storage is the volume that would exist if uniform flow occurred at the downstream depth, i.e. the volume formed by an imaginary plane parallel to the channel bottom drawn at the outflow section of the flow. On the other hand, wedge storage is a wedge-like volume formed between the actual water surface profile and the surface of the prism storage. These storages are illustrated on Fig. 2.11 (a) and (b) below.



(a)



(b)

Fig. 2.11 Prism and wedge storage in a river channel during flood flow

One of the most commonly used hydrologic channels routing procedure is the Muskingum method. This method was developed during the period 1934-1935 for studies of the Muskingum Conservation District Flood Control Project (MCDFCP) of the U.S Army Corps of Engineers. The method which utilises the concept of both wedge and prism storage is of the Eq. (37):

$$S = K\left[xI^{m} + (1 - x)O^{m}\right] \tag{37}$$

Where, K is a channel coefficient usually called the storage-time constant. It has the dimension of time. It is approximately equal to the time of travel of a flood wave through the channel reach. The coefficient x is a weighting factor that takes values between 0 and 0.5. When x=0 Eq. 1 reduces to the linear storage equation. When x=0.5, then the inflow and outflow are equally important in determining the storage. On the other hand, m is a positive exponent which varies from 0.6 for rectangular channels to a value of about 1.0 for natural channels. When m=1.0, Eq. (37) reduces to the linear form as Eq. (38):

$$S=K[xI+(1-x)O] \tag{38}$$

And Eq. (38) is commonly referred to as the Muskingum Equation.

Fig. 2.9 (a) shows a typical inflow and outflow hydrographs through a channel reach. It is important that unlike the case with the reservoir routing, the outflow peak does not occur at the point of intersection of the inflow and the outflow hydrographs. The increment in storage at time t and the time increment Δt can be calculated. Summation of the various incremental storage-values enables one to find the channel storage S versus time relationship (Fig 2.9 (a)). If the inflow and outflow data is available for a given reach, values of S at various time intervals can be determined by the above approach. By choosing a trial value of x, values of S at time t are plotted against the [xI+(1-x)O] values. If the value of x is chosen correctly, a straight-line relationship as given by Eq. (38) is obtained. An incorrect value of x gives a plot of S versus [xI+(1-x)O] values which trace a looping curve. By trial and error, a value of x can be chosen for which the plot very nearly describes a straight line. The inverse of the slope of such line gives the value of K. In a given channel reach the values of x and K are assumed to be constant.

For a given channel reach, by selecting a routing interval Δt and using the Muskingum equation, the change in storage is expressed as Eq. (39):

$$S2 - S1 = K\,[x\,(I2 - I1) + (1 - x)\,(O2 - Ol] \tag{39}$$

Where, suffixes 1 and 2 refer to the conditions before and after the time interval Δt. The continuity equation (Eq. (35)) for the reach is shown as Eq. (40):

$$S_2 - S_1 = \left(\frac{I_2 + I_1}{2}\right)\Delta t - \left(\frac{O_2 + O_1}{2}\right)\Delta t \tag{40}$$

From the above equation, O2 is evaluated as Eq. (41-45):

$$O2 = C0I2+C1I1+C2O1 \tag{41}$$

$$C0 = (-Kx + 0.5\,\Delta t)/(K-Kx+0.5\,\Delta t) \tag{42}$$

$$C1 = (Kx+0.5\Delta t)/(K-Kx+0.5\Delta t) \tag{43}$$

$$C2 = (K-Kx - 0.5\,\Delta t)/(K-Kx+0.5\Delta t) \tag{44}$$

$$C0 + C1 + C2 = 1.0 \tag{45}$$

And Eq. (41) can be written in a general form for the n-th time step as Eq. (46):

$$On = C0In+C1In-1 + C2On-1 \tag{46}$$

Eq. (46) is known as Muskingum Routing Equation and provides a simple linear equation for channel routing. It has been found that for best results the routing interval Δt should be so chosen that K > Δt > 2Kx. If Δt < 2Kx, the coefficient C0 will be negative. Generally, negative values of coefficients are avoided by choosing appropriate values of Δt

To use the Muskingum equation to route a given inflow hydrograph through a reach, the values of K and x for the reach and the value of the outflow, Ol, from the reach at the start are needed. The procedure is indeed simple as (1) Knowing K and x, select an appropriate value of Δt (2) Calculate C0 , C1 , and C2. Starting from the initial conditions I1 , O1 , and known I2 at the end of the first time step Δt calculate O2 by Eq. (41) or Eq. (42).

The outflow that is calculated in step (c) becomes the known initial outflow that is used for the next time step. Repeat the calculations for the entire inflow hydrograph.

One of the modified methods that have worked well in river routing is the Muskingum-Cunge method. As shown earlier, the Muskimgum method is based on the storage equation with coefficients K and x derived by trial and error. Cunge showed that K and x could be derived by considering the hydraulics of the flow in the channel. Recall that K was shown to be approximately equal to the time of travel of a flood wave through the reach. This assumption was used by Cunge to give K=ΔL/c, where c is the average speed of the flood peak and ΔL is the length of the river reach. Substituting for K=ΔL/c in Eq. (39) and (40) gives Eq. (47):

$$\frac{\Delta Lx}{c\Delta t}(I_2 - I_1) + \frac{\Delta L}{c\Delta t}(1-x)(O_2 - O_1) + \frac{1}{2}(O_2 - I_2 + O_1 - I_1) = 0 \tag{47}$$

Multiplying through Eq. (47) by c/ΔL and rearranging gives Eq. (48):

$$\frac{x(I_2 - I)_1}{c\Delta t} + \frac{(1-x)(O_2 - O_1)}{\Delta t} + \frac{c}{2\Delta L}[(O_2 - I_2) + (O_1 - I_1)] = 0 \tag{48}$$

With K==ΔL/c as an acceptable approximation, a means is required for obtaining the x factor. Cunge derived the following expression for x from the channel properties as Eq. (49):

$$x = \frac{1}{2} - \frac{Q_p}{2sBc\Delta L} \tag{49}$$

Where, Q_p is the mean peak discharge, s is the average bed-slope and B is the mean channel width and ΔL is the channel reach. In practice, the Muskingum coefficients are evaluated according to each reach forming the subdivisions of the total length of the river reach being considered. Then the routing of the inflow could proceed as shown earlier to obtain the outflow by recurrent application of the Muskingum routing equation.

2.5. Prediction of Water Demand

The prediction of water demand is one of key issue for assessment of water balance and it is complicated due to many variables to be concerned about. Water is all around human being and natural eco-system within highly variable purposes such as drinking, irrigation, fire control, industrial processes, cleaning, and preservation of aquatic eco-system and so on. Thus, water demands are very uncertain and affected by many factors such as population within the characteristics of its growth, scale of region, land use condition of region, natural characteristics, economic condition, industrial establishments, climatic condition and cost of water supply [107]. Needless to say, prediction of water demand is important. Under estimation of water consumption may give rise to shrinking economic activities and afflict the people through constraints on industrial activities, decline of agricultural product and water supply cutting off and so on. In the other hand, over estimation can give rise to over public investment and over activities on additional water resources development which put a big financial burden on both public and private.

Statistical and regression analysis are mainly used for prediction of the future water demands from the various dependent factors such as climatic condition, water price, economy and population and so on. Realistically, water demand can be divided broadly into three groups such as domestic water, industrial water and agricultural water in terms of water utilization. And there are many methodologies to estimate water demand to be used for each purpose. This chapter discusses mostly common method to predict the future water consumption. And summarized methodologies to predict the water demand are displayed in the Fig. 2.12 below.

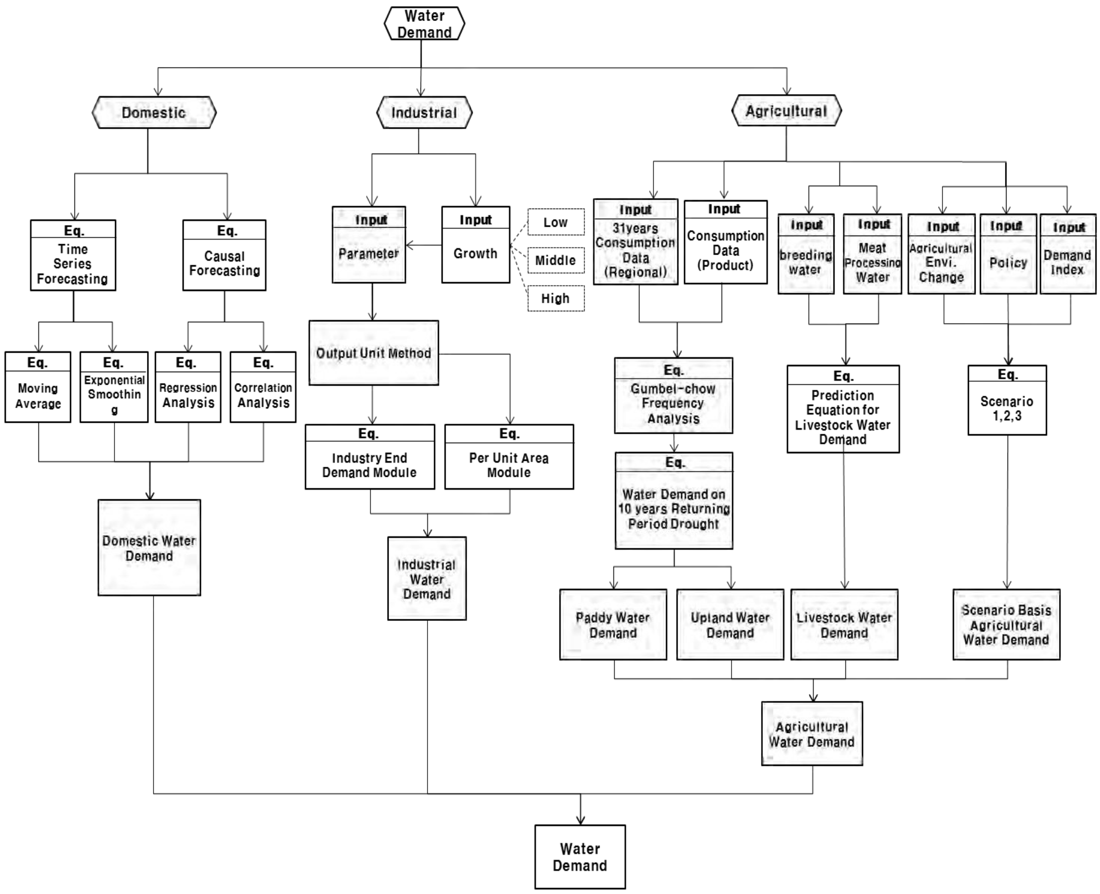


Fig. 2.12 Summarized methodologies on water demand prediction

2.5.1 Prediction of Domestic Water Demand

The actual definition of domestic water is water supplied through distribution system after appropriate treatment from water purification plant for purpose of water for living. And the domestic water includes drinking water such as household water, water for business and public water and non-drinking industrial water. However, this chapter discusses only drinking water since non-drinking water (i.e. industrial water) would be discussed in the following chapter as prediction of industrial water demand.

Domestic water demand could usually depend on the scale of population to use water. The easiest way to predict water demand is simply multiplying a predicted population in target year within consideration of natural growth ratio and a unit consumption of domestic water use per person. However, it is not really easy to use the simple calculation method because a natural growth rate of population must always be varied and there must be at least one development projects especially urbanized region. Moreover, it is really unpredictable if there are projects to develop tourism spots, new towns or militarized facilities, which could potentially change overall population characteristics of target region. Thus, the prediction of domestic water should have formal procedures within accordance with the purpose of prediction.

The prediction consists of complicated processes such as survey, analysis, stochastic procedure and assessment. And the prediction methodologies could broadly be divisible into qualitative method and quantitative method from whether their key process is numerical value calculation. However, this study is mainly focus on quantitative method because the qualitative method is usually depending on subjective view of an experts and it usually is used when the past data is not prepared. The quantitative method could also be classified into two types as time series analysis and causal forecasting method.

A. Time Series Analysis

The time series means a sequence of data set which is surveyed at a target point within time spaced at time intervals specified and it includes temporal dynamic data and is normally sorted chronological order. And the prediction method by time series analysis includes methods for investigating time series in order to obtain significant features of the data so there is an assumption that the current trend, average, seasonality, random fluctuation and cycle pattern which are analyzed through surveyed past time series must be continuously applied for future time series. This type of prediction is actually appropriate to apply if the trend is certain and stable and sufficient long term data can be applicable. So this method is usually applied for short or middle term prediction because water consumption trend is dramatically varied and it cannot be continuously kept as time goes by. This study discusses three different types of time series analysis methods for water demand prediction.

The first method is a trend model. It predicts a future water demand by assuming a formula similar to polynomial regression model and parameter. The assumed formula normally uses a time dependent explanatory variable as linear or non-linear function of time such as first or second order, logarithmic function or exponential function. The simplest methodology is arithmetic series method with assumption of continuous and uniform pattern of quantity wise variation. This is method simply expressed as Eq. (50):

$$P_{t+n} = P_t + b \cdot n \tag{50}$$

Where, P_{t+n} is varied value after n time step, P_t is value at current time step t, n is the number of time step and b is mean variation which can be calculated by Eq. (51):

$$b = \frac{\sum_{t=2}^{d}(P_t - P_{t-1})}{m} \tag{51}$$

Where d is the latest time step and m is the number of time step to calculate a variation. On the other hand, if the assumption of uniform pattern of quantity wise variation is changed into the rate of change, arithmetic series is also changed into geometric series as Eq. (52).

$$P_{t+n} = P_t(1+r)^n \tag{52}$$

Where, r is annual averaged rate of change and can be calculated by Eq. (53);

$$r = \left(\frac{P_{t+1}}{P_t}\right)^{1/n} - 1 \tag{53}$$

The trend model can be also performed through exponential function as exponential growth method. This type of model is appropriate if there is a dramatically varied environment and it can be calculated by Eq. (54).

$$P_{t+n} = P_t e^{rn} \tag{54}$$

Where, r is annual mean rate of change and can be calculated by Eq. (55).

$$\mathrm{r} = \frac{1}{\mathrm{m}} \sum_{t=2}^{d} \frac{(P_t - P_{t-1})}{P_{t-1}} \tag{55}$$

Where d and m can be calculated by the formula above. If the past growth pattern is linear and the trend line shows simple linear formula like Eq. (56).

$$Y = aX + b \tag{56}$$

Where Y is the value, X is the number of time step. If the number of past time series data is n, a and b can be calculated by least square method as Eq. (57) and (58).

$$a = \frac{n\sum XY - \sum X \sum Y}{n\sum X^2 - (\sum X)^2} \tag{57}$$

$$b = \frac{\sum Y}{n} - a\frac{\sum X}{n} \tag{58}$$

The second method is moving average method. It is useful to predict water demand when there only is a chance variation without trend, seasonality and cycle points to be duly considered. In addition, as well as this method might be applied to calculate trend or seasonal index when the time series variable factor exists. The chance variation can be removed through simple moving average method. And a water demand can be predicted through estimating average water demand of certain period on the brink of the target time step as Eq. (59).

$$F_t = \frac{\sum_{i=1}^{n} A_{t-i}}{n} \tag{59}$$

Where, F_t is a predicted value at target time step, i is a variable representing a time step number, n is the number of time step during the moving average period and A_{t-i} is real water demand at time step $t-i$. And this formula can be improved through the additional weighting factor and this improved formula is called as weighted moving average method. The weighting factor is the bigger when the time step is the closer to the target time step. However it is necessary to be careful of determining appropriate weighting factor because the weighting factor is occasionally determined by the subjective judgment as Eq. (60).

$$F_t = \sum_{i=1}^{n} W_{t-i} \cdot A_{t-i} \tag{60}$$

Where W_{t-1} is weighting factor at time step $t-i$ and total sum of weighting factor throughout the simulation period must be 1.

The third method is exponential smoothing method. This method is similar to the weighted moving average method described above because it also gives chronological weighting factor which is the bigger, the time step is the closer to the target step. However the weighting factors from the past to target time step exponentially increase. It is similar to the moving average method that it is also useful to predict water demand when the trend, seasonality and cycle variation of water demands are not duly considered. And it has big advantage that it properly works although insufficient data set for past period. The predicted water demand at target time step can be calculated by adding two variables such as predicted water demand of previous time step and real water demand of previous time step and both variables have weighting factors. These weighting factors are exponential smoothing coefficient and the summation of each coefficient multiplied by each variable must be one and it can be expressed as Eq. (61).

$$F_t = aA_{t-1} + (1-a)F_{t-1} \tag{61}$$

Where, F_{t-1} is predicted value of one step before and a is exponential smoothing coefficient. To solve this formula, there must be an initial predicted value and the value of a to be determined. The initial predicted water demand can be calculated through moving average method or qualitative method. There also is an alternative method using a real water demand of the first time step as initial predicted water demand. However the determination of an exponential smoothing coefficient a is key issue of this method. This coefficient affects sensitively on the result of prediction and must be determined by subjective judgment. Thus, the coefficient a should be determined through sufficient optimization processes such as a trial calculation.

B. Causal Forecasting Method

Causal forecasting method is a strategy that involves the effort to predict future water demand, based on the range of variables that are likely to influence the future movement within that water demand. There must be an assumption that the relationship between dependent and independent variables is determined through the analysis of past data and this relationship is not varied in the future. The typical causal forecasting method is regression analysis. In statistics, regression analysis is a statistical process for estimating the relationships among variables. It includes many techniques for modeling and analyzing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables.

Another example of causal forecasting method is econometric model. Econometric models are statistical models used in econometrics. An econometric model specifies the statistical relationship that is believed to hold between the various economic quantities pertaining to a particular economic phenomenon under study. An econometric model can be derived from a deterministic economic model by allowing for uncertainty, or from an economic model which itself is stochastic. However, it is also possible to use econometric models that are not tied to any specific economic theory.

C. Comparison

According to the basic concept and characteristics of each model, time series analysis is better in short or middle term prediction and causal forecasting method is better in long term prediction. However, it is necessary to secure sufficient past data set for water demand and reliable future prediction of independent variables for causal forecasting method otherwise causal forecasting cannot provide reliable prediction or cannot produce the result. Therefore, it is important to compare the results from 2~3 methods to produce appropriate predictions. The advantages and disadvantages of each model are described in the table 2.3 below.

Table 2.3 Per unit water demand at different sector of industry

Index	Time Series Analysis (fit for growing pattern)	Causal Forecasting Method (fit for steady pattern)	
		Regression Analysis	Econometric Model
Method	Estimation of growing trend Mainly using mathematical model	Estimation of pattern change trend Similarly predicting as time series analysis with additional variables	Advanced method from regression analysis with additional economic variables
Advantages	Well positioned to concern characteristics of study area Fast and easy (low cost) Easy to consider connectivity with past projects Strong cogency on predicted value (more objective)	Fit for steady area or multiregional water supply projects Easy to consider policy target Possible to consider flexibility of individual variables	Fit for steady area or multiregional water supply projects with high realize-ability of governmental policy Possible to consider flexibility of individual variables Easy to consider policy target such as water cost
Disadvantages	Hard to consider additional variables such as policy target and water cost Hard to consider flexibility of individual variables	Necessary to secure big data set verified Only reliable when the social consensus is built High cost due to long study time and difficult works	Necessary to secure big data set verified Only reliable when the social consensus is built Very high cost due to long study time and difficult works Necessary to recheck or reset policy target and policy effect

2.5.2 Prediction of Industrial Water Demand

Water is used mainly three categories such as domestic water, industrial water and agricultural water. There actually are several methodologies developed by many significant experts with very scientific backgrounds on prediction for domestic water and agricultural water. However, very few systems on prediction method for industrial water are developed relatively. It might be because of difficulties on collecting reliable data from non-governmental firms since they are using very small proportion of water supplied through official distribution system which is gauged and charged. Therefore prediction of industrial water demand usually depends on regionally or nationally developed systems and the systems actually varies whenever the region or nation develops a plans such as water distribution plan, water resources management plan and water infrastructure maintenance plan and so on. This study discusses some industrial water demand prediction methods which are recently used in Korea and inserted in the water balance assessment model developed in this study.

Despite these extremely unlike uses for water, a common area of interest for policymakers and hence researchers is the estimation of water demand and with it the price elasticity of demand. This is essential work as it allows water providers, often in highly regulated sectors, to better understand and manage the needs of their customers. Moreover, it is especially important in the face of declining rainfall associated with climate change, pressing needs for maintaining and expanding expensive water supply infrastructure, jurisdictional, sectoral and environmental conflicts over existing surface and groundwater supplies, and sometimes rapid population growth and urbanization.

Nevertheless, we choose to focus on commercial and industrial water demand. The main reason is that very little work on water demand modelling has been undertaken outside the residential water sector, primarily because commercial and industrial use traditionally accounts for a smaller proportion of urban water use, which in turn is substantially less than rural (agricultural) use. This is not to say that commercial and industrial water use is insignificant. For example, across Europe, 42% of total water use is for agriculture, 23% for industry, 18% for urban purposes (including commercial uses) and 18% for energy production (United Nations Environment Programme, 2004). However, the breakdown of water consumption between the sectors varies considerably from one country to another. For instance, in France (64%), Germany (64%) and the Netherlands (55%) relatively more water is used for the production of electricity (share in brackets), while in Finland (66%) and Sweden (28%) water is mostly used for other industrial purposes (including cellulose and paper production).

Likewise, in the US, publicly supplied commercial and industrial purposes accounted for about 10% of water use, a further 4% for self-supplied industrial use, 3% for aquaculture and mining and 49% for thermoelectric power generation. Finally, overall water consumption was 21,703 gigalitres in 2000/01, of which 70% was for agriculture, 10% for households and 20% for commercial and industrial uses (including water supply, sewerage and drainage services). By

2004/05, water consumption had fallen to 18,767 gigalitres, with agriculture falling to 65%, households increasing to 11% and commercial and industrial increasing to 24%. One final consideration is while residential and agricultural uses have accounted for much water use in the past, the shift from agriculture-orientated activities to commercialorientated activities in many developed economies and to industrial-orientated activities in many developing economies means that these sectors will play an increasingly greater role in water consumption and a closer examination of commercial and industrial water demand is clearly warranted.

The neoclassical economic theory of production provides a useful framework for examining firm's use of water and the sensitivity of commercial and industrial water use to market prices [108][109][110]. Unlike consumer demand, where a household has a set of preferences for goods and services (including water) that may be represented by a utility function, for commercial and industrial firms the demand for water is derived along with other inputs as part of a production function. Accordingly, the demand for water, and hence the price elasticity of demand, is a function of not only the price of water but also the price of the firm's outputs, the prices of complementary and substitutable inputs, and the level of available technology, amongst others. Moreover, at least some commercial firms may have substantially more choice over some aspects of water use than typical households, and may have ready availability to different qualities of water, including intake water, water recycling, treatment of water prior to use and water discharge. These and other theoretical considerations considerably complicate the empirical modelling of water demand by commercial and industrial firms.

The industrial water is the water used in the industrial firms with the purpose of operation of industrial equipment through running, washing, cooling and so on or the water to be a material of product [111]. In the majority of cases, the industrial water demand is predicted within consideration of determined per unit of output or industrial area. The per unit water demand can be determined through the analysis of past water demand data or preliminary research output on industrial water demand within different sectors of industries. Within these procedures, it is necessary to classify industrial zone (or complex) into existing zone and planned zone. In case of existing industrial zone, it is possible to consider the past water use data as a predicted future water demand if there is not a plan to expand the water use. However, per unit data for industrial water occasionally is necessary if the target area is planned industrial zone or there is plan to change the type of water for example from self-supply water such as ground water to using water from official water distribution system. In Korea, there is preliminary study to investigate per unit water demand of area for industrial water and it provides per unit water demand on 24 sectors of industries [112] as described in the table 2.4.

Table 2.4 Per unit water demand at different sector of industry

Sector of industry	Per unit water demand (㎥/1,000㎡/day)	Remarks
Food	11.13	
Beverage	6.94	
Fabric	36.20	
Clothing	13.90	
Leather, bag and shoes	32.71	
Wood	1.88	
Paper	3.22	
Printing	9.51	
Cokes, coal and petroleum	2.68	
Chemistry	8.08	
Medical	9.82	
Plastic	4.64	
Nonmetallic mineral	4.31	
Primary metal	3.66	
Metal working	6.47	
Electronic	14.62	
Precision manufacture and optical instrument	19.35	
Electrics	6.24	
Other equipment and machines	4.95	
Automobiles	3.59	
Other transportation equipment	2.89	
Furniture	2.18	
Unclassified	10.05	

There are additional terms to be concerned to predict water demand in the new industrial zone planned.

In order to predict industrial water demand, model factors are recognized by considering the changes in industry structure and industrial water supply structure and the case studies in other countries. By evaluating domestic practices and foreign models, a model that is more suitable for Korean circumstances is selected. With the critique on per unit area approach which has long been used in forecasting industrial water demand in Korea, output unit method is proposed as an alternative and the methodology for its application is studied. Output unit method consists of industrial interrelationship module, industry end demand module, per unit area module. The aim of this study is to show the forecast of industrial water demand for each scenario is possible through the application of the model in conjunction with DB for each of these modules.

In the preliminary study of industrial water demand estimation technique, output per unit method was found to be the most suitable one for the use in Korea after analyzing the nature of industrial water as production material, stabilizing trend in supply structure, change in industry structure, and practical applicability[113]. Output per unit method based forecasting model consists of end demand module, industrial interrelationship module, per capita module (including return ratio), and reflects the changes in industry structure, per capita, and return ratio. Using the developed model, industry interrelationship module (MRIO model consisting of 6 region and 14 industries) has been developed. In addition, the development of end demand module for each industry have been completed utilizing metric method, and end demand for each industry has been forecasted for each economic scenario. Long-term change has also been forecasted using the time series of output per unit area and return ratio. However, due to the flaws in the time series data of output per unit area and return ratio, it was not used for test application of the model. As an alternative, a virtual scenario has been written utilizing Japanese data, and forecasting results were obtained for each virtual scenario. From the results, the model was found applicable given the necessary information, and strongly suggests that accumulation of reliable statistics on return ratio and output per unit area should follow in the future. From these results, the demand forecasting guideline has been prepared for the prediction of end demand for each industry per each management scenario.

2.5.3 Prediction of Agricultural Water Demand

In the development of agricultural water demand forecasting technique, the details of estimation technique for upland and livestock water are presented from the review of existing forecasting techniques and the identification of potential improvements. In addition, the demand change in agricultural water with respect to the water source structure is analyzed. Using this information, a guideline for agricultural water demand forecasting technique is provided as a final product.

In agricultural water demand estimation technique, the problem of traditionally used per unit area method has been identified. For the uplandwater-demand estimation, the need for the inclusion of orchard area, which mostly has own hydraulic structure, and of cultivated area with structure in the analysis, has been pointed out. In case of livestock water, the use of Japanese data has been suggested due to the lack of data and research in Korea. For the estimation of grassland water, demand estimation technique that is applicable to normal irrigated upland, has been suggested. Structures for agricultural water sources include reservoirs, pumping stations, and weirs. Among these, reservoirs and weirs are commonly used for most irrigated area, and there exists some differences in their operational characteristics and conditions. Therefore, there are differences in water usage for these structures. Reservoir is affected by its storage, and pumping station is affected by the river flow and power consumption in their operation. Irrigation canal loss can be reduced by structurizing the irrigation canal, and the progress in structurization is predicted to be 51.1% in 2001, which would lead to the reduction of 8 million m^3 in loss. As the final product, the guideline for agricultural water demand forecasting has been prepared.

Chapter 3 Development of Model and Application

3.1. General Composition of Model

As per described in the previous theoretical background chapter, the model under developing through this study consists of water resources modeling and water demand modeling.

The first thing to be concerned in order to develop a model is general and very detailed procedure on producing a compulsory result. To meet the objectives of this study, the result must be a balance of water whether it is sufficient. A general framework of modeling system is illustrated into Fig. 3.1.

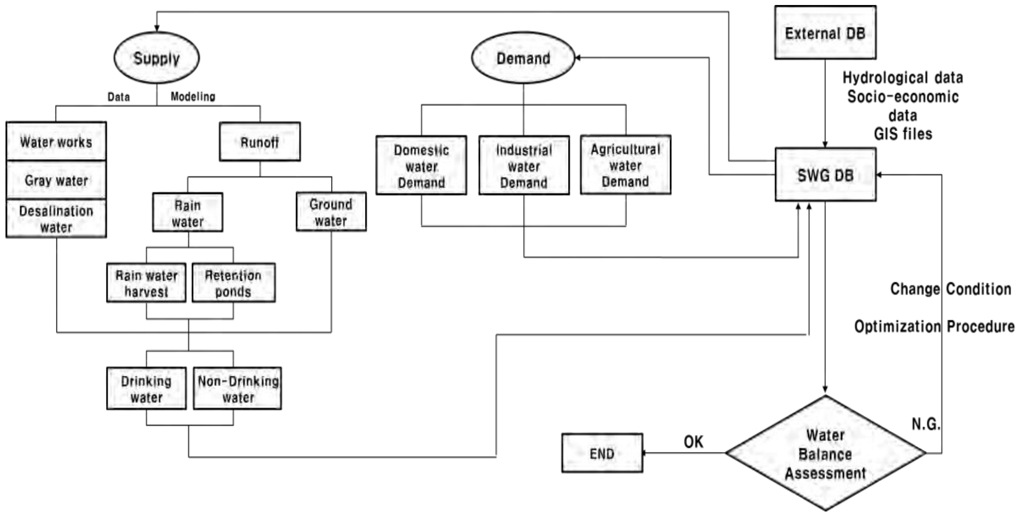


Fig. 3.1 Overall framework of modeling system

There are two major parameters such as water supply data including drinking water and non-drinking water and three types of water demand data within purpose of domestic, industrial and agricultural use. Some of them need modeling modules and the others can get from planning or designing documents which are stored in the database. One important factor to be concerned is water supply from official waterworks. It is treated water through water purification plant and its source is external water resources such as rivers or dams. It is very stable and normally sufficient since it is designed to cover a whole domain with surplus portion. However, it occasionally cover more than one region with pretty complicated network and have risks at the source itself or pipe line. Thus, it is necessary to secure self-sufficient water resources from internal sources in the domain to cover potential risks especially in the island region.

The previous types of models have limited functions for catching the problems on water cycle due to separated modeling on different cycle of water and too wide scale of domain such as a whole major river basin, a metropolitan province or wide watershed. Moreover those models basically don't concern about multiple water sources. However, this study attempts to develop a model to cover all necessary procedures on resolving a problem encountered at previous models as table 3.1.

Table 3.1 General comparison of this model with previous models

Issues	Previous models	This study
Scale	River basin Wide watershed Metropolitan province	Micro scale (up to 1km^2)
Catchment Type	Urban or Rural	Urban and rural
Standardization	Separated modules	Integrated modeling with standardization
Integration	Integrated with climate data	Integrated with climate data, multiple water sources and all smart water grid components (sensor, platform and waterloop etcs)

Modules which are necessary to cover the integrated modeling framework described above are listed up to table 3.2.

Table 3.2 Description of necessary modules

Module	Named	Procedure	Remarks
GIS interface	SWG-PP	Providing basic interface, GIS pre-processing, Projection and transformation	
Rainfall-runoff	SWG-Runoff	Climate data management, Rainfall-runoff modeling	
Channel flow	SWG-UDS	Routing channel, Open channel flow modeling(Sewer and river)	
Water demand	SWG-Demand	Prediction of water demand(According to the scenario)	
Water balance	SWG-WB	Water budget analysis, Predicting and quantifying water shortage	

3.2. Interface and data composition

Within the interface of model, the results from modeling and water balance can be displayed. For the data composition, all data can be inputted upon the GIS based interface all predicting procedures including modeling are automatically done short afterward revision of data. Basic interface of model is shown in the Fig. 3.2 below.

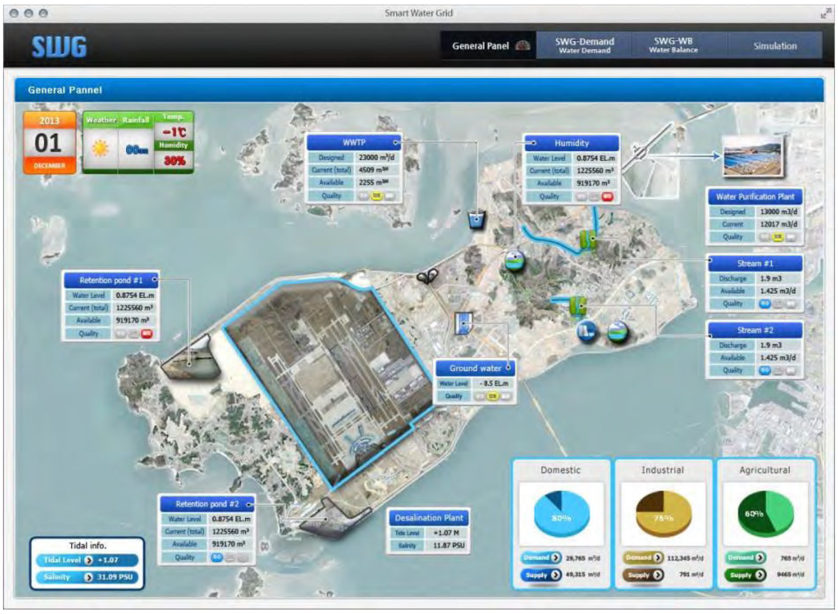


Fig. 3.2 General interface to display general result from the model Figure soon be revised. (in English)

The model generates a dataset including water demand and supply. The water balance is assessed through the result from the model. It covers daily, monthly and annual water balance through the chart as shown in the Fig. 3.3.

Fig. 3.3 Water balance chart interface

For the application of model result, detailed data is shown in the water balance assessment part of the model interface. In this interface, water balance information is displayed through the map of target area. And below the map, there is a data sheet displaying the prediction result of water demand and modeling result of water supply as shown in Fig. 3.4.

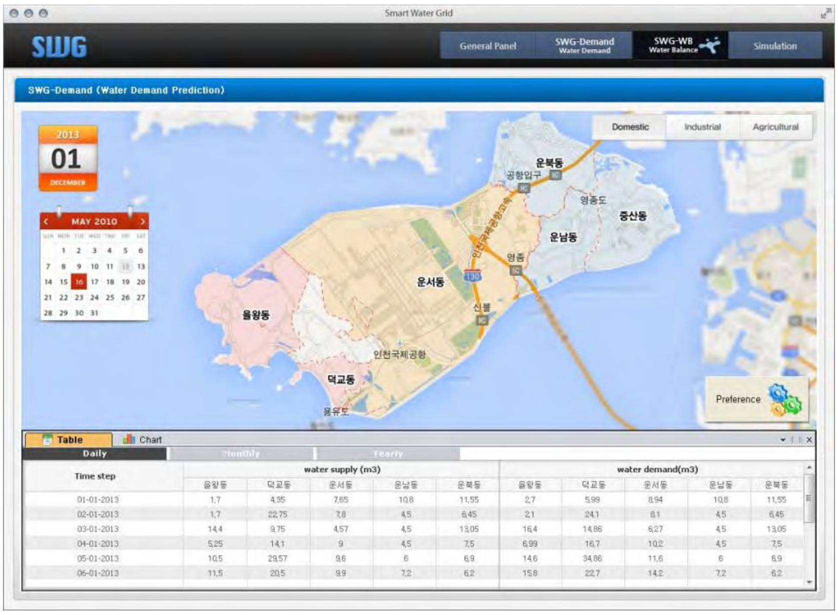


Fig. 3.4 Detailed information on water balance assessment interface

3.3. Descriptions of modules

3.3.1 SWG-PP GIS interface modules

SWG-PP module is pre-processing tool for the model. Purposes of this model are to make all input files into same spatial projection, to show raster input files visually, to provide basic interface for modeling and to calculate basic spatial factors such as flow routine, flow path, roughness and CN value. This module provides a basic input data interface within the raster file viewer similarly to GIS tools. At the starting of the model, this module asks spatial information data such as digital elevation model (DEM), land use map and soil map within the format of ASCII (American Standard Code for Information Interchange) grid as shown in the Fig. 3.5.

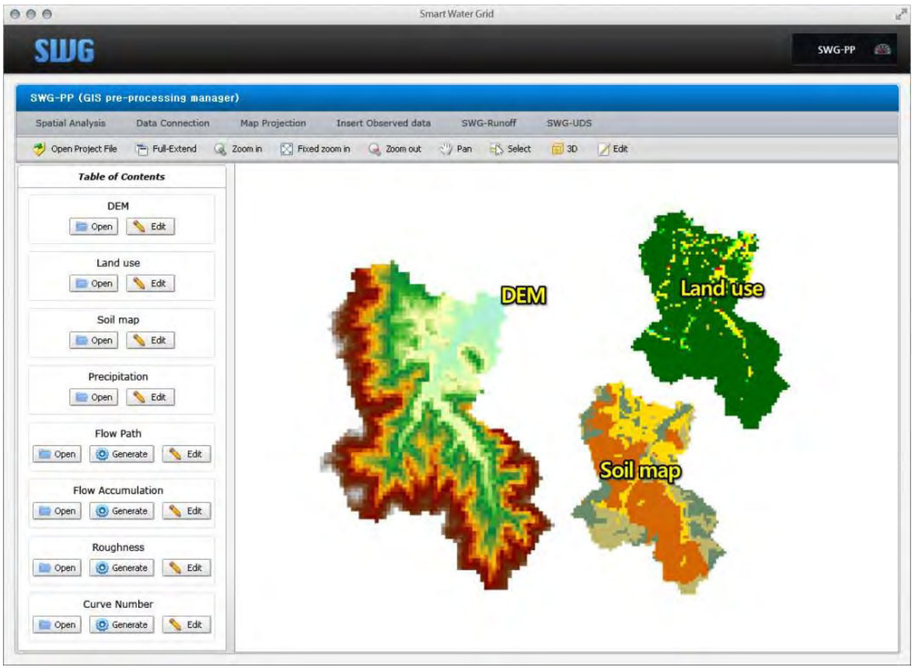


Fig. 3.5 Spatial information data as input file of model

This module calculates automatically basic spatial information for producing hydrologic base information such as a flow routine, flow accumulation, SCS CN (The Soil Conservation Service Curve Number) and roughness coefficient as Manning's n value as shown in the Fig.

3.6. In order to have advanced simulation of water flow through open channel hydraulics, DEM can occasionally be used as burn DEM with detailed information of channel such as river and storm sewer network so that overland flow and open channel flow can be precisely divided. A spatially distributed runoff analysis would be applied for overland flow part in the map and an open channel flow with specific cross section would be applied for routed channel part.

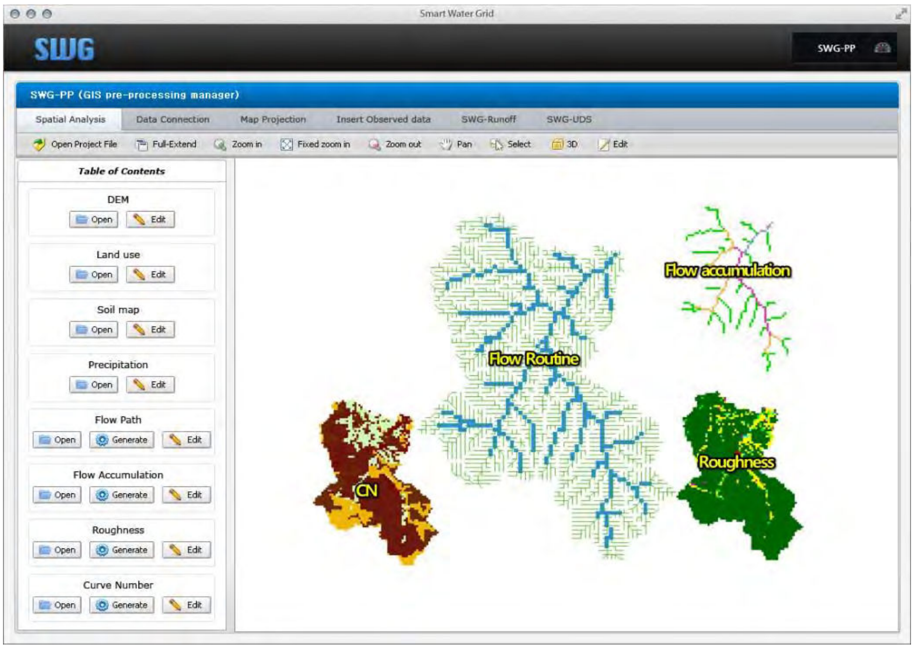


Fig. 3.6 Automatic calculations for spatial information

A spatial information data as ASCII code is used in several GIS (Geographic Information System) tools with spatial projections which each country in the world has their own systems about. Therefore several input data as raster ASCII files has occasionally different projection which causes problems on disagreement among maps with a location, a coordination and base units of maps as Fig. 3.7. Therefore this module makes the maps into same spatial projection systems as modelers' requirement. It provides ITRF2000 coordinate system and GCS 1985 Korean Datum as metric unit and WGS 84 as longitude/latitude coordination.

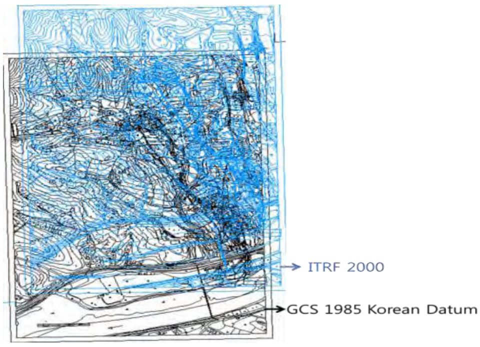


Fig. 3.7 Example of disagreement between different projections

3.3.2 SWG-Runoff spatially distributed runoff module

SWG-Runoff module is one of major calculation modules which provides spatially distributed rainfall-runoff calculation within physically based numerical solution described in the previous theoretical background chapter. This module consists of climate data management and rainfall-runoff modeling. General framework of data flow and calculation is described in the Fig. 3.8.

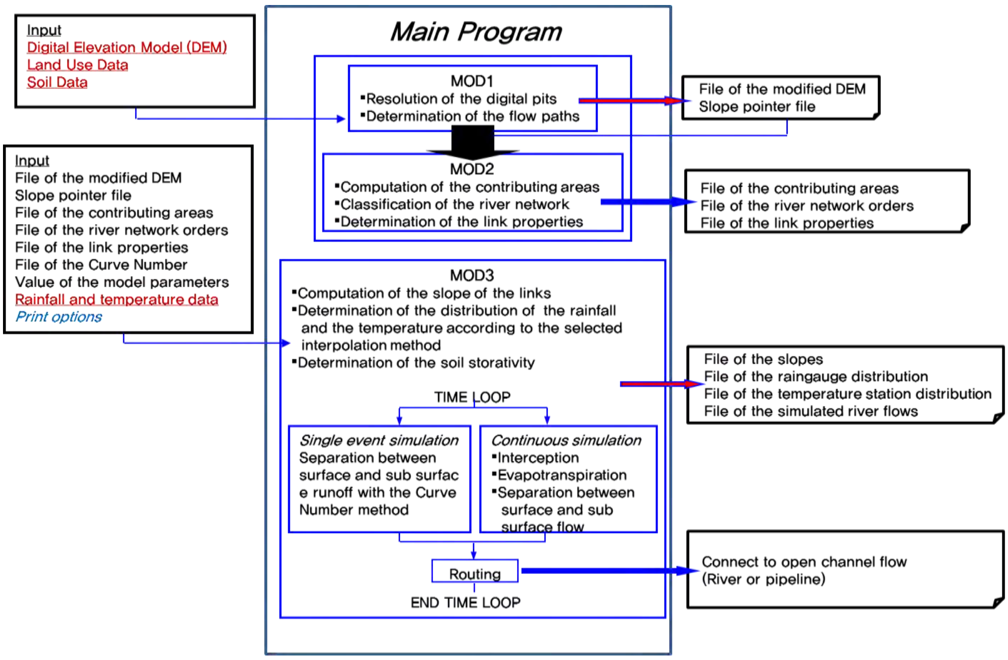


Fig. 3.8 General framework of data flow and simulation

A climate data as an input data can be inserted as point time series or spatially varied raster data. In order to simplify the input data set, this model uses only two types such as atmospheric temperature and precipitation data which are occasionally used as major output from several climate change research so that the climate change can be applied in this model. Fig. 3.9 shows spatially and temporally varied raster climate data as an input data of the model.

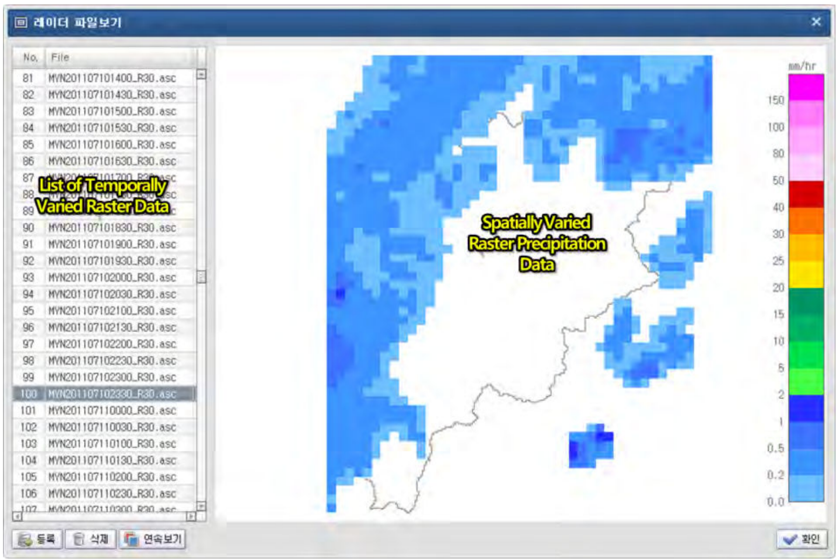


Fig. 3.9 Raster climate data

Once simple input files are prepared, major outlet of domain should be specified with boundary condition. It is allowed to specify multiple outlet point in case the domain has several outlet points. And if the observed data at certain point is prepared, modeling parameters such as coefficient of permeability, roughness factor, bottom discharge parameter and multiplying parameter for infiltration and interception can be optimized. After the simulation, an instant result figure (Fig. 3.10) is automatically displayed as a mark of simulation finish and the decision whether the automatic calibration is necessary can be made after the first simulation.

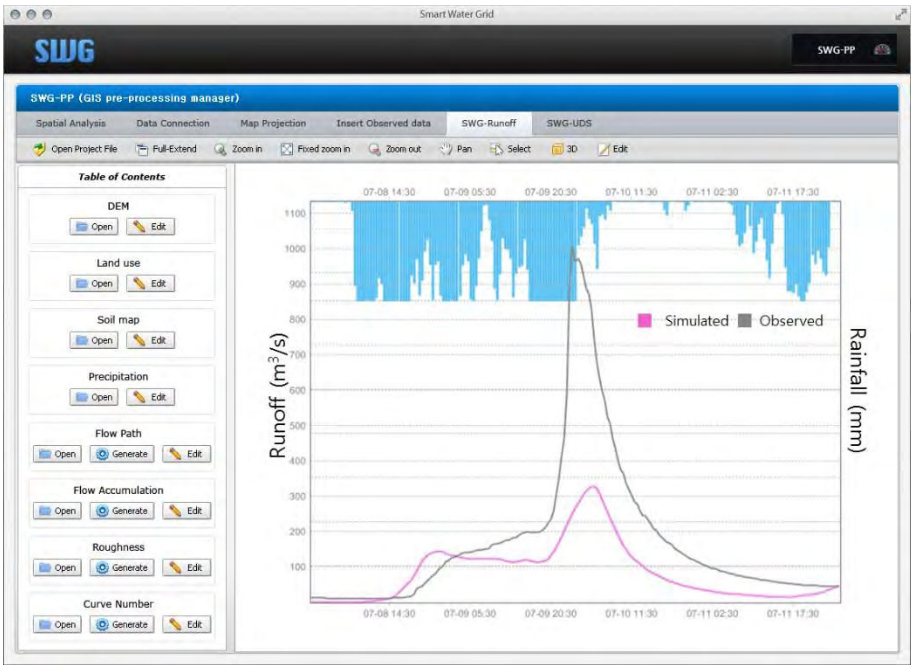


Fig. 3.10 The instant result window after the first simulation

3.3.3 SWG-UDS open channel flow module

SWG-UDS module is a component of flow calculation model and integrated into the rainfall-runoff module. The data for this modeling is quite simple by inserting the geometric and hydraulic characteristics of channel at the flow path as shown in the Fig. 3.11. Once the characteristics are inserted into the model, the model automatically consider the flow path as open channel and the channel can be both overland river and underground drainage system as sewer network. And the flow discharge inflowing to the channel is flowing through the drainage network.

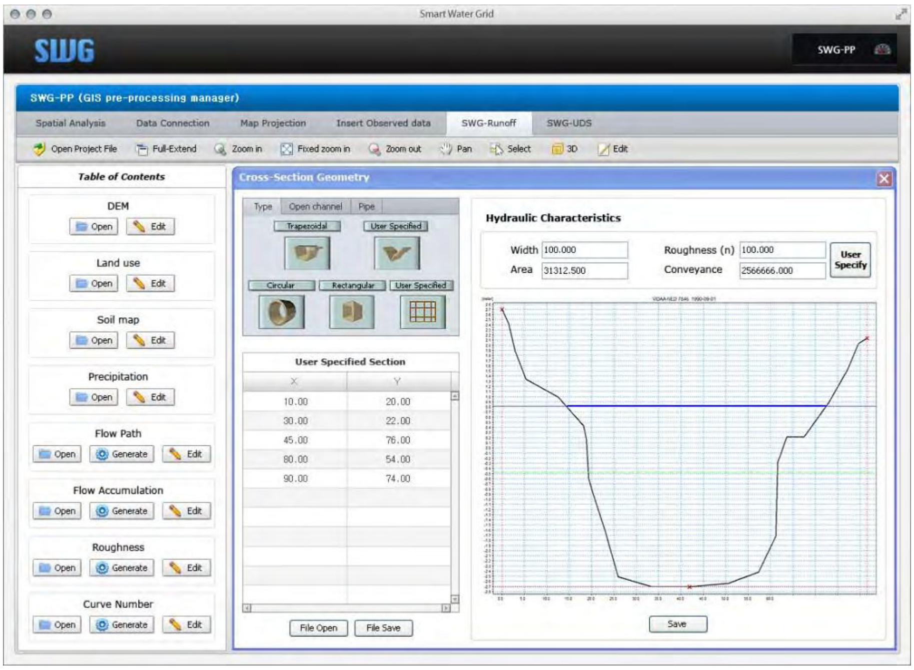


Fig. 3.11 Description of open channel flow modeling

3.3.4 SWG-Demand water demand prediction module

SWG-Demand module is a prediction module for future water demand within purpose of several field for specific region. As per described in the theoretical background chapter, the methodologies for water demand prediction can be summarized as table 3.3.

Table 3.3 Summarize of methodologies for water demand prediction

Domestic	Industrial	Agricultural
Moving average	Industry end demand module	Gumbel-Chow frequency analysis
Exponential smoothing Regression analysis Econometric model	Per unit area module Output per unit method Scenario based analysis	Prediction equation for livestock water demand Scenario based analysis National Water Resources Plan1)
Scenario based analysis	National Water Resources Plan1)	
National Water Resources Plan1)		
Trend Models Arithmetic series Geometric series Exponential growth method Logistic curve		

1) future water demand prediction method used for Korean National Water Resources Plan

This module is categorized into three different purposes of water demands such as domestic water, industrial water and agricultural water. The domestic water is the water used by residences, commercial enterprises and governmental facilities and needs to secure safe quality as drinking water since it is spent by mainly human for drinking or equivalent purpose. And the industrial water is used as a valuable resources and compulsory tool for manufacturing and managing industrial products. As well as, the agricultural water, which is occasionally referred to as irrigation water, is artificially supplying water from the lack of natural supply which occasionally provided insufficient quantity to produce agricultural products. The agricultural purpose of water use also includes drinking water for livestock, anti-freezing protection, leaching of salts and so on and it is the widest category of water use.

There are several methods to predict water demand as described in the theoretical background chapter. Domestic water has two major methods to predict such as time series forecasting and causal forecasting. The biggest issue of domestic water is a population of domain. The major procedure of domestic water prediction is estimating the population and classifying the population into a residential population and a floating population. So if there is a specific development plan which includes a population plan, the prediction procedure can simply be achieved through multiplying a population and per capita water use. However, it must be done through methods above by inserting data necessary to carry out the method selected.

In terms of industrial water, there are two methods provided through this module and both methods are using water use per unit. The first method is output per unit method which uses per value (unit of currency, e.g. Korean Won (KRW)) of output product water use. And the second method is per unit area module which uses per unit area water use. Both methods simply estimate the water demand by multiplying per unit water use and their multiplier respectively. Within the decision of method to use, the prediction of change of industrial complex must precedence in order for the reliable estimation. Therefore scenario of development plan on industrial complex occasionally implemented simultaneously the prediction.

Unlikely the domestic and industrial water demand described above, the procedure of agricultural water prediction is a bit more complicated. As the range of agricultural water use is much larger than the others, the methods of prediction for different area of agriculture (e.g. livestock, paddy, fruit and so on) should also be different. So it is necessary to collect sufficient data about agriculture of modeling domain. After figuring out the predicted agricultural characteristics of domain, water demand on different purposes would be predicted through different methods respectively. Actually the water demand should also include another water uses such as gardening water, surface washing water and instream water. This model also provides prediction of those water uses.

Water demand on entire domain can also be predicted through the scenario developed through development plan or maintenance plan. So this module provides additional table to enter user specified data on water demand prediction which is determined through preliminary studies as plan.

The interface for water demand prediction is shown in the Fig. 3.12 and the methods for prediction can be selected through option window shown in the Fig. 3.13.

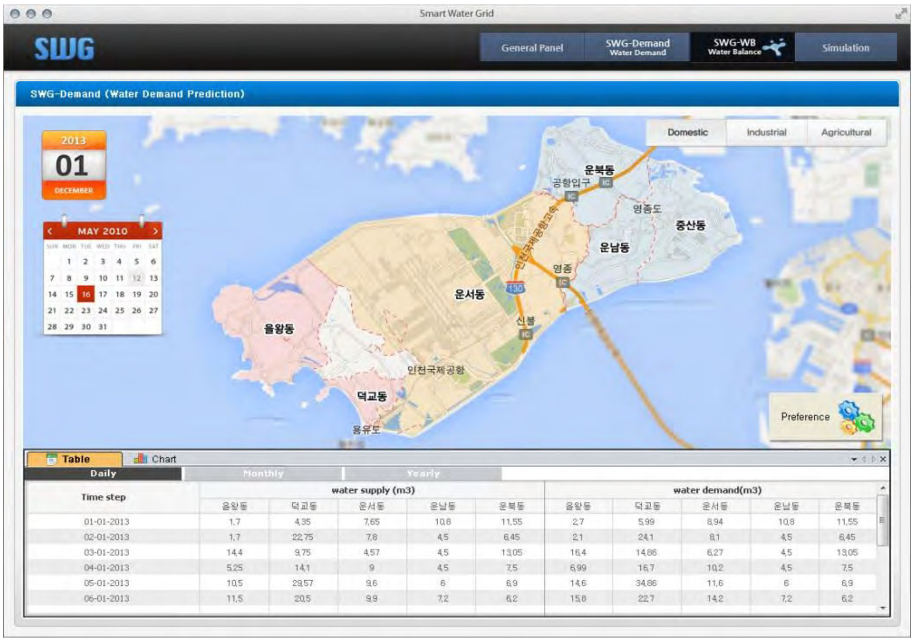


Fig. 3.12 Detailed information on water balance assessment interface

Fig. 3.13 Methods applicable for water demand prediction

3.3.5 SWG-WB water balance assessment module

SWG-WB module is a water balance assessment calculation by comparison between water resources available and predicted water demand. This module mainly uses calculated values through modeling with modules described above however additional water resources such as desalinated sea water, treated waste water, ground water well and external water supply from water purification plant which are available regularly basis can be added through the additional table.

The basic equation to preserve the water balance can be performed as Eq. (62);

$$\mathrm{W_B} = W_A - W_D \tag{62}$$

Where, $\mathrm{W_B}$ (m^3) is a water balance which shows if the water supply system is alright, $\mathrm{W_A}$ (m^3) is water resources available in the study area and $\mathrm{W_D}$ (m^3) is water demand in the region. And $\mathrm{W_A}$ can be calculated through the Eq. (63);

$$\mathrm{W_A} = W_E + W_O + W_M \tag{63}$$

Where, W_E (m^3) is an emergency water stored in the water supply reservoir, W_O (m^3) is the water officially distributed and can become zero if there is an emergency status. And W_M (m^3) is water resource available through smart water treatment plant which can supply non-drinking water if it is not an emergency stage.

This module basically provides the water balance with total water resources available and total water demand. This is purely quantity wise water balance which can occasionally provide the state of water balance as sufficient although the water use which needs to secure sufficient water quality such as drinking water. Therefore each water resource from simulation or user specification is available to choose the purpose of water. For example, ground water, desalinated sea water and stream water can be used for all purpose of water use but collected rain water at retention pond, treated waste water and gray water can be used only for agricultural water and partially for industrial water unless the water is used as the material of food product. However the description from the example above is not always truth but it is just a common sense because the water quality of the sources is always variable and it occasionally depends on the method of water treatment. As well as, there is another issue about the quantity of water from the source. Sometimes a source in the domain can supply very little amount of water and it needs huge pipe line and treatment facility, this event can easily be happened and unless it is the only source to take water, the source may be excluded from the selection. Thus this module allows users to specify each source if it is used and the purpose of water use. The water balance is provided as a graphical view as shown in the Fig. 3.14.

Fig. 3.14 Water balance chart interface

If the value of WB in the Eq. (61) is more than zero as ordinary state of water supply, the system shows only general state of water cycle in the target area as Fig. 3.15 and the general procedure in the ordinary water supply system is illustrated in the Fig. 3.16.

Fig. 3.15 System display during ordinary water cycle in the study area

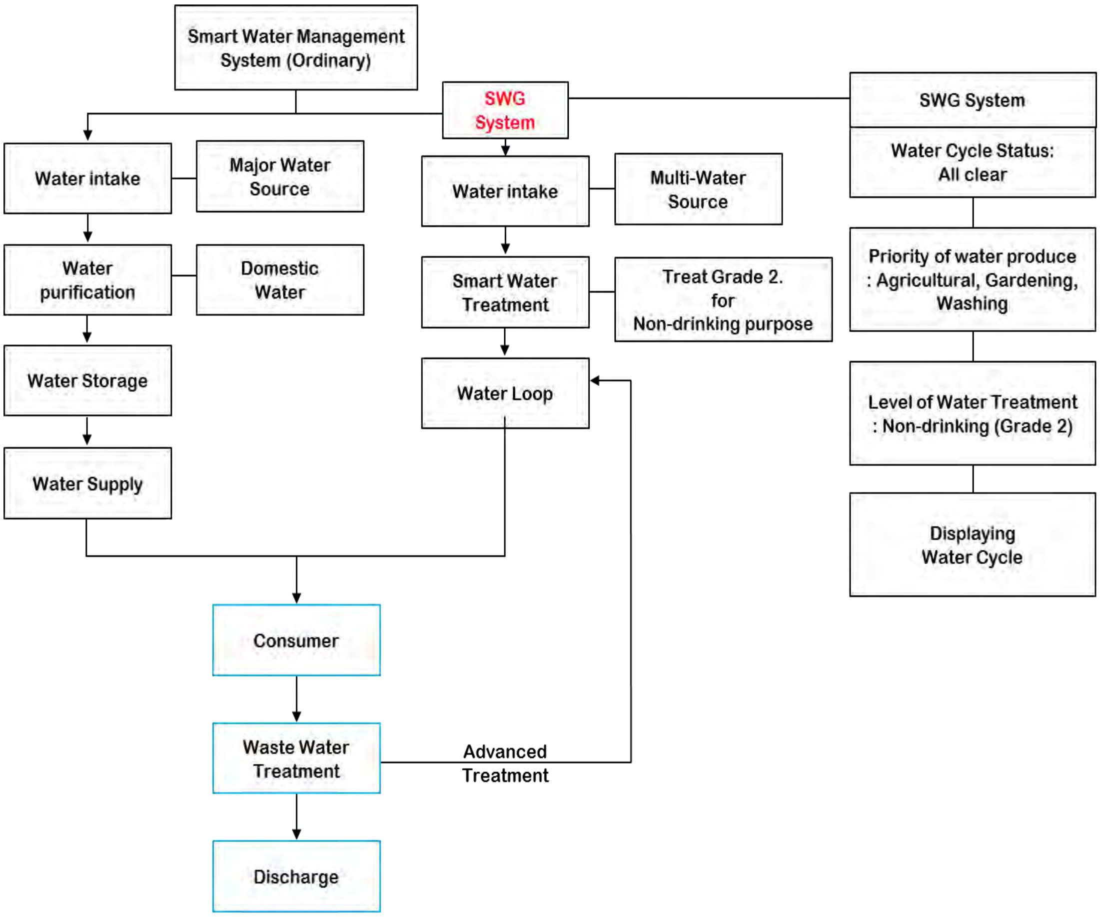


Fig. 3.16 Ordinary water distribution with smart water technologies

However, if the value of WB in the Eq. (61) is less than zero by cutting off water supply within reasons of accident or drought, it is an emergency state and it is necessary to secure water to supply to the customers. The system shows the emergency warning message at the place in trouble as Fig. 3.17 and the general procedure should be changed for emergency water management mode illustrated in the Fig. 3.18.

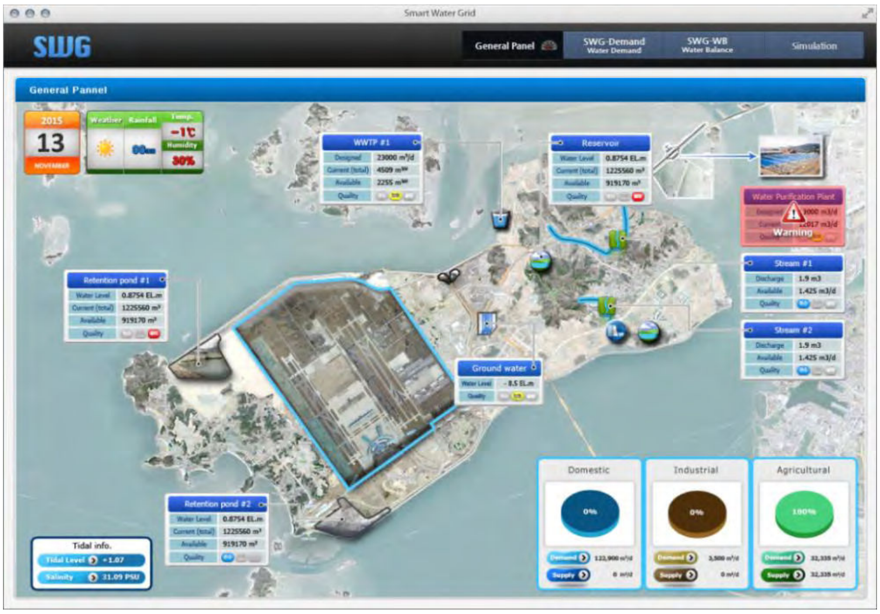


Fig. 3.17 System display during emergency water cycle in the study area

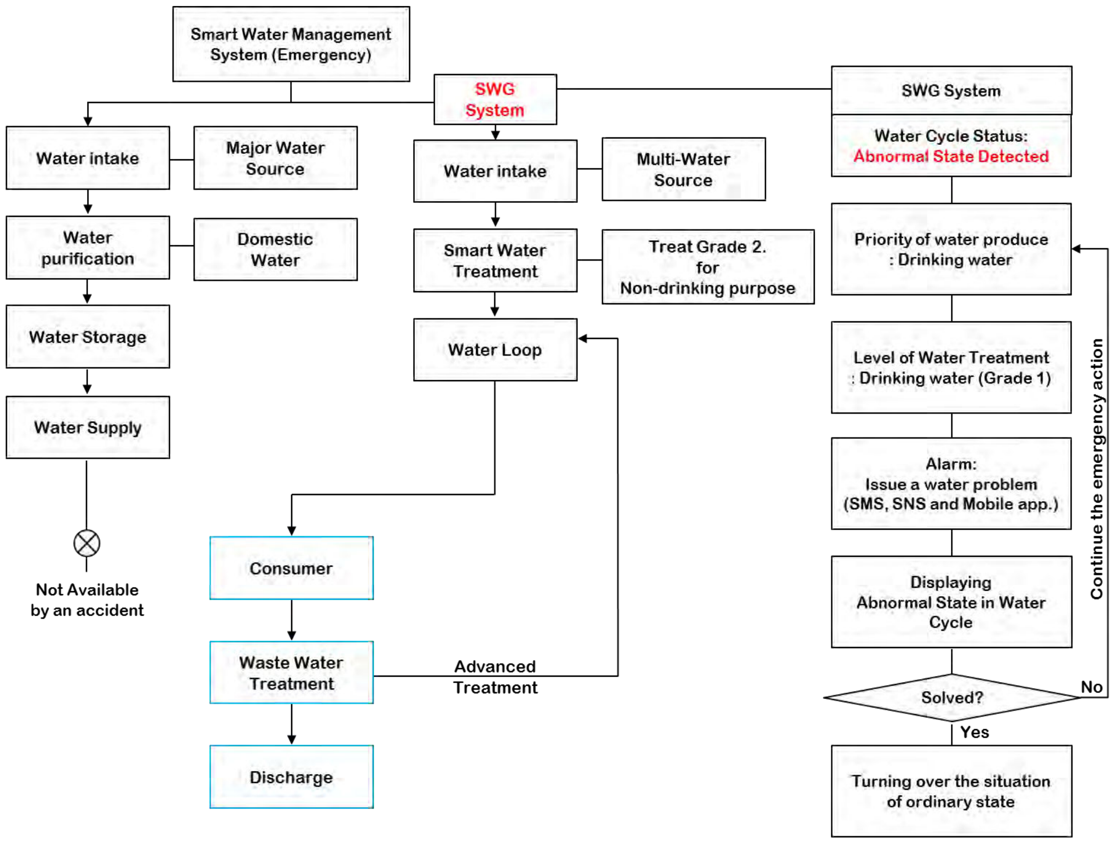


Fig. 3.18 Emergency water distribution with smart water technologies

Chapter 4 Applying the model at the study area

4.1. Study Area

In this study, the water balance assessment model is being developed as a Smart Water Grid research. In order to decide the target region for smart water balance assessment system, 3 different scales for major system and 1 overseas type have been defined as shown in the Fig. 4.1.

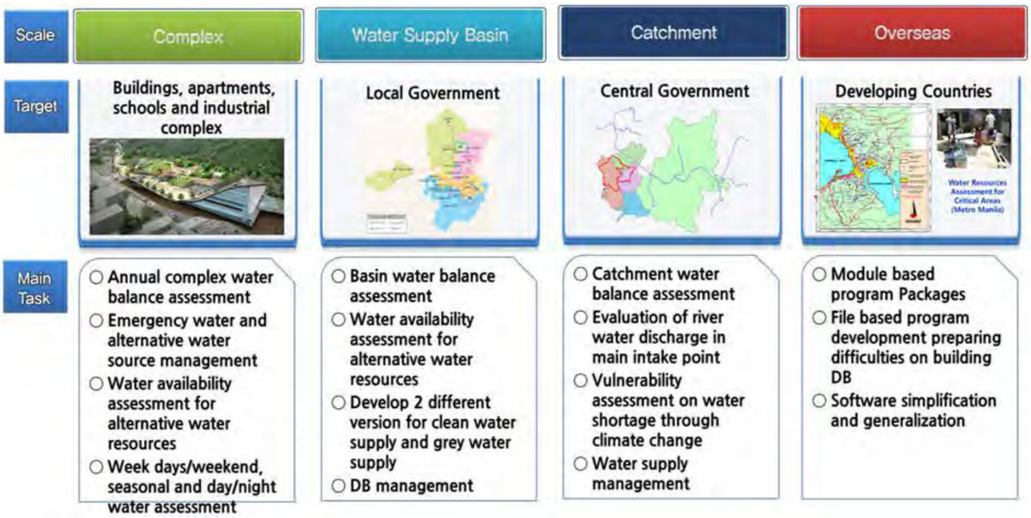


Fig. 4.1 Targets for system development and main task for each scale

Major issues in the preliminary studies on water balance or water budget analysis were catchment scale or bigger which might be referred to as a mega grid because the unit to discuss water resources was mainly the unit of a river basin or a metropolitan region and this kind of metropolitan and mega-scale water resources management makes easy and convenient implementation of function on water management as a government led water resource management. Nonetheless, as public concerns on water goes increasing, smaller scale water management and water information service for citizen are getting necessary. Moreover there are several important complexes such as airport, school and so on whose protection is necessary in terms of water to secure public health in smaller zones. Therefore this study discusses a water balance in the complex scale, island scale or an influenced basin of a water purification plant. And there also are other conditions to choose a study area for this study in mind. In terms of water use, three major types of water use such as domestic use, industrial use and agricultural use must be available to simultaneous consideration. There also must be problems or potential risks on water supply system within the sight of common sense. Consequently there are 2 potential study areas selected as Fig. 4.2. [114]

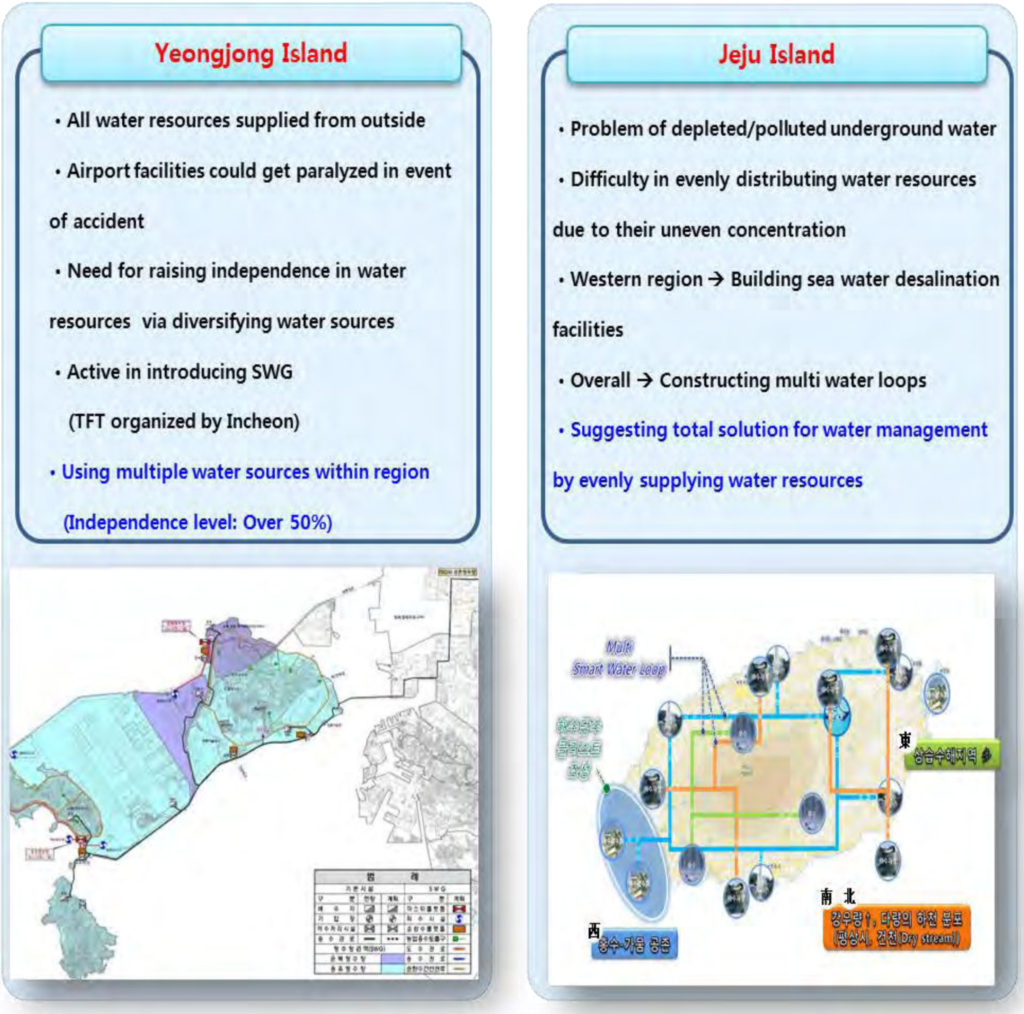


Fig. 4.2 Comparison of candidate study area

In Yeongjongdo Island, there is the Incheon International Airport which is a major airport in Korea and huge new towns are under construction or under inception phase. Water is coming from a water purification plant in Incheon city and the water comes to the island across the sea. There actually is not a problem on water supply system but it seems that there must be some potential risks on water distribution system. On the other hand, there also is Jeju Island which is the biggest touristic spot in Korea. Ten millions of people from Korea and overseas are visiting this island every year and there are several special products from the agricultural zone in Jeju island. There is very limited quantity of self-supply water in both islands and there are various purposes on water uses as well. So it actually seems that both islands are appropriate to be selected as a study area in this study. However Yeongjongdo Island is selected because of some reasons. In terms of the accessibility of study area, there are two bridges between Incheon metropolitan city and the Yeongjongdo Island and railroads in the island but the accessibility of the Jeju Island is relatively inconvenience. And the area of the Jeju Island is approximately 1,833.2 km^2 which is roughly 30 times broader than the Yeongjongdo Island which is approximately 63.8 km^2 and too big to use as a pilot area. And the Jeju Island itself is metropolitan province which must be considered as mage scale and this study discusses smaller scale.

4.1.1 General Description of Study Area

In fact, large proportions of water resources in Korea rely on river fresh water. Also in the Youngjongdo Island, tap water from water purification plant which use original source from the Han River. However the water supply system in the island is quite dangerous since the water purification plant is located in Incheon city and the water comes to island through the sea and no other source is used in the island. Therefore, once the accident at main water pipe in the sea, no water is available in this island as shown in the Fig. 4.3.

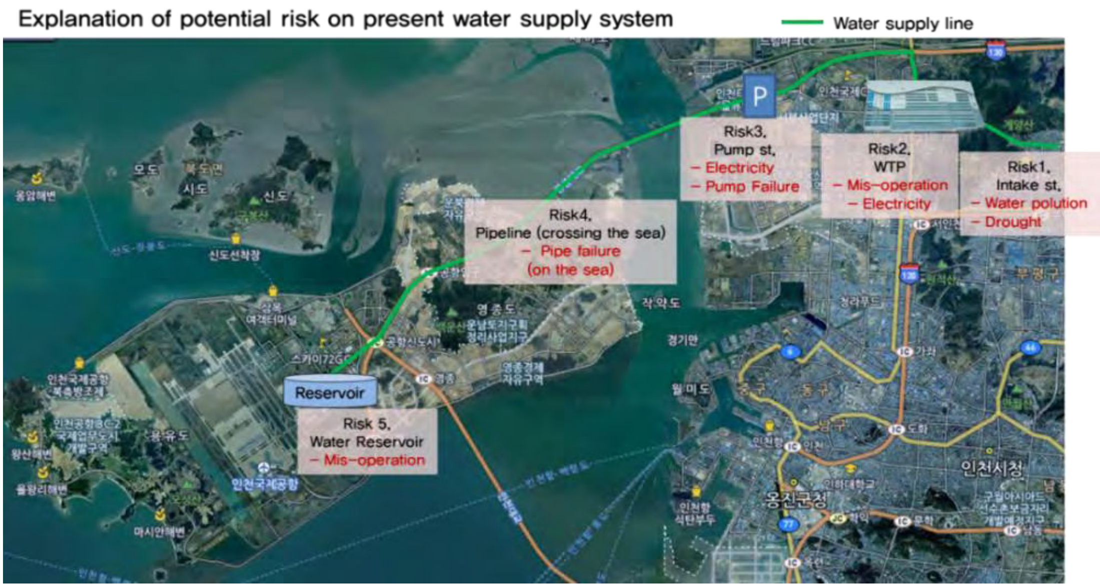


Fig. 4.3 Potential risks on present water supply system of the Youngjongdo Island

The Yeongjongdo Island is located at west of Incheon city. It used to be three different islands which consist of the Yeongjongdo Island, Yongyu-Island and Muui- Island. Within current state, there are only Yeongjongdo Island and Muuido Island due to the reclamation project to build new international airport which is currently the major airport in Korea. The international airport started their service in March, 2001 and simultaneously there are several new town projects still on going and partially finished. Current population of this island is

52,300 and total area including reclaimed area is 116 km^2 as table 4.1 below and it is divided into 3 administrative villages as Fig. 4.4.

Table 4.1 General information of villages in the Yeongjongdo Island

Name of Village	Population (Person)			Area (km^2)	No. of Household	Remarks
	Men	Women	Total			
Yeongjong-dong	13,331	12,491	25,822	33.0	10,645	
Unseo-dong	11,275	10,107	21,382	58.9	8,828	
Yongyu-dong	2,299	1,883	4,182	14.6	2,390	
Muui-dong	457	408	865	10.3	463	
Sum	27,362	24,889	52,251	116.77	22,326	

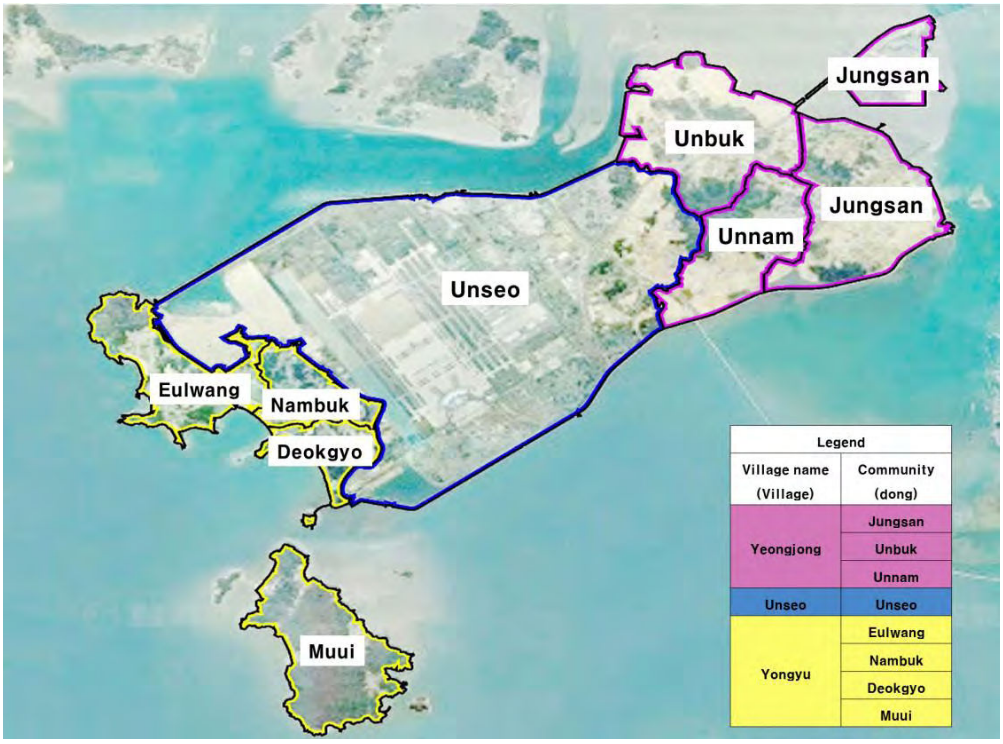


Fig. 4.4 Villages and communities of the Yeongjongdo Island

The total area of study area is 116.77 km^2. And it consists of 14.9 km^2 of agricultural area, 35.9 km^2 of forrest, 2.6 km^2 of park, 0.7 km^2 of industrial zone, 7.4 km^2 of residential area and 15.3 km^2 of public and the other purposes as shown in the table 4.2 below [115].

Table 4.2 Land use data of the Yeongjongdo Island (unit: km^2)

Land use type		Yeongjong	Unseo	Yongyu	Muui	Sum	Remarks
Agriculture	Farm	3.024	1.475	1.505	0.413	7.922	
	Paddy	5.035	1.606	1.425	0.263	9.754	
	Orchard	0.090	0.029	0.032	0.025	0.208	
	Ranch	0.003	0.011	0.000	0.000	0.014	
	Sum	8.152	3.121	2.962	0.701	14.936	
Forest	Forest	10.768	7.311	8.578	9.154	44.389	
	Cemetery	0.041	0.021	0.079	0.022	0.242	
	Sum	10.809	7.332	8.657	9.176	35.974	
Park	Park	0.839	0.665	0.000	0.000	1.504	
	Sports	0.000	0.056	0.000	0.000	0.056	
	Amusement	1.046	0.000	0.000	0.002	1.048	
	Sum	1.885	0.721	0.000	0.002	2.608	
Public	School	0.128	0.270	0.030	0.009	0.467	
	Parking	0.054	0.107	0.000	0.001	0.162	
	Road	2.655	4.028	0.935	0.042	8.595	
	Railroad	0.161	0.468	0.000	0.000	0.629	
	Stream	0.036	0.021	0.003	0.000	0.063	
	Embankment	0.257	0.565	0.018	0.011	0.869	
	Conduit	0.257	1.209	0.091	0.033	1.681	
	Pond	0.335	3.397	0.105	0.040	3.982	
	Waterworks	0.000	0.023	0.000	0.000	0.023	
	Sum	3.883	10.088	1.182	0.136	15.289	
Industry	Industry	0.639	0.000	0.000	0.000	0.639	
	Gas station	0.017	0.010	0.003	0.000	0.033	
	Warehouse	0.005	0.003	0.003	0.000	0.014	
	Sum	0.661	0.013	0.006	0.000	0.680	
Other purposes	Salt-pond	0.846	1.608	0.324	0.000	3.102	
	Fishery	0.047	0.000	0.000	0.000	0.047	
	Church	0.017	0.007	0.008	0.001	0.041	
	Others	2.191	34.353	0.480	0.027	37.531	
	Sum	3.101	35.968	0.812	0.028	39.909	
Residential		4.513	1.624	1.000	0.237	7.374	
Total sum		33.004	58.867	14.619	10.280	116.770	

To generally review the weather statistics, annual rainfall is 1,412 mm, annual average air temperature is 12.5 and the numbers of annual average rainy day are 115 days. The general weather condition of study is shown in the table 4.3.

Table 4.3 Weather statistics in the study area

Items		2007	2008	2009	2010	2011	Average
Air Temperature (℃)	Min.	-13.3	-8.1	-11.4	-12.8	-14.9	-12.1
	Max.	32.5	31.8	33.6	33.2	32.9	32.8
	Average	12.7	12.9	12.8	12.3	12.0	12.5
Rainfall (mm)		1,299.8	1,120.0	1,137.4	1,777.7	1,725.5	1,412.1
Rainy days (days)		97	118	100	125	133	115
Relative Humidity (%)		67.0	68.8	66.0	68.3	66.4	37.3
Daytime hours (hours)		2,092.3	2,012.3	2,284.4	2,075.9	2,150.1	2,123.0
Wind speed (m/s)		2.5	2.6	2.8	3.1	3.0	2.8

4.1.2 Relative Projects

A. Incheon Urban Master Plan (Target Year: 2025)

The urban master plan has been completed and announced in 2010 and currently been under revision in order to concern about additional plan on Incheon Free Economic Zone (hereinafter, referred to as "IFEZ") and so on. And the Yeongjongdo Island as a study area is currently referred to as 'Yeongjong Community Zone' which is specified as center of air logistics and tourism. Therefore there are several plans to enlarge the scale of town and population within 4 phases as in the table 4.4 below. And land use data after phase 4 is described in the table 4.5 [116].

Table 4.4 Summarize of Incheon urban master plan

Development Type		Phase 1		Phase 2		Phase 3		Phase 4		Sum
		Project	Pop.	Project	Pop.	Project	Pop.	Project	Pop.	
Incheon Free Economic Zone				UB[2]	5,000	UB	10,000	UB	5,600	20,600
				YS[3]	20,000	YS	30,000	YS	100,000	150,000
		YM[1]	5,269	YM	4,731	YM	15,000	YM	125,000	150,000
New Town Development Project						YJ[6]	20,000	YJ	30,000	50,000
		US[4]	1,200	US	3,700					4,900
		UN[5]	800	UN	6,500					7,300
Sum	Step Sum		7,269		39,931		75,000		260,600	382,800
	Accumulated		7,269		47,200		122,200		382,800	382,800

1) Yongyu-Muui Culture/Tourism/Leisure City Project
2) Unbuk Leisure Complex Project
3) Yeongjong Sky City Project
4) Yeongjong Rural Area Rehabilitation Project
5) Unseo New Town
6) Unnam New Town

Table 4.5 Land use data after phase 4 of Incheon urban master plan

Land Use Type	Area (km^2)	Remarks
Residential	19.9	
Commercial	13.7	
Industrial	2.7	
Park	6.5	
Sum	42.8	

B. Yeongjong Sky City

The Yeongjong Sky City project is one of major business to enlarge the Yeongjongdo Island's economic scale and population and it is planned by IFEZ. The main purposes of this project are to make following innovative plans;

- Creative city of disposable time where culture, arts, and leisure activities are free
- Future-oriented industrial city where information, technology, and new industries are vitalized
- Multinational city of global exchange that keeps up with the global lifestyle of the 21st century

And it goes to form pleasant low-density living space where Green (park), Blue (sea), White (wind), and Network are harmonized. Such space presents the magnificent view of the sea from all areas. The location of Yeongjong Sky City project in planning is shown in the Fig. 4.5 and land use and population plan are as shown in the table 4.6 and 4.7 respectively. [117]

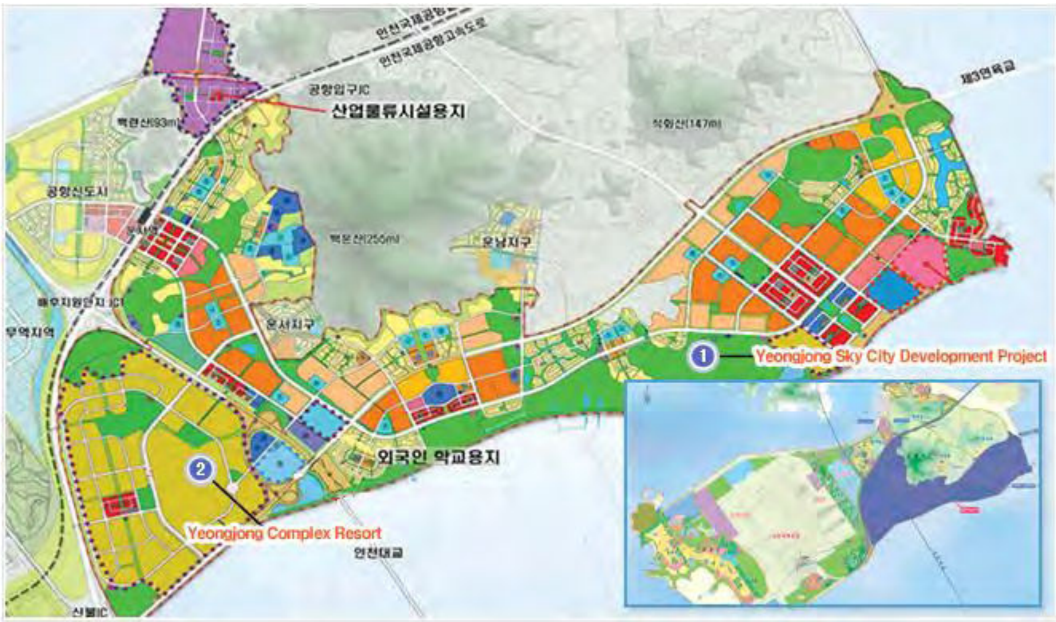


Fig. 4.5 Map of the Yeongjong Sky City plan (source: IFEZ official website, www.ifez.go.kr)

Table 4.6 Population plan of the Yeongjong Sky City plan

Household Type	Area (km^2)	Proportion (%)	Population (person)	Remarks
Detached House	1.49	34.0	3,442	
Apartment	2.76	62.9	43,708	
High-rise apartment	0.14	3.1	1,894	
Sum	4.39	100	49,044	

Table 4.7 Land use plan of the Yeongjong Sky City plan

Landuse type	Area (km^2)	Proportion (%)	Remarks
Residential	4.36	22.5	
Industrial	0.49	2.6	
Commercial	0.72	3.7	
Touristic	0.19	1.0	
Business and culture	0.14	0.7	
Public	10.96	56.8	
Vacant	2.46	12.7	
sum	19.32	100	

C. Midan City Project

The Midan City Project is one of urban development project on northeast part of the Yeongjongdo Island. Similarly to the Sky City, this project should also be concerned in the estimation of environmental change of study area since this project is also planned pretty low developed area of the island and the goal of this project is to make touristic and commercialized area which a huge number of floating populations is expected at. The plan map is shown in the Fig. 4.6 and land use plan is described in the table 4.8. [118]

Fig. 4.6 The plan map of Midan City Project (Source: www. ifez.go.kr)

Table 4.8 The land use plan for Midan City Project (Source: www.ifez.go.kr)

Type	Area (m^2)	Proportion (%)	Remarks
Residential	602,114.7	22.4	
Commercial	311,492.2	11.5	
Touristic	257,648.4	9.5	
Urban Infra.	1,442,254.8	53.4	
The others	86,435.4	3.2	
Sum	2,699,945.5	100	

D. Preliminary Feasibility Assessment of Desalination Project

In order to maximize a possibility of using self-supplying water resources in the Yeongjongdo Island to counter potential risks on water distribution system coming across the sea, there actually are plans to make desalination plant to use sea water as drinking water. Within the purposes above, Incheon Waterworks Headquarter has carried out the preliminary feasibility assessment of overall desalination projects for this island. Desalination projects are as in the table 4.9 and Fig. 4.7 and these projects can be considered as projects to secure additional multi potential water resource. [119]

Table 4.9 Summarize of desalination plant in the Yeongjongdo Island

Items	Project 1	Project 2	Remarks
Location	Unbuk-dong	Deokgyo-dong	
Designed Capacity	50,000 m^3/day	50,000 m^3/day	
Plant Area	50,000 m^2	50,000 m^2	
Cost	70 billion KRW	70 billion KRW	

Fig. 4.7 Location map of desalination plant planned

4.1.3 Official Water Distribution System

This section discusses a water distribution of the Yeongjongdo Island. Water in this island is supplied from Gongchon Water Purification Plant in Incheon city through the submarine pipeline as Fig. 4.8 below. This system includes 2.3 km of submarine pipeline and its designed capacity is 155,600m^3/day. In present state, averaged use of water per day is 40,865 m^3/day and maximum use of water per day is 47,280 m^3/day including the water use in the airport.

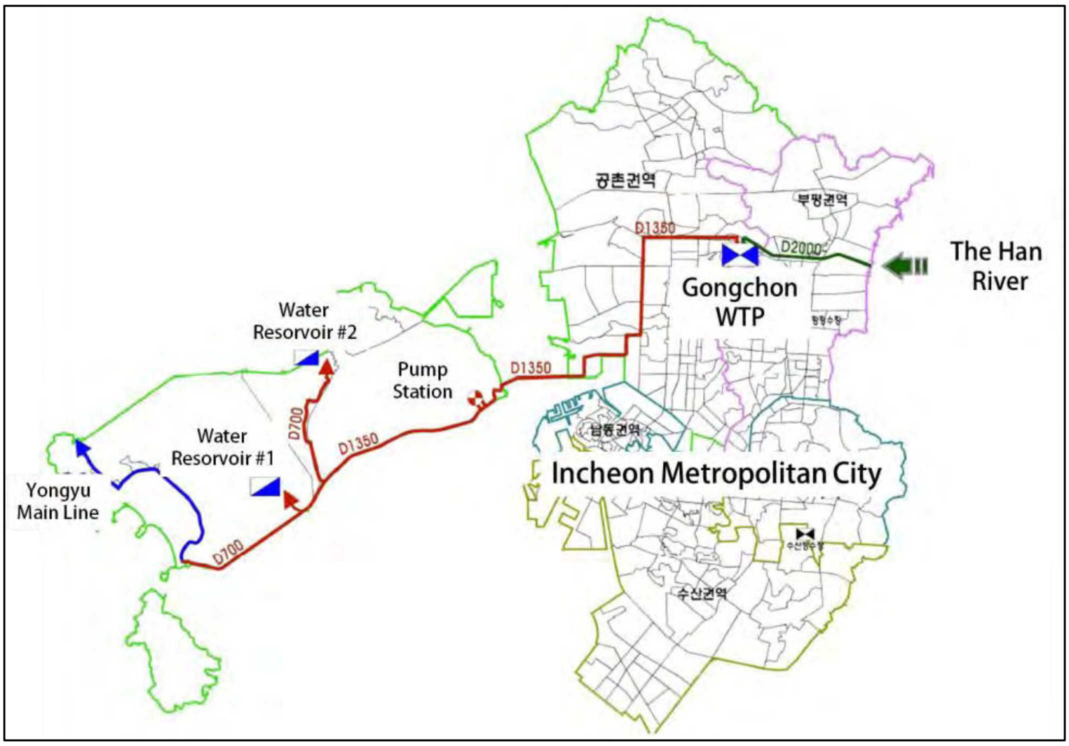


Fig. 4.8 Main pipe line of official water distribution system

There are two water reservoirs which currently exist in the Yeongjongdo Island and 4 more water reservoirs are planned to be installed in the island. According to the Fundamental Plan for Incheon Waterworks Maintenance (2013), water allocated for the Yeongjongdo Island is up to 129,320 m^3/day and the plan estimated the averaged water use as 112,006 m^3/day [120].

4.1.4 Collection System

In the Yeongjongdo Island, there is a waste water treatment plant at Unbuk-dong in Yeongjong village and 5 more plants are under construction or planned as shown in the table 4.10 below with 3 phase's plan of urban master plan[121].

Table 4.10 Current and planned WWTP in the Yeongjongdo Island (Unit: m^3/day)

Plants' name		Phase 1 (2015)	Phase 2 (2020)	Phase 3 (2025)	Remarks
Unbuk	Designed capacity	23,000	23,000	28,000	Operating
	Inflow	12,263	21,329	27,638	
Yeongjong	Designed capacity	24,000	24,000	41,000	Under Construction
	Inflow	12,589	17,304	40,714	
Songsan	Designed capacity	30,000	30,000	46,000	Under Construction
	Inflow	8,104	22,010	45,247	
Yongyu #1	Designed capacity	12,000	12,000	40,000	Planning
	Inflow	6,204	12,408	39,472	
Yongyu #2	Designed capacity	Planned for phase 3 only		13,000	Planning
	Inflow			12,408	
Muui	Designed capacity			11,000	Planning
	Inflow			10,160	
Sum	Designed capacity	89,000	89,000	179,000	
	Inflow	39,160	73,051	175,639	

* Inflow data for future time is estimated value by designed population.
* Source: Basic plan for maintenance of Incheon waste water (2013)

4.2. Application Results and Discussions

4.2.1 Available water resources data from model

The model developed for this study generated 11 sub catchments through the analysis of surface elevation of the island. There are three control points to drain inland water to sea from the Incheon International Airport such as the North, South and East reservoirs so the airport zone is divided into three sub catchment. A sub catchment covering the Donggang stream which is a small river flows across eastern part of the island is also divided into two different catchments because there is the Unbuk reservoir which is irrigation reservoir and compulsory point to check the agricultural water use. Therefore catchments for the Donggang stream are sub catchment of Unbuk reservoir and sub catchment of lower Donggang. And the model separated a catchment for the Unbuk Waste Water Treatment Plant. Following Fig. 4.9 shows the divided sub catchment in the island. The annual runoff generated at each sub catchment is shown in the table 15 and annual runoff on each control point is shown in the table 4.11. And that data set can be used as basic information to calculate water resources available in the whole domain.

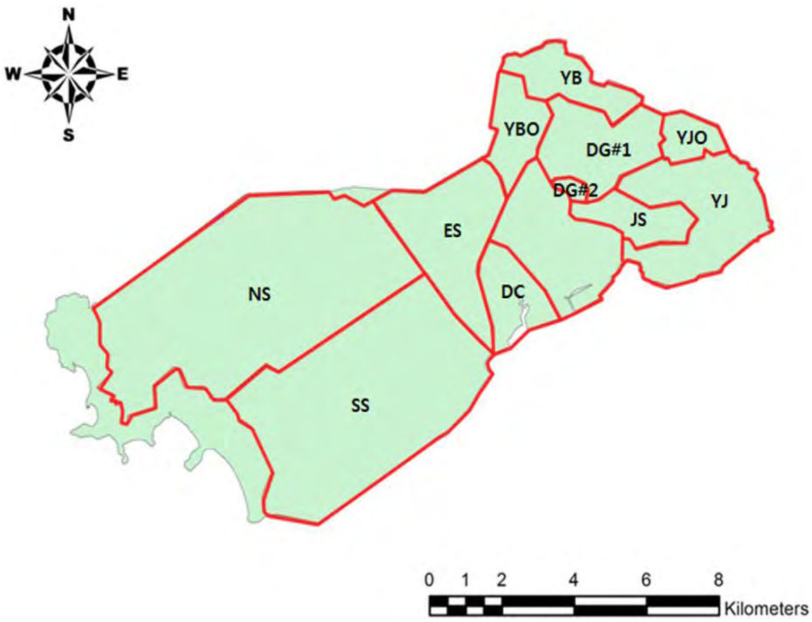


Fig. 4.9 Subcatchments in the Yeongjongdo Island (to be updated)

Table 4.11 Result of runoff modeling

Sub-basin	Characteristics	Annual Runoff (1,000 m^3)	
		2024	2025
NS	Incl. North Reservoir	68,221	44,306
SS	Incl. South Reservoir	65,042	37,454
ES	Incl. East Reservior	39,796	26,698
YB	IFEZ Youngjong (planned)	9,271	3,387
YBO	Incl. Unbuk WWTP	8,182	4,985
DG	Donggang stream	16,217	9,789
YS	Unseo Newtown	33,420	21,280
DC	Milano Design City	9,029	5,374
YJ	IFEZ Yongjong (developed)	42,457	26,577
YJO	Adjoins IFEZ Yongjong	3,992	2,290

There are three irrigation reservoirs such as Unbuk reservoir, Eungol reservoir and Narutgae reservoir. However it seems Eungol reservoir is not being used recently since its neighboring area has been already urbanized but it still exists. According to the modeling, the water elevation is calculated and at the same time the water resources available is also calculated as table 4.12 below.

Table 4.12 Result of water capacity in the reservoirs

Data	Unbuk	Eungol	Narutgae
Capacity (1,000 m^3)	130	21	22
Depth (m)	7	3	3
Available Source(1,000 m^3/year)	237	38	40

There are three retention ponds installed for flood control to protect the Incheon International Airport since the sea around the island has extremely high tidal gap. They are located at south, north and east of the airport as shown in the Fig. 4.10. The water level and capacity have been calculated through modeling and the potential water resources available through the retention ponds as rain water storage are described at the table 17.

Fig. 4.10 Location map of retention ponds

Table 4.13 Result of capacity of retention ponds

Data	North	South	East
Capacity (1,000 m^3)	8,800	6,400	2,040
Depth (m)	5.5	5.5	5
Available Source(1,000 m^3/year)	10,280	7,480	2,380

The streams flowing across the island are two as the Donggang stream and Jeonso stream as shown in the Fig. 4.11. Upstream of the Donggang stream is mixture of natural open channel and concrete covered open channel conduit. And there is a gate to control flood but there is not reliable data on flow regime thus it seems this stream is used as a water way to drain rain water. So is the Jeonso stream which has similar characteristics. The calculation of flow characteristics of those two streams are described in the table 18 below.

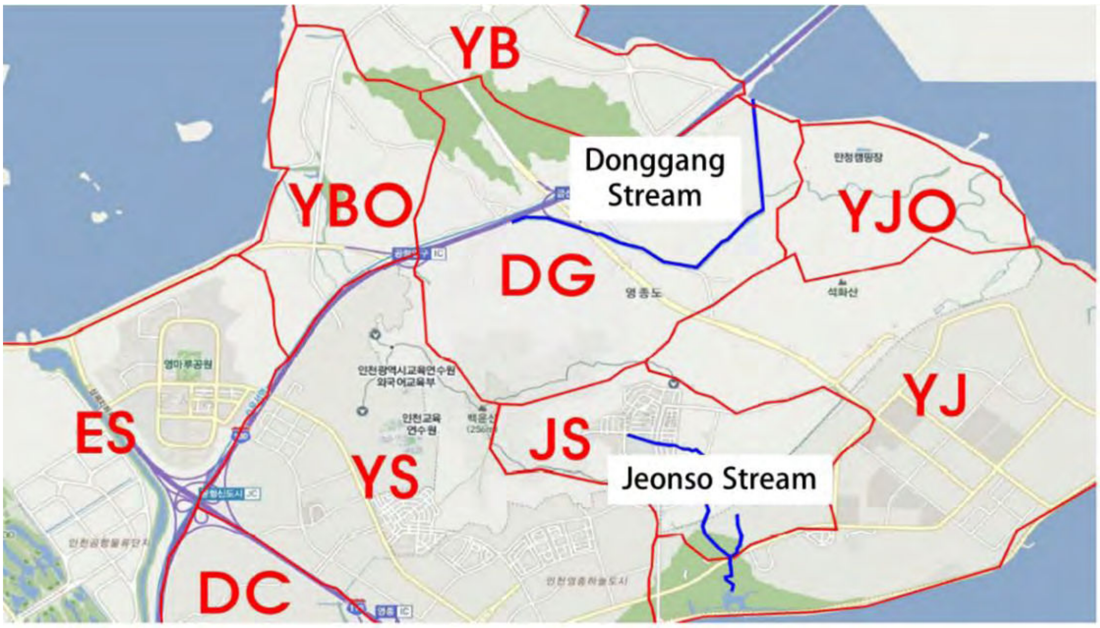


Fig. 4.11 Location map of streams

Table 4.14 Results of water discharge of streams

Items		Donggang	Jeonso	Remarks
Catchment Area (km^2)		8.14	5.25	
Flow Regime (m^3/s)	Minimum flow (Q355)	0.021	0.014	Designed
	Low flow (Q275)	0.049	0.031	
	Six Month flow (Q185)	0.087	0.055	
	Maximum flow (Q95)	0.166	0.107	
Annual Runoff (1,000 m^3/year)	Flood Season	3,630	2,816	Calculated
	Dry Season	2,630	899	
Water Resources (1,000 m^3/year)		9,890	6,089	

The Donggang stream catchment has 33.5% of agricultural area as 2.73km^2 at downstream area and the Jeonso stream catchment has 24.2%. However there is not a facility for irrigation use of stream water in those two streams. As long as there is not an additional project to secure more water in the stream, it easily be declined to be included in the multi water source project because the total amount of water from streams is very little.

4.2.2 Additional Sources from literature study

Ground water in the Yeongjongdo Island has been surveyed through preliminary studies such as "The 3rd Fundamental Plan on Ground Water Management in Korea (2012-2021)" (GIMS, MLTM), "2007 Ground Water Management Plan in Incheon Metropolitan City" (Incheon) [122][123]. Within accordance of the literature review of those reference papers on ground water, it could be calculate the quantity of ground water available and ground water uses as shown in the table 4.15 below.

Table 4.15 Summarize of ground water (unit: 1,000 m^3/year)

Village	No. of Wells	Recharge	Source Available	Source Used	Rate of Use	Additional Source Available	Remarks
Unseo	323	9,056	6,322	772	12	5,550	
Unnam	456	1,129	788	1,180	150	-	
Unbuk	398	1,685	1,177	859	73	318	
Nambuk	208	793	554	328	59	226	
Deokgyo	191	608	425	576	136	-	
Muui	73	2,106	1,470	198	13	1,273	
Total	1,649	15,377	10,736	3,911	36.4	6,824	

There is a waste water treatment plant at Unbuk-dong in the Yeongjongdo Island and currently 10-25 % of treated waste water is recycled for the purpose of industrial water. As well as, there are planned waste water reuse project for two streams instream flow and potential quantity of reuse can be calculated with the plans to build additional plants within the target year 2025 as shown in the table 4.16 below.

Table 4.16 Summarize of treated waste water (unit: 1,000 m^3/day)

Name of WWTP	Designed Capacity	Expected Real Capacity	Planned Internal Use	Gray Water Available	Remarks
Unbuk	28	22.4	2.2	20.2	
Yeongjong	41	32.8	3.3	29.5	
Songsan	46	36.8	3.7	33.1	
Yongyu #1	40	32.0	3.2	28.8	
Yongyu #2	13	10.4	1.0	9.4	
Total	168	134.4	13.4	121.0	

Additional water source available is desalinated sea water. As described in the previous chapter, Incheon Waterworks Headquarter is planning to build desalination plants as the table 4.17.

Table 4.17 Potential plan for desalination plants in the study area

Items	Project 1	Project 2	Remarks
Location	Unbuk-dong	Deokgyo-dong	
Designed Capacity	50,000 m^3/day	50,000 m^3/day	
Plant Area	50,000 m^2	50,000 m^2	
Cost	70 billion KRW	70 billion KRW	

4.2.3 Result from prediction of water demand

A. Domestic water demand

In order to predict the domestic water demand, the change of population including the floating population to use the Yeongjongdo Island as their work space or touristic venue and Incheon International Airport. Thus it is important to review the development plan for the island itself and the airport. So this calculation has been done within accordance of the plans to develop this area as described in the previous chapter. As the target year of this water balance management is year 2025 and planned population of the Yeongjongdo Island in the target year is 382,800 persons. According to the plan of water demand management in Incheon Metropolitan City, daily maximum water use per capita for residential use has been calculated as 393 L/capita/day in year 2025. Within those statistical data and the water demand prediction modeling, water demand could be calculated at each district as the table 4.18 below.

Table 4.18 Predicted domestic water demand (unit: m^3/day)

District	2014	2020	2025	Remarks
Unseo	6,500	5,900	6,300	
Yeongjong	9,600	26,600	79,300	
Unbuk	0	5,900	8,300	In 2014, included in Yeongjong
Yongyu	3,500	7,900	48,200	
Muui	900	2,000	12,100	
Sum	20,500	48,300	153,900	

However, a floating population using the international airport or working in the airport have been excluded in the demand prediction. There also is a water use within the airport and airplane wash. Therefore the water demand in the airport must also be included in the assessment and the data calculated through Incheon Waterworks Maintenance Basic Plan as table 4.19 below.

Table 4.19 Prediction of floating population and water demand

	2014	2020	2025	
Floating population (person/year)	43,234,000	55,699,000	68,882,000	
Water Demand (m^3/day)	15,995	26,527	29,097	Only from official water distribution system

B. Industrial water demand

The industrial complex in the Yeongjongdo Island is planned as 494,000m^2 for year 2020 in the Yeongjong Sky City project. The list of industries and their water demand calculated through the model is as table 4.20 below.

Table 4.20 Result from prediction of industrial water demand

Type	Area (m^2)	Per unit Water demand (m^3/1,000 m^2/day)	Water Demand (m^3/day)	Remarks
Transport Service	42,000	2.89	120	
Transport Business	92,200	3.59	330	
Machinery	226,200	4.95	1,120	
Communications	32,400	14.62	470	
Computer	101,200	14.62	1,480	
Sum	494,000		3,520	

As summarize, the water demand modeling calculated water demands in the target years as table 4.21 for daily maximum water use.

Table 4.21 Summarize of water demand prediction result (unit: m^3/day)

Zone	2015			2020			2025		
	Res.1)	Ind.2)	Sum	Res.	Ind.	Sum	Res.	Ind.	Sum
Unseo	6,500	-	6,500	5,900		5,900	6,000		6,000
Airport	16,000	-	16,000	26,500		56,500	29,100		29,100
Yeongjong	9,600	-	9,600	26,600	3,500	30,100	79,300	3,500	82,800
Unbuk	0	-	0	5,900		5,900	8,300		8,300
Yongyu	3,500	-	3,500	7,900		7,900	48,200		48,200
Muui	900	-	900	2,000		2,000	12,100		12,100
Sum	36,500	-	36,500	74,800	3,500	78,300	183,000	3,500	186,500

1)Res.: Residential water
2)Ind.: Industrial water
*Residential water includes airport water

C. Agricultural water demand

As shortly mentioned in the previous chapter, instream water, gardening water and surface washing water which represent the major consumer of recycling water (or gray water) are included in the agricultural water demand in this study so that the recycling water can be used as supplementary water in case of emergency status such as a drought event. However, this study separately achieves the prediction of agricultural water demand from the others and instream water, gardening water and surface washing water would be included at the end of this chapter.

The agricultural water demand has been predicted through this study with the scenario based analysis method since the development plan of this area shows dramatic change of land use characteristic. There are 14.94 km^2 of agricultural area in a whole island. Within the area of each product, agricultural water demand has been calculated as table 4.22 below.

Table 4.22 Expected scale of agricultural zone and water demand

Village	Area (km^2)	Water Demand (1,000 m^3/year)	Remarks
Yeongjong	8.15	3,985	
Unseo	3.12	3,355	
Yongyu	3.66	2,017	
Muui	0.70	954	
Total	16.66	10,311	

In order to complete the agricultural water demand in the whole domain, gardening water and surface wash off water should also be calculated. They can be estimated through reviewing the current situation and future plan of land use by checking the area of urbanized zones and parks multiplying per area water use. And they are calculated as table 4.23 below.

Table 4.23 Agricultural water demand including gardening and washing water

Village	Agricultural Water (1,000 m^3/year)	Gardening and Washing Water (1,000 m^3/year)	Total	Remarks
Yeongjong	3,985	738	4,723	
Unseo	3,355	157	3,512	
Yongyu	2,017	563	2,580	
Muui	954	-	954	
Total	10,311	1,458	11,769	

So the total water demand in the whole island is determined as table 4.24 below.

Table 4.24 Summarize of total water demand calculated at the Yeongjongdo Island

Purpose	Demand (1,000 m^2/year)	Remarks
Domestic Water	46,830	
Airport	10,622	
Industrial Water	1,278	
Instream Water	3,285	
Agricultural Water	10,311	
Gardening and Washing	1,458	
Total	73,780	

4.3. Water Balance Assessment

From what has been calculated through the modeling, available water resources for self-supply are summarized in the table 4.25.

Table 4.25 Summarize of total water resource available

Source	Resource Available (1,000 m^3/year)	Remarks
Streams	15,979	
Ground Water	6,824	
Reservoir	277	
Retention Pond	20,140	
Desalination Plant	36,500	Not confirmed to be installed
Treated Waste Water	44,165	Not for potable water
Total	123,885	87,385, if desalination plants won't be installed

According to the water resources and demands analyzed through this study, the total quantity of water can cover fully self-sufficient water supply in the study area. However different types of water demands have different minimum quality requirement to meet for water supply and very limited water source can meet full coverage of water quality requirement. For example, water taken at streams or ground water can be used as drinking water with sufficient water purification process but treated waste water can never be used as drinking water due to safety problem of water quality and aesthetic factor of consumer. Therefore water resources should be classified into appropriate purposes of water use. As well as, types of water demand should also be classified into quality necessary to meet the purpose.

It is necessary to secure the quality of drinking water if the water demands are for domestic use of water, water used for airport service and sometimes industrial use of water. And the drinking water quality can be produced from well protected water resources through special water purification process. In this study area, a ground water and desalination plant can provide the necessary quality. In addition, it is also possible to secure the drinking water quality from streams, reservoirs and retention ponds since the water from the selected source is mainly filled with rainfall water however very intensive care to protect the source and high class purification process such as reverse osmotic which occasionally require very high cost. So it is possible to see four different scenarios to check the water balance in this study area as shown in the table 4.26.

Table 4.26 Scenarios of water balance assessment

Type	Desalination Plant	Additional High-Level Treatment	Multi Source with additional purification	Remarks
Scenario 1	X	X	X	
Scenario 2	X	X	O	
Scenario 3	X	O	O	
Scenario 4	O	O	O	

The first scenario is same as the current situation with fully receiving official water supply without self-sufficient water resources. The pipe line crossing the sea has actually enough capacity to cover the full capacity of water demand in the study area although there are several potential risks on water supply system. It will be necessary to develop a plan to secure the safety of water supply system and some additional water supply reservoir to cover the growth of urbanization and population.

The second scenario is using part of water resources available for drinking purpose. The ground water can be used as drinking water after normal water purification process. The result of water balance assessment is shown in the table 4.27. And the self-sufficient water supply is calculated as 12 % for drinking water. And it is still necessary to take water from water purification plant and submarine pipe line for additional 88% of drinking water.

Table 4.27 Water balance on scenario 2 (unit: 1,000 m^3/year)

Quality	Demand	Available Source	Shortage	Remark
Potable	58,730	6,824	51,906	12% self-sufficient
Not potable	14,100	80,561	-	
Total	72,830	87,385	51,906	

The third scenario is using the potential water resources as drinking water which is always short. It is necessary to build additional and advanced facilities to treat water for potable purpose however the self-sufficient for drinking water supply could be increased up to 74%. Therefore it is possible to minimize the water supply through the submarine pipeline and it can be possible to keep the water from inland purification plant as emergency purpose. The results are summarized in the table 4.28.

Table 4.28 Water balance on scenario 3 (unit: 1,000 m^3/year)

Quality	Demand	Available Source	Shortage	Remark
Potable	58,730	43,220	15,510	74% self-sufficient
Not potable	14,100	44,165	-	
Total	72,830	87,385	15,510	

The forth scenario is securing the sea water desalination plant as the scenario of preliminary feasibility assessment of desalination project described in the study area chapter. For the time being, it is not very sure of the feasibility of this project but this scenario concern about two desalination plants planned through the project. In accordance of this scenario, water can fully self-sufficient in the study area. However it is necessary to check if it is possible for the real situation since it must be require very high budget to install fully equipped facilities. The results are summarized in the table 4.29.

Table 4.29 Water balance on scenario 4 (unit: 1,000 m^3/year)

Quality	Demand	Available Source	Shortage	Remark
Potable	58,730	79,720	-	100% self-sufficient
Not potable	14,100	44,165	-	
Total	72,830	123,885	-	

This study assessed the water balance of the study area however it is difficult to say what scenario is optimal for real situation.

Chapter 5 Suggestion of Smart Water Management Plan for Study Area

5.1. Definition of the Scenario

According to the water balance assessment analyzed through previous chapter, there are many multi water sources to use. However, only limited water resources are currently being used in the study area. Therefore this study suggests the way countering water shortage problem by using multi water sources through some specific scenarios within the assumption of accident at the current water supply system.

First of all, it is necessary to describe some assumptions on the scenario to make more realistic scenario. The sea water desalination plants, described through the preliminary feasibility study, are not included in this scenario as future multi source since the probability of their installation is non-realistic as the plan has been almost suspended. Instead, the desalination as a part of smart water treatment is concerned as an option to counter the water problem.

Securing technology of existing water resources is limited to single source of water. However, through the various studies regarding on the Smart Water Management, several water treatment technologies to improve efficiency and to save energy for water treatment have been discovered through combination of water treatment process and water source blending technology based on intelligent and smart management. Water treatment process should be organized existing surface water (river water, lake water, etc.), rainwater, ground water, sewage water, sea water, and so on through the replaced water resource from water blending. In water treatment process, water blending can be distributed in each unit process and treatment water is possible to use when there is not available enough water. The smart water treatment process is summarized through the Fig. 5.1 [124].

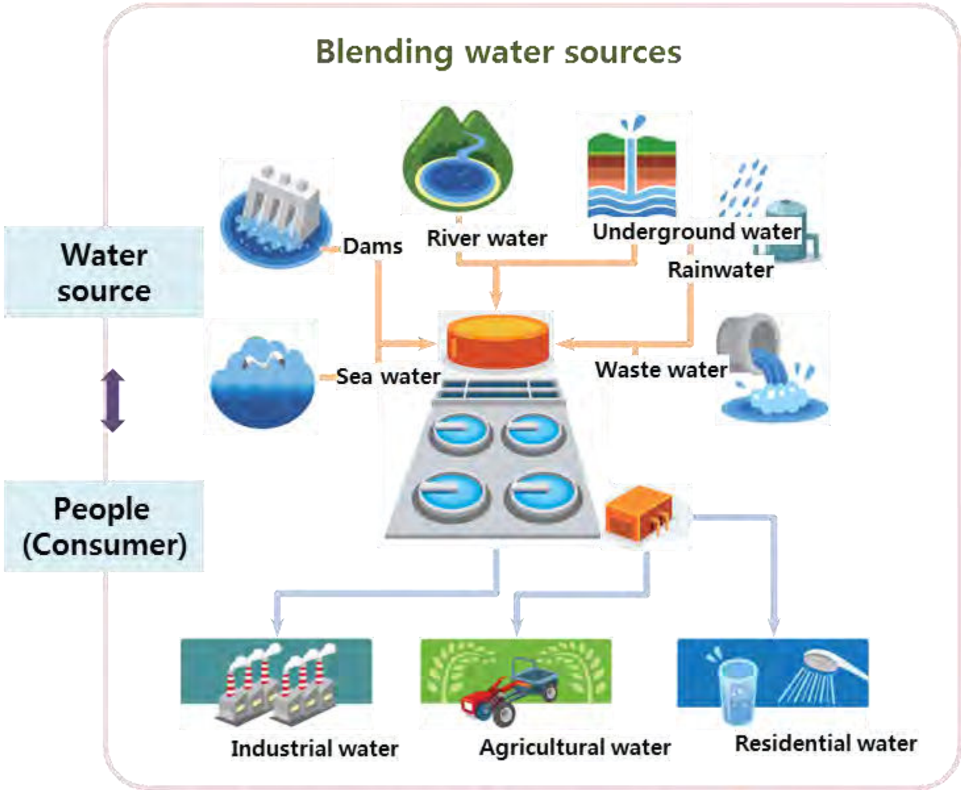


Fig. 5.1 Conceptual diagram for smart water treatment process

As well as, the land cover type of the study area is assumed as the major plans on urban development and water related designs. And the proportions on several different purposes of land use to calculate the water demand would also be followed the land cover. However, none of them includes the variation of agriculture. The only information is the size of agricultural zone in the study area as integrated agricultural products. Therefore, the next assumption is that the detailed information on agriculture at the study area is not been changed from current states. The condition on collection systems (waste water treatment plants) and water distribution system can be assumed as the plans on those water systems are favorably carried out and it is under operation as designed states unless there is an accident. However, the water purified through drinking water treatment process can be circulated through the smart water supply system within concept of water loop system and gray water treated in the waste water treatment plant can be circulated through gray water loop within the same concept of water loop [125].

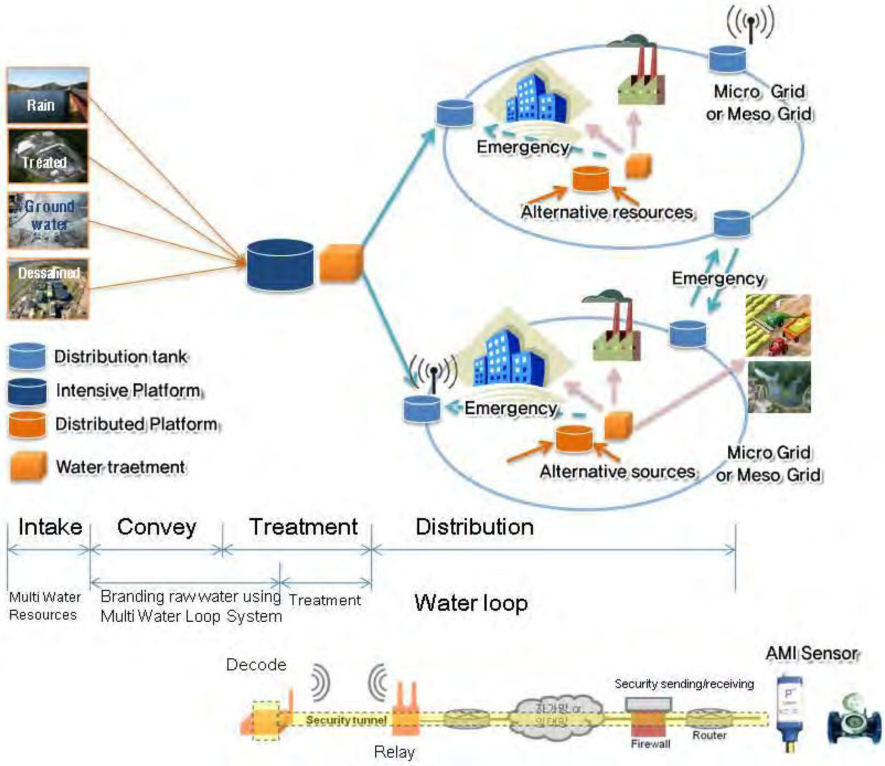


Fig. 5.2 Conceptual diagram for smart water loop

The first scenario is an accident at the water pipe coming across the sea. This scenario can be assumed easily and it is simple however it can be a huge problem since the sub marine pipe line is the only way to transport drinking water for the island itself and the airport. As actually described in the general information of study area, the water supply system of the Yeongjongdo Island depends on the single pipe line. It is 2.3 km long and its current capacity is 155,000 m^3/day. It has been installed in November, 1999 by Incheon International Airport Corporation and currently under the management of Incheon Waterworks Headquarter. For the time being, there has not been experienced an accident since its installation however there are several risks. According to the past experience on the submarine pipe line, there have been several accidents occurred due to ship anchoring, fishery activities and trouble of pipe line itself and those accidents cause cutting off the water supply as shown in the table 5.1 [126][127].

Table 5.1 Examples on accidents of submarine pipe line

Location	Time	Dimension	Length	Action	Remarks
Eobul Island	07/2010	150	0.6	Damaged on Pipeline during fishing activities 5 days cut off the water	Korea
Samma Island	04/2010	200	3.8	Damaged on Pipeline during fishing activities Long term maintenance with cutting off the water supply	Korea
Takamatsu	05/2002	100	3.5	Damaged on Pipeline during fishing activities Several accident during 3 years (1999~2002) Maximum 4 months cut off	Japan
Yeongjongdo	-	1,350	3.4		(Study Area)

As described in the table 5.1, it takes long time maintenance once the accident occurs. Submarine pipe line supplying water to the Yeongjongdo Island has been installed through the towing method of submarine pipeline. This method has advantage on economical point of view but has disadvantage on difficulties on maintenance after installation. If the accident occurs, it is so inevitable to cut off the water supply during minimum 5 days and maximum several months in accordance of previous experience. However, the Yeongjongdo Island as the study area has a specialty that the existing of Incheon International Airport which is Korean major airport in the area and is under special national protect and this fact works as one of reasons which there has never been a single accident due to. Therefore, although there is an accident on pipeline, it will take no longer than the other case studies to fix the problem. Thus, the assumption of cut off time in this study would be specified as 3 days.

$$\mathrm{W_B} = W_A - W_D$$

$$\mathrm{W_A} = W_E + W_O + W_M$$

5.2. General Status on Water in the Study Area

For an application of the technologies of Smart Water Grid, the study area has been divided into two different zones as water grid as Fig. 5.3. The first grid is eastern part of the island. This grid includes Yeongjong district which used to be a traditional island before the reclamation projects, Yeongjong Sky City, Unbuk new town and Airport new town. The second grid is western part of the island including the Incheon International Airport Yongyu district and Muui district.

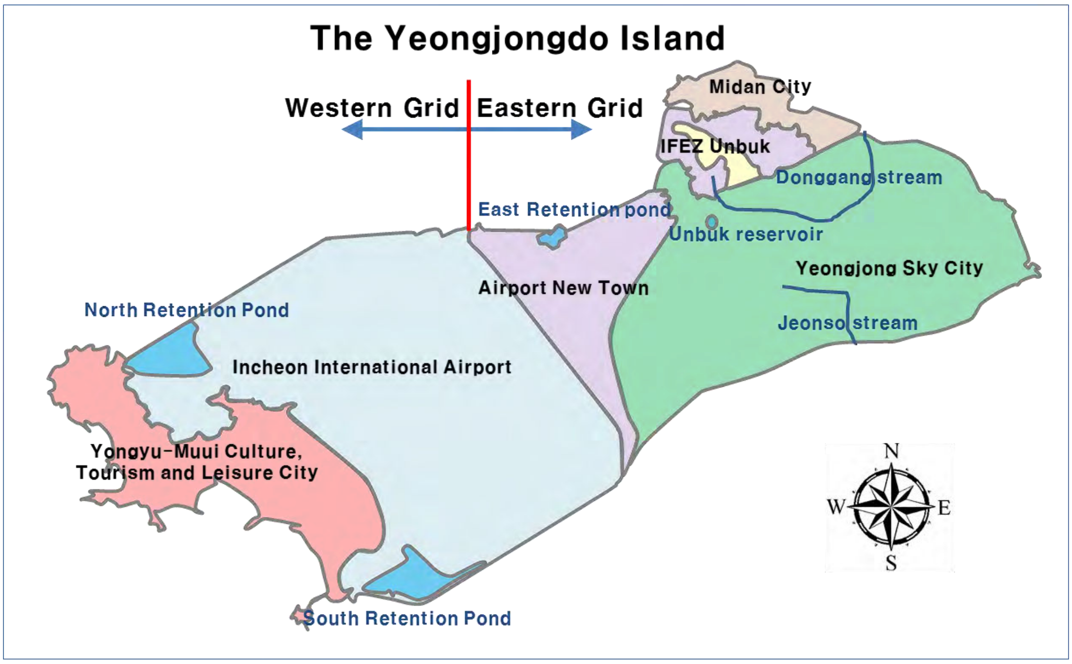


Fig. 5.3 The division map of western and eastern grid in the study area

There are currently two reservoirs under operation and four more reservoirs under planning or construction. However, these reservoirs under planning or construction would be completed in the target year (i.e. year 2025). And basically, ground water and gray water is being used as minor water resources. As per described in the previous study area chapter, this study includes waste water treatment plants under planning and construction. Therefore, if the accident occurs, the water resources available can be described as table 5.2.

Table 5.2 Basic water available at each grid (unit: m^3)

	Eastern Grid	Western Grid (incl. Airport)	Remarks
Water stored at the reservoirs	66,000	54,000	Assuming the maximum capacity
Ground water	12,135	2,770	Daily availability
Gray water	82,800	38,200	
Total	160,935	94,970	

However, if there is not a facility for water treatment and distribution, ground water and gray water can only be supplied very limited area. So the real basic water available is only the water stored at the reservoir in this case.

Although the accident occurs, water demand of study area cannot easily be reduced unless the number of water consumer is not changed. Therefore water consumption at each grid can be described as table 5.3.

Table 5.3 Water demand at different grids (unit: m^3/day)

Grid	Domestic	Industrial	Agricultural	Others (Non-drinking)	Total
Eastern	70,100	3,500	20,110	2,452	96,162
Western	52,800	-	8,140	1,543	62,483
Total	122,900	3,500	28,250	4,085	158,645

The first priority of water use is definitely drinking water and the agricultural water demand occasionally can be non-drinking water. Even if the drinking water is only the one considered to be covered, it is not sufficient for even a single day use of water with the existing water. Therefore it is necessary to consider multi water source for covering water demand.

As analyzed in the previous water balance assessment, multi water sources available in this study area are all around the island. There are ground water and gray water which already have been described in the table 5.2. As well as, there are 2 streams, a natural reservoir and a retention pond in the eastern grid and 2 retention ponds are located in the western grid as described in the table 5.4.

Table 5.4 Summarized table for multi water sources at each grid (unit: 1,000 m^3/year)

Grid	Streams	Natural Reservoir	Retention pond	Total
Eastern	15,979	237	2,380	18,596
Western	-	-	17,760	17,760
Total	15,979	237	10,140	

5.3. Water Sources Available in Eastern Grid

In the eastern grid in this island, there are 2 streams, a natural reservoir and a retention pond. There actually is not a spring which provides water to streams or ponds within regularly basis. Therefore the water volume at each source must be depending on the precipitation. So the result from the rainfall-runoff computation is very important to estimate the water available volume at the source points.

The first source is the Donggang stream. In year 2025, the maximum flow discharge is occurred in May and it is 9.8 m^3/s as shown in the Fig. 5.4. And the total water volume from the Donggang stream is 13,160 m^3 as shown in the Fig. 5.5.

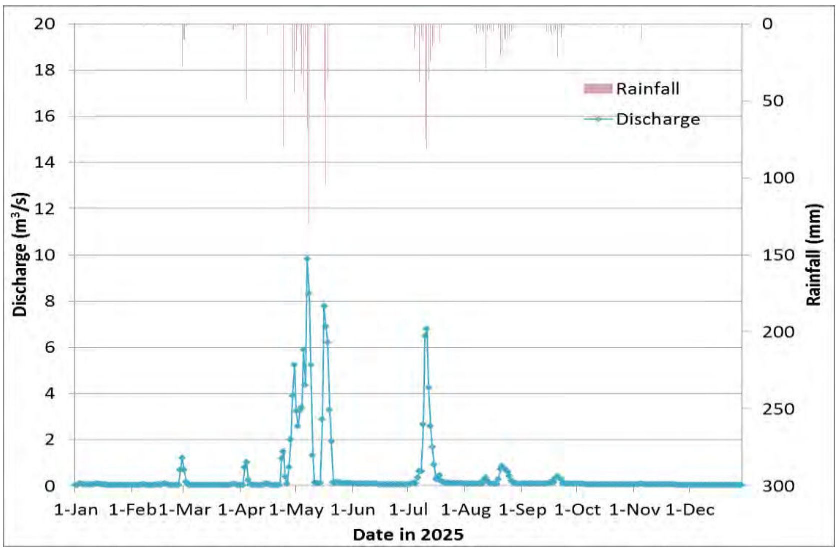


Fig. 5.4 Daily flow discharge of the Donggang stream

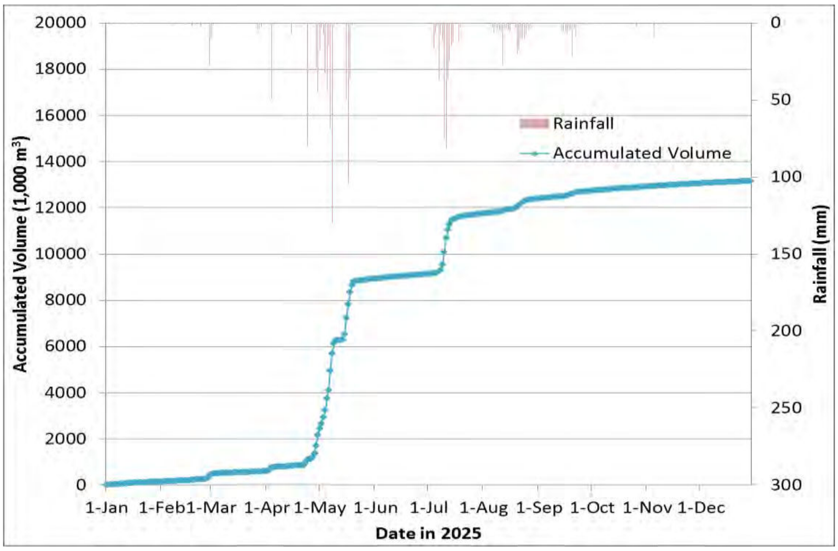


Fig. 5.5 Accumulated water volume of Donggang Stream

The second source is the Jeonso stream. In year 2025, the maximum flow discharge is occurred in May and it is 4.7 m^3/s as shown in the Fig. 5.6. And the total water volume from the Jeonso stream is 6,183 m^3 as shown in the Fig. 5.7.

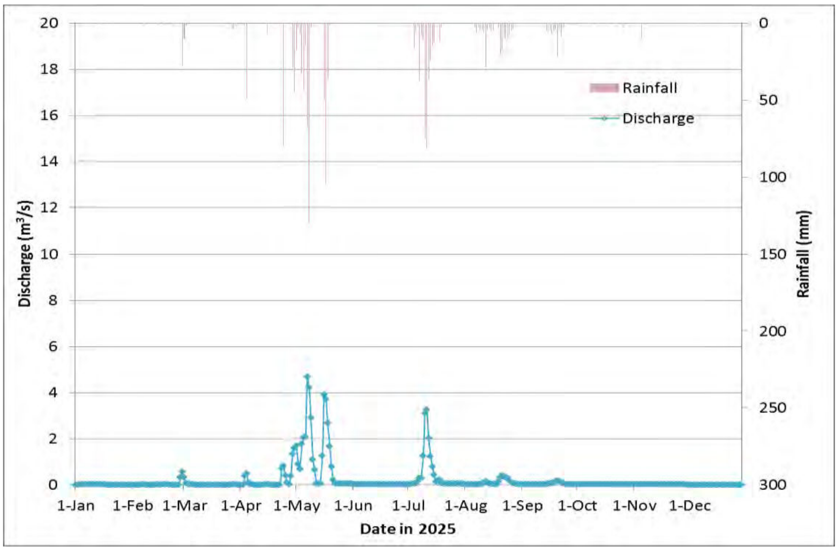


Fig. 5.6 Daily flow discharge of the Jeonso Stream

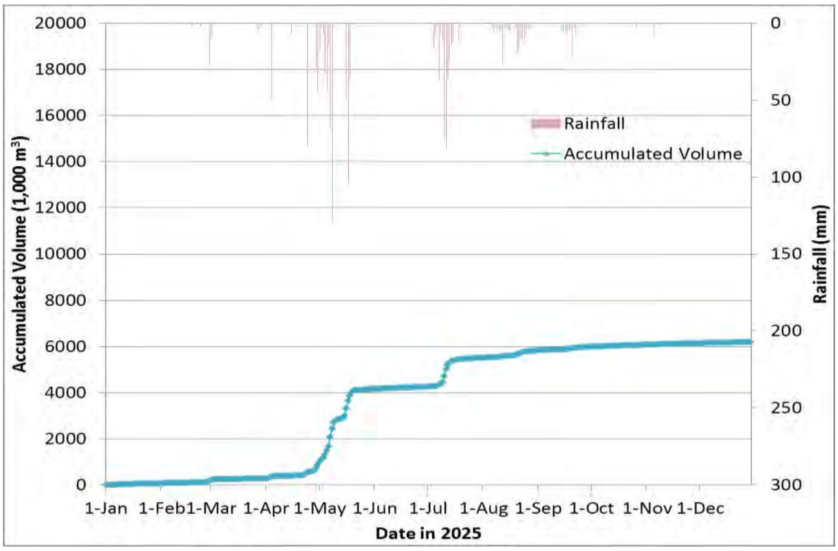


Fig. 5.7 Accumulated water volume of Jeonso Stream

The third source is the Unbuk reservoir. In year 2025, the maximum flow discharge is occurred in May and it is 0.71 m^3/s as shown in the Fig. 5.8. And the total water volume from the Unbuk reservoir is 837 m^3 as shown in the Fig. 5.9.

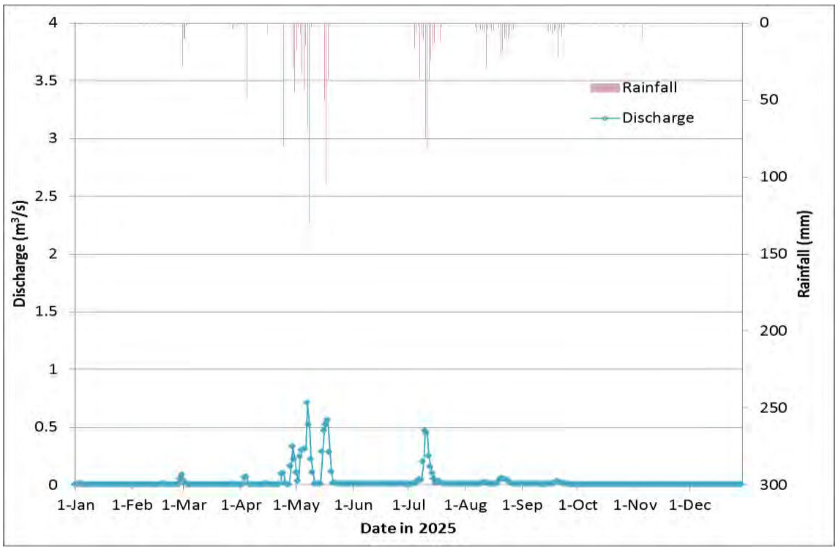


Fig. 5.8 Daily flow discharge of the Unbuk reservoir

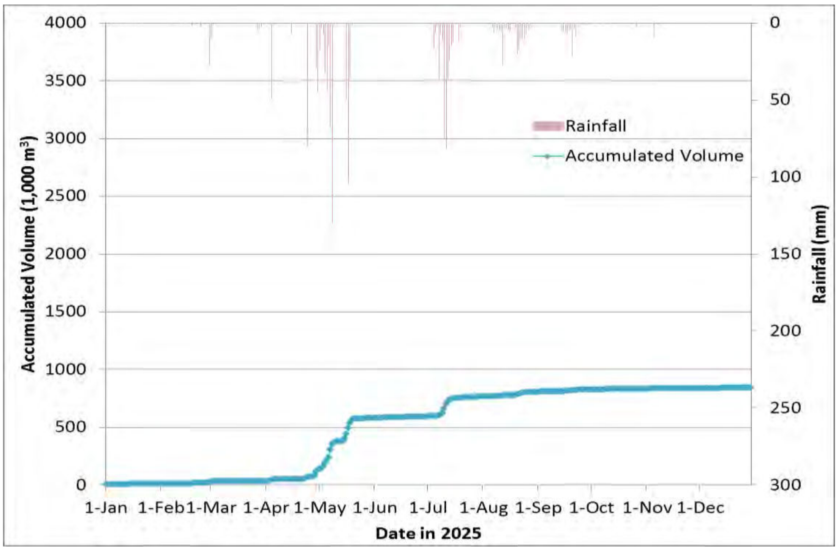


Fig. 5.9 Accumulated water volume of Unbuk reservoir

The forth source is the East retention pond. In year 2025, the maximum flow discharge is occurred in May and it is 26.4 m^3/s as shown in the Fig. 5.10. And the total water volume from the East retention pond is 39,259 m^3 as shown in the Fig. 5.11.

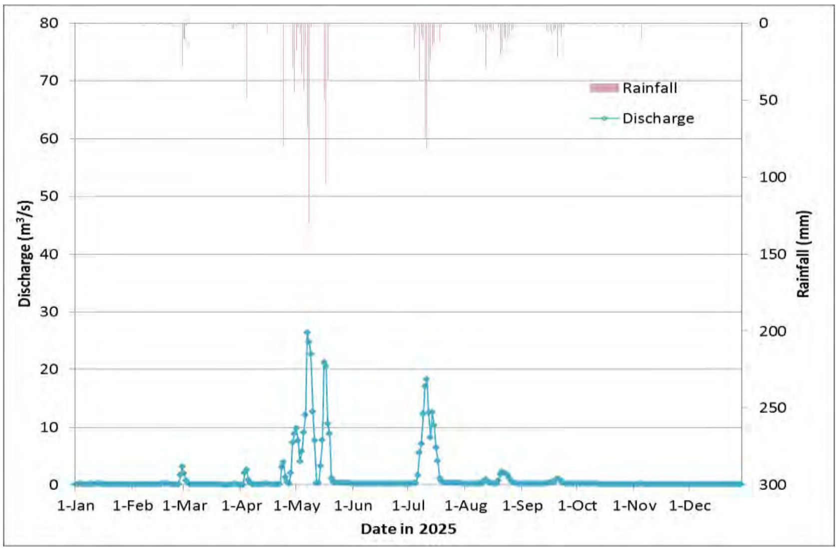


Fig. 5.10 Daily flow discharge of the East retention pond

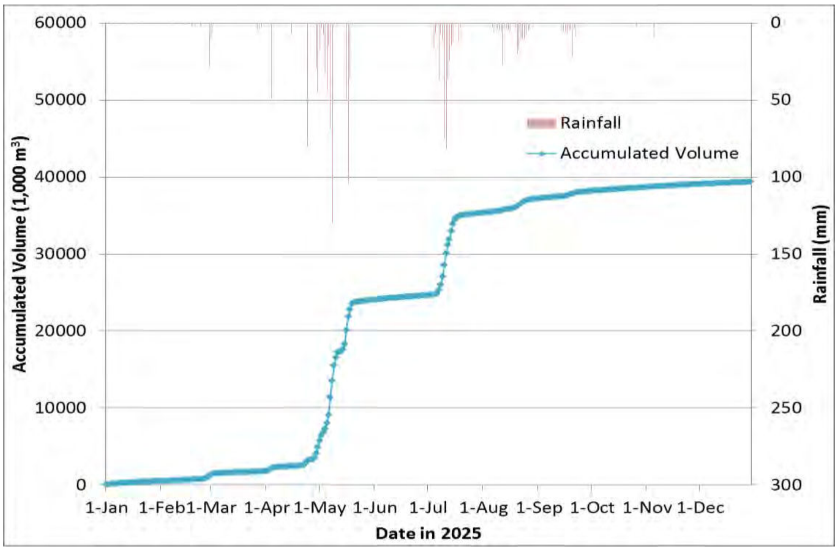


Fig. 5.11 Accumulated water volume of East retention pond

Within consideration of the rainfall runoff result, it seems that the water from the multi water sources is sufficient to cover the water demand. However, the storage of Unbuk reservoir is too little and the water from the stream is flowing to the sea. Therefore it is necessary to concern about additional facility for optimal use of multi water source.

5.4. Water Sources Available in Western Grid

In the western grid in this island, there are 2 retention ponds. Although there actually is not a spring which provides water to streams or ponds within regularly basis, the storage volume of ponds are huge comparing with the sources of eastern grid and ponds themselves can be used is nice storage platform. Similarly to the eastern grid the water volume at each source must be depending on the precipitation. So the result from the rainfall-runoff computation is very important to estimate the water available volume at the source points.

The first source is the North retention pond. In year 2025, the maximum flow discharge is occurred in May and it is 48.1 m^3/s as shown in the Fig. 5.12. And the total water volume from the North retention pond is 55,247 m^3 as shown in the Fig. 5.13.

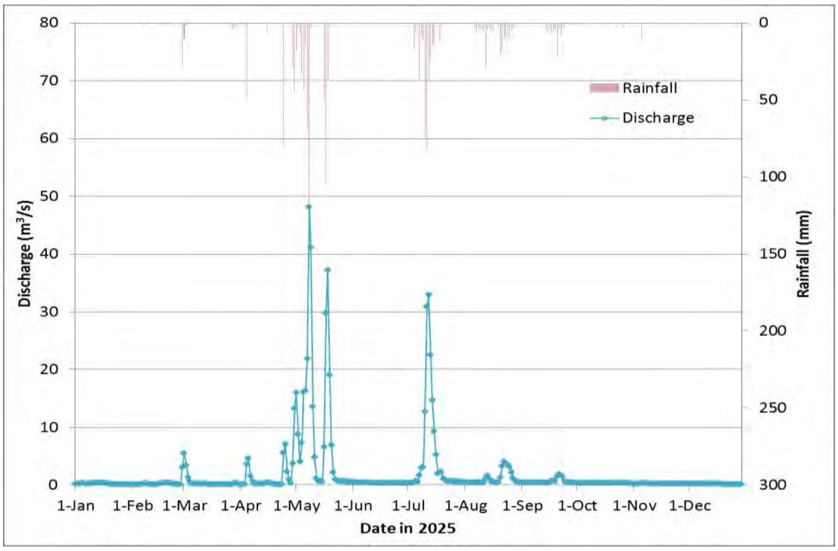


Fig. 5.12 Daily flow discharge of the North retention pond

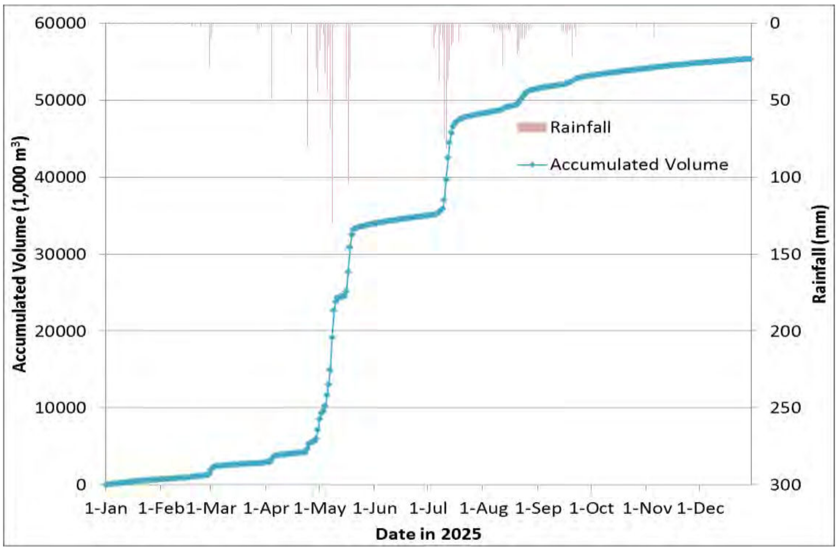


Fig. 5.13 Accumulated water volume of North retention pond

The second source is the South retention pond. In year 2025, the maximum flow discharge is occurred in May and it is 39.3 m^3/s as shown in the Fig. 5.14. And the total water volume from the South retention pond is 51,398 m^3 as shown in the Fig. 5.15.

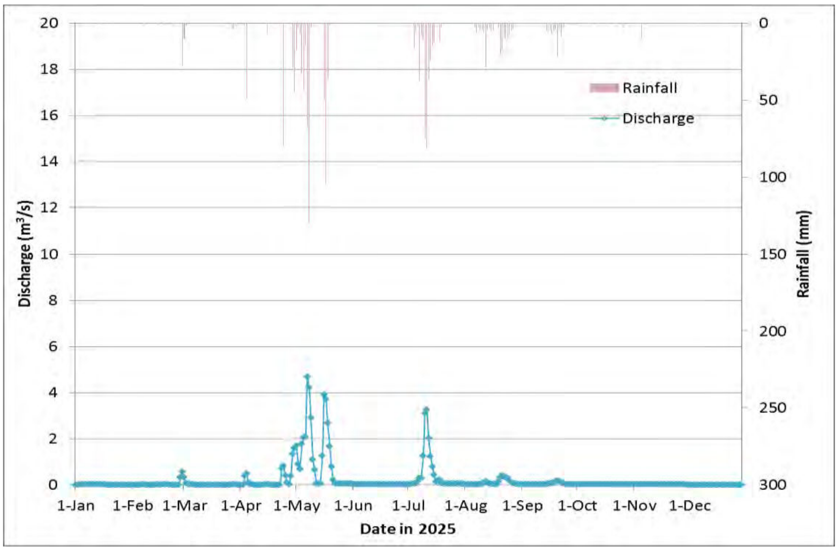


Fig. 5.14 Daily flow discharge of the South retention pond

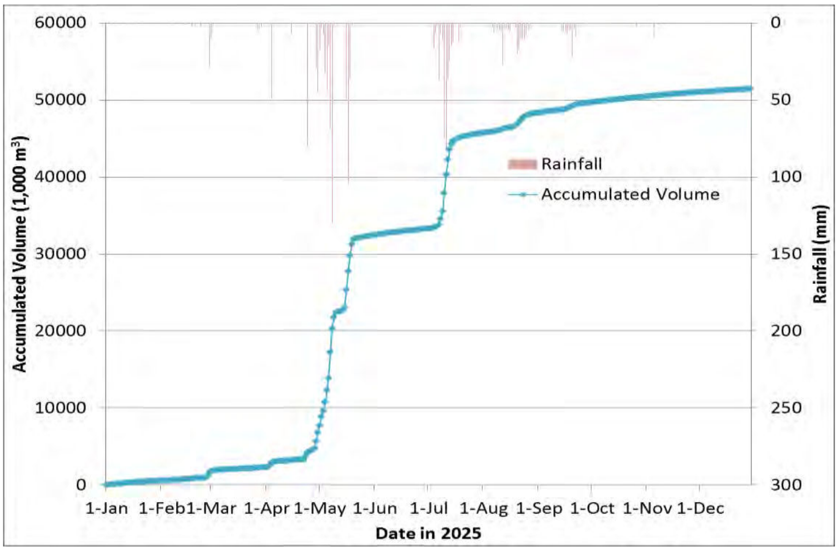


Fig. 5.15 Accumulated water volume of South retention pond

In the western grid, it seems that the total amount of water can cover the water demands if the appropriate water treatment process can be applied in this domain.

5.5. Smart Water Supply Plan

According to the results of water resources simulation, it is proved that the total quantity of water which can be used as alternative water resource is sufficient to cover water demand in the study area. However, the quantity of water is varied continuously day by day and this quantity varied cause the instability of water supply. And the water distribution system should secure certain water quality through stable water quality of source and indisputable water treatment process. Thus, some additional facilities such as water treatment plant and water storage platform for stable procure of both water quantity and quality. This chapter discusses the suggestion of water distribution plan within the concept of smart water management.

5.5.1 Water Balance of Eastern Grid

Water sources of eastern grid are analyzed at four different spot such as a reservoir and a retention pond which are able to be both water source and water storage and two streams which flow to the sea and available only at which intensive precipitation occurs. So it is basically not possible to use the water from streams without additional storage facility. As well as, it is also necessary to concern about a possibility of use of the Unbuk reservoir since the quantity of water resource is dramatically little by comparing with other sources.

Basically, the maximum quantity of each water source can be estimated by accumulated water volume. If it is possible to keep the water through infinite storage, the total quantity of water from local sources can be more than enough to cover total water demand as simple water balance assessment summarized in the table 5.5.

Table 5.5 Simple water balance in eastern grid

	Yearly maximum volume of water (A) (1,000 m^3)	Daily availability (A/365) (1,000 m^3)	Remarks
Donggang Stream	13,160	36.1	
Jeonso Stream	6,183	16,9	
Unbuk Reservoir	837	2.3	
East Retention Pond	39,259	107.6	
Ground Water	4,417	12.1	Table 5.2
Total (B)	63,856	175	
Water Demand (C)	35,099	96,2	Incl. agricultural water
Water Balance (B-C)	28,757	78.8	

However, as described characteristics of water sources, water is basically flow into the sea and there must be additional facility to store and to treat water sources.

5.5.2 Water Balance of Western Grid

Water sources of western grid are analyzed at two different spots as two retention ponds which are able to be both water source and water storage. However, there is one more matter to be concerned about retention ponds which are pretty close from the airport because the major purpose of retention pond is to prevent flood disaster of the airport which is very important infra-structure and is under national protect. As well as, those spot cannot store much amount of water because of the birds which are harmful for airplanes and used to come if there is water and fishes. Therefore it can never be fully stored and those matters should also be considered.

Similarly to the eastern grid, the maximum quantity of each water source can be estimated by accumulated water volume. If it is possible to keep the water through infinite storage, the total quantity of water from local sources can be more than enough to cover total water demand as simple water balance assessment summarized in the table 5.6.

Table 5.6 Simple water balance in western grid

	Yearly maximum volume of water (A) (1,000 m^3)	Daily availability (A/365) (1,000 m^3)	Remarks
North Retention Pond	55,247	151.4	
South Retention Pond	51,398	140.8	
Ground Water	1,011	2.8	Table 5.2
Total (B)	107,656	295	
Water Demand (C)	22,806	62.5	Incl. agricultural water
Water Balance(B-C)	84,850	232.5	

However, as described characteristics of water sources, water is basically flow into the sea and there must be additional facility to store and to treat water sources.

5.5.3 Suggestion of Improvement on Water Supply

Currently water distribution system in the study area is simple as shown in the Fig. 5.16. Two reservoirs are providing water to Incheon International Airport and Airport Newtown and the water is provided directly from the pump station for the other area in the study area. Therefore, except two zones provided water through reservoirs, water is not being supplied stable condition.

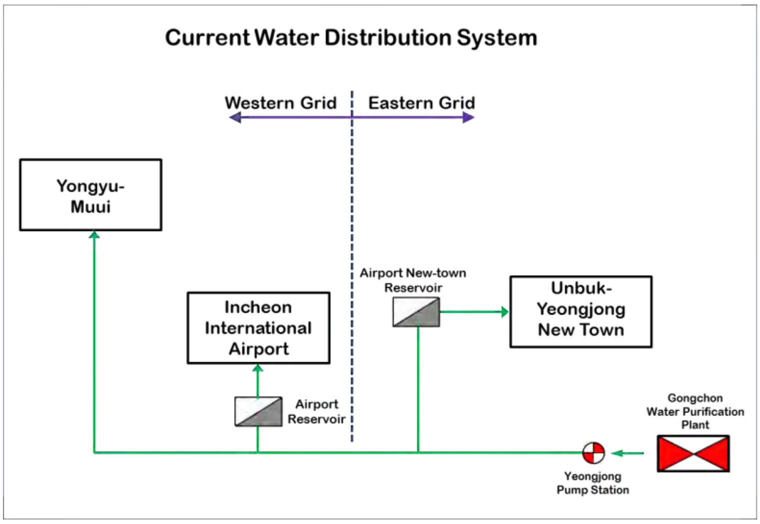


Fig. 5.16 Current water distribution system of study area

Therefore, Incheon Waterworks Headquarter decided to install additional reservoirs at districts to secure stable water supply as Fig. 5.17. The Fig. 5.17 shows the planned water distribution system in 2025 after completion of all development plan of the study area.

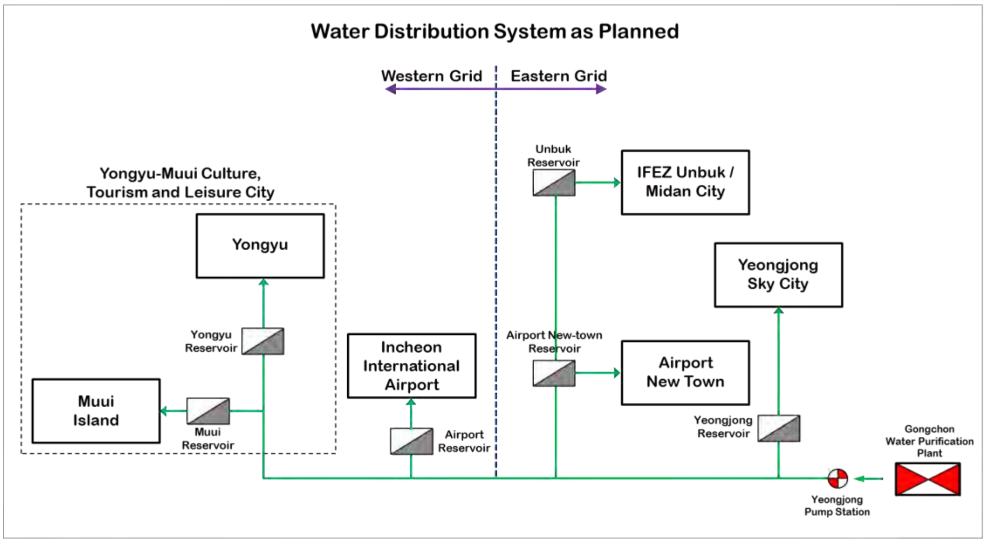


Fig. 5.17 Water distribution system as planned in 2025

However, the planned water distribution system also has risk to be cut off if the submarine pipeline system would be damaged. As analyzed, water stored in regularly basis is limited and there must be an emergency plan to counter the potential accident.

The suggestion of this study is to apply smart water loop to secure emergency water which can be distributed if the water from external water purification plant cannot be inflow to the study area and smart water treatment plant to maximize use of internal water resources as several purposes of water demand. Water consumption spots share the water reservoirs and appropriately treated multi water sources is blended into the water in the reservoir in emergency states. And blended water can be supplied to the consumers through the water loop system. Fig. 5.18 shows the concept of smart water distribution plan suggested in this study.

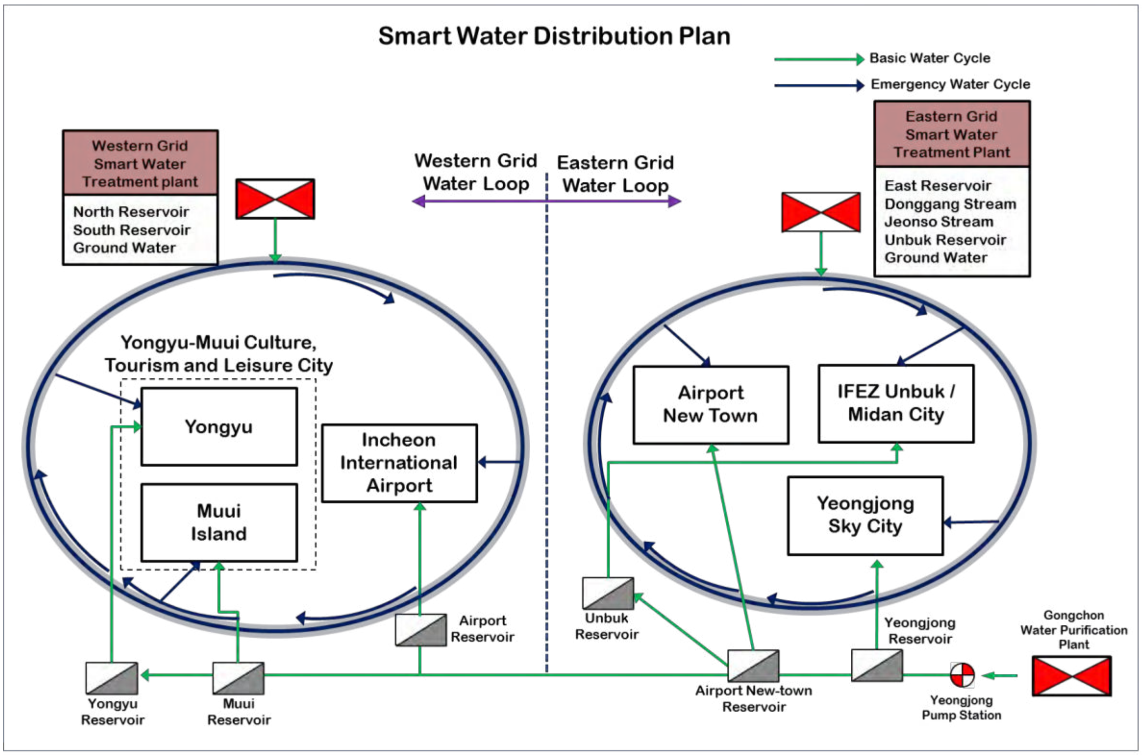


Fig. 5.18 Suggestion of smart water distribution plan

For the planning the system, it is easy to encounter the questions such as;

- How to store water from the stream
- How is the scale of treatment plant and water loop
- How to divide the drinking water and non-drinking water
- If this plan is economically beneficial

In the eastern grid, daily water demand is 96,162 m^3/day and it can be divided into drinking water as 73,600 m^3/day with purpose of domestic water and non-drinking water as 22,562 m^3/day with purposes of agricultural, washing and gardening water. Therefore, the covering quantity of water distribution system through the water loop can generally be 25,000 m^3/day as much as the water for non-drinking purpose and some additional marginal capacity for emergency state. And according to the basic concept of water supply in the study area, drinking water would be inflowing from the Gongchon Water Purification Plant for normal state.

However, there must be additional capacity to cover also the drinking water for emergency state if there is an accident to cut off the water supply from the purification plant. If the duration of fixing the accident on submarine pipeline is three days as the description of scenario, there must be drinking water stored in specific storage within the capacity of 220,800 m^3 at least as three times of daily drinking water quantity of entire grid.

There are three water distribution reservoirs in eastern grid as illustrated in Fig. 5.17 and Fig. 5.18. Yeongjong reservoir is providing water to Yeongjong Sky City and its capacity is 40,000 m^3 as maximum capacity. And Airport New-town reservoir has 15,000 m^3 of storage capacity as well as the Unbuk reservoir has space of 11,000 m^3. And if the smart water treatment plant can produce 25,000 m^3/day as explained above, it can produce 75,000 m^3 of drinking water for three emergency days. Then, the storage capacity is still necessary to secure 79,800 m^3 for covering water during three days without water supply from external water plant. The insufficient water supply can be added from the waste water treatment plants under the consumers' approval.

There are three waste water treatment plants which are currently being operated or planned in the eastern grid at Unbuk, Yeongjong and Songsan as described in the chapter 4.1 and 4.2. Those are recently installed or designed so they can provide water through pretty advanced water treatment process. The maximum capacity for waste water treatment plant in the study area is 115,000 m^3/day and according to the analyzed date at previous chapter, there are 20,200 m^3/day, 29,500 m^3/day and 33,100 m^3/day at Unbuk, Yeongjong and Songsan respectively. And there actually are waste water reuse plans in Yeongjong and Songsan treatment plants as 18,000 m^3/day respectively. The Unbuk treatment plant can be allocated just 3,900 m^3/day of highly treated water.

The suggested system for emergency water supply is installing a smart water treatment plant as a platform for water loop as capacity of 25,000 m^3/day and maximizing use of treated waste water in advanced treatment technology. Fig. 5.19. shows the system suggested.

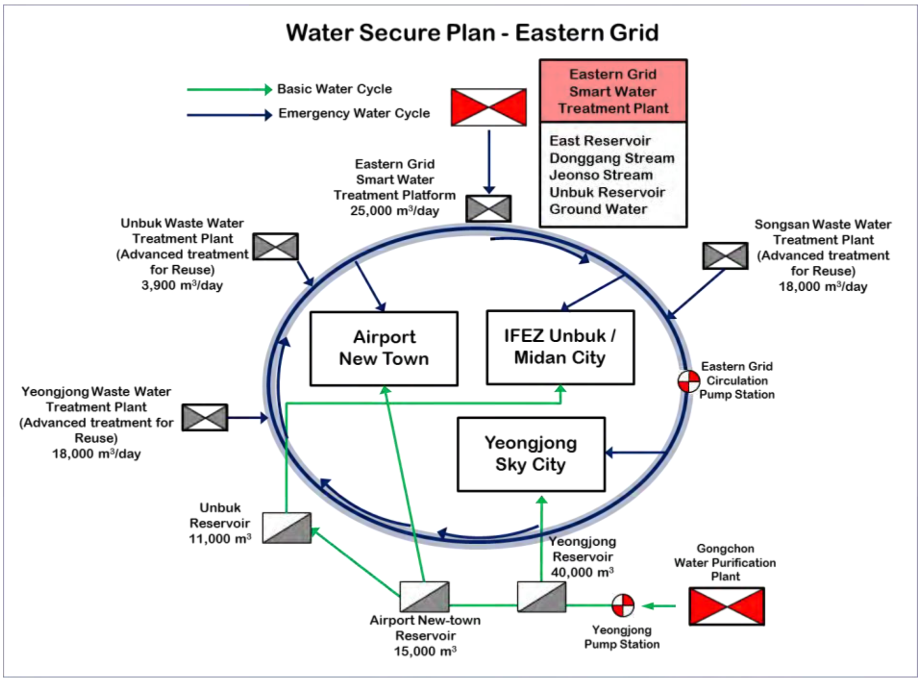


Fig. 5.19 Water secure plan for emergency state (eastern grid)

In the ordinary condition in the eastern grid, the water balance can be displayed as Fig. 5.20. As performed in the graph in Fig. 5.20, the water balance is completely alright with some additional water.

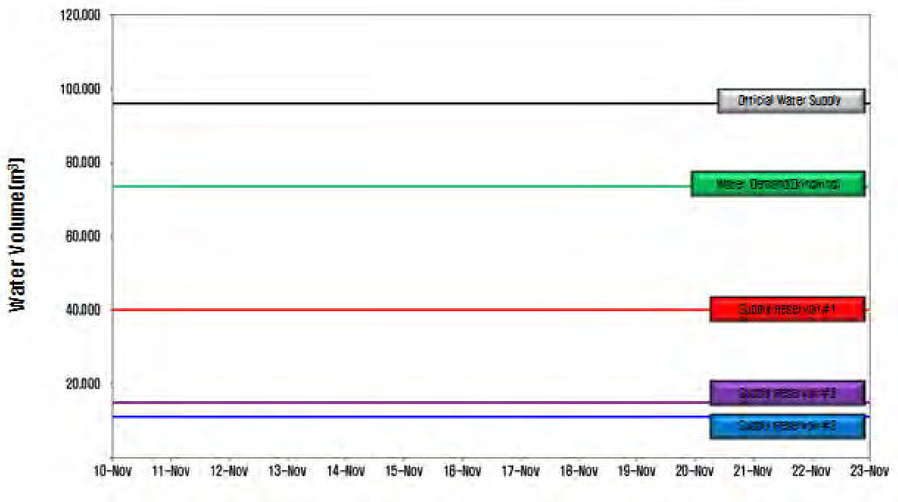


Fig. 5.20 Water balance in ordinary state at eastern grid

However, if the accident is happened, the water balance can be broken as shown in the Fig. 5.21.

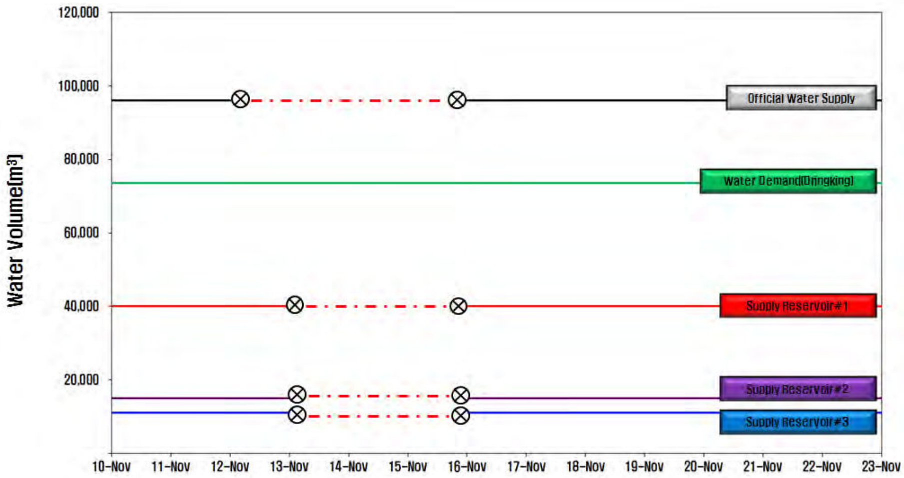


Fig. 5.21 Broken water balance due to the accident at eastern grid

To counter the situation with the accident at the official water distribution system, if the alternative multi water resources can be used, the water balance can be preserved as Fig. 5.22.

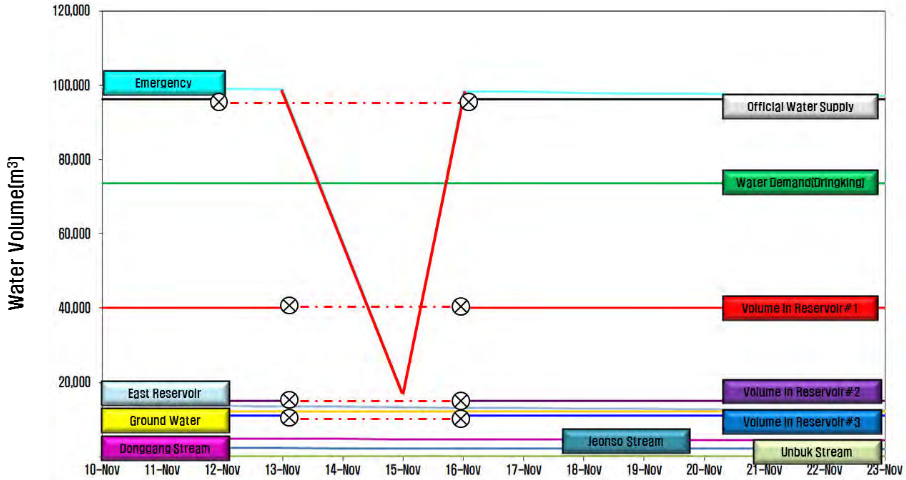


Fig. 5.22 Water balance preservation at eastern grid

Similarly to the eastern grid, daily water demand of western grid is 62,483 m^3/day and 52,800 m^3/day is for drinking purpose and 9,683 m^3/day is used as non-drinking purposes. Therefore, the covering quantity of water distribution system through the water loop can generally be approximately 10,000 m^3/day as much as the water for non-drinking purpose because drinking water is basically inflowing from the Gongchon Water Purification Plant for normal state same as eastern grid. However, in terms of emergency preparedness, it could be better to let smart water treatment plant to cover at least one third of total water demand. Thus this study would apply the smart water treatment plant as the maximum capacity of 20,000 m^3/day.

And there must be additional capacity to cover the drinking water for emergency state. There must be drinking water stored in specific storage within the capacity of 158,400 m^3 at least as three times of daily drinking water quantity of entire grid.

There are three water distribution reservoirs in eastern grid as illustrated in Fig. 5.17 and Fig. 5.18. Airport reservoir is providing water to Incheon International Airport and its capacity is 42,000 m^3 as maximum capacity. And Yongyu reservoir has 9,000 m^3 of storage capacity as well as the Muui reservoir has space of 4,000 m^3. And if the smart water treatment plant can produce 20,000 m^3/day as explained above, it can produce 60,000 m^3 of drinking water for three emergency days. Then, the storage capacity is still necessary to secure 40,400 m^3 for covering water during three days without water supply from external water plant. The insufficient water supply can be added from the waste water treatment plants under the consumers' approval.

There are three waste water treatment plants which are currently being planned in the western grid at two places in Yongyu as described in the chapter 4.1 and 4.2. Those are currently under planning phase so they can provide water through pretty advanced water treatment process if appropriate plan can be applied in the planning. The maximum capacity for waste water treatment plant in the study area is 53,000 m^3/day and according to the analyzed date at previous chapter, there are 28,800 m^3/day and 9,400 m^3/day respectively.

The suggested system for emergency water supply is installing a smart water treatment plant as a platform for water loop as capacity of 20,000 m^3/day and maximizing use of treated waste water in advanced treatment technology. Fig. 5.23. shows the system suggested.

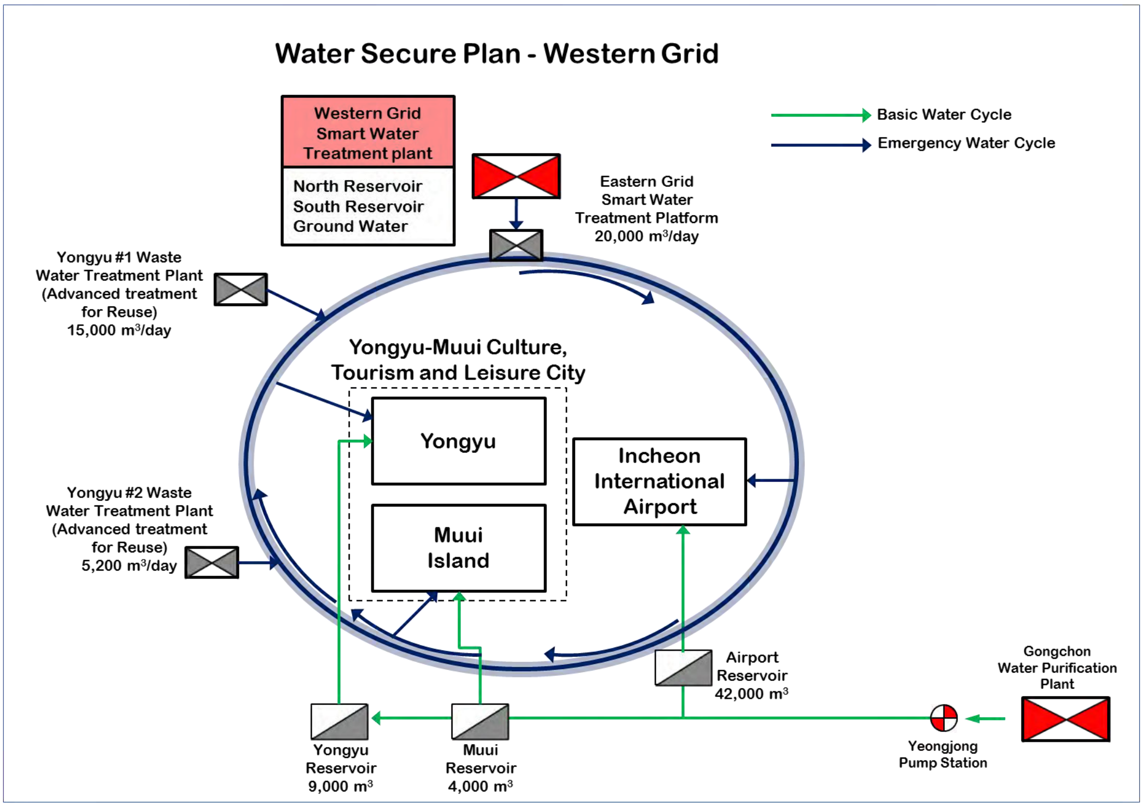


Fig. 5.23 Water secure plan for emergency state (western grid)

In the ordinary condition in the western grid, the water balance can be displayed as Fig. 5.24. As performed in the graph in Fig. 5.24, the water balance is completely alright with some additional water.

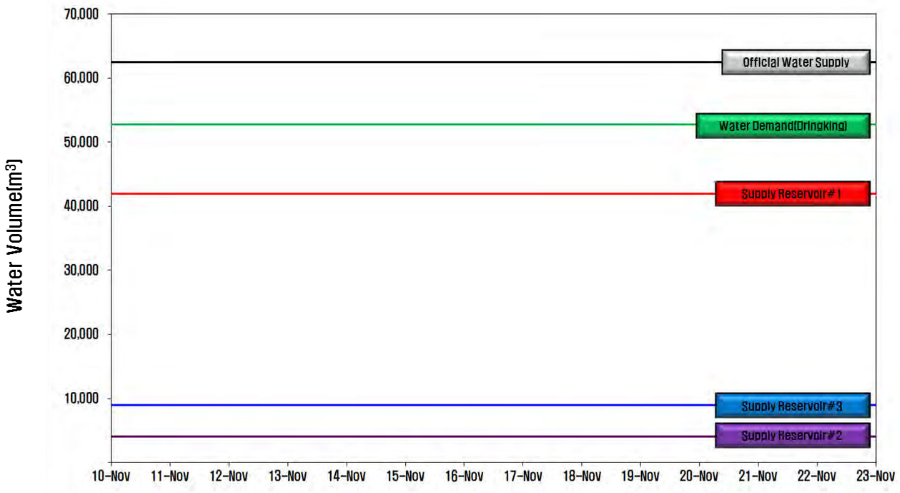


Fig. 5.24 Water balance in ordinary state at western grid

However, if the accident is happened, the water balance can be broken as shown in the Fig. 5.25.

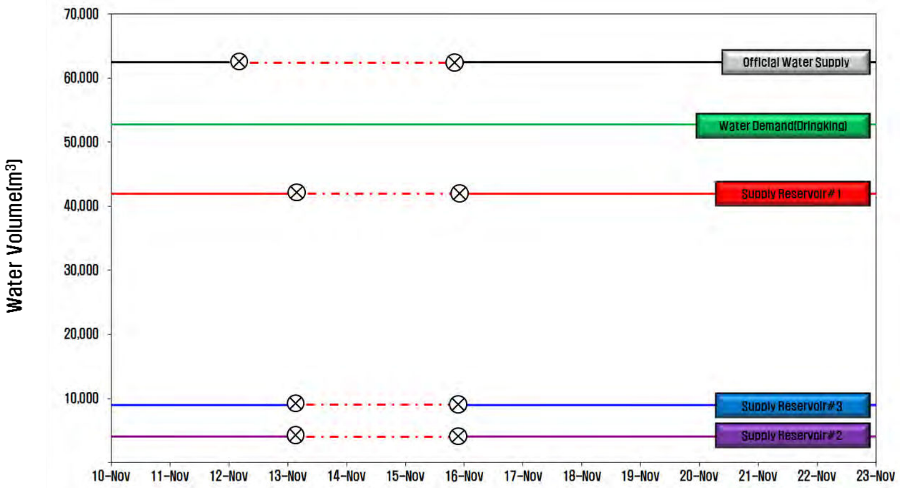


Fig. 5.25 Broken water balance due to the accident at western grid

To counter the situation with the accident at the official water distribution system, if the alternative multi water resources can be used, the water balance can be preserved as Fig. 5.26.

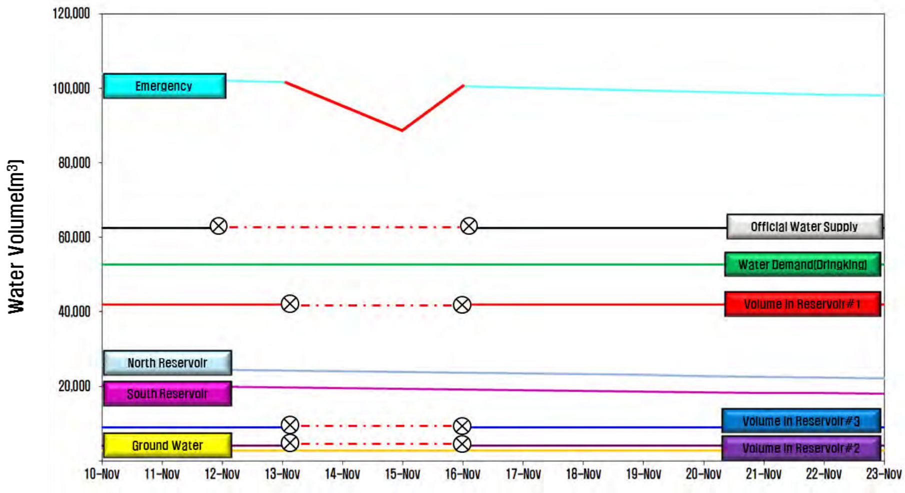


Fig. 5.26 Water balance preservation at eastern grid

As summarize of smart water management system described above, there are duplicated systems such as an ordinary water supply system and smart water system. The ordinary system supplies majorly drinking water by taking major water source and official water purification managed by local government. And the smart water system provides multiple purpose water to satisfy mainly non-drinking water demands for general state, however from an accident on ordinary water supply system, smart water supply system switches into drinking water supply system to minimize the damage from the water shortage disaster.

Chapter 6 Conclusions

This study developed a new water balance assessment system which is being developed as a part of smart water grid project in Korea and suggested a smart water management system to counter potential risks on the water distribution system for the Yeongjongdo Island as a study area. This study has carried out through several scenarios with future estimations for the study area and following conclusions show the summary of the study.

1. This study proposed an general equation to assess the regional water balance to preserver the water supply system
2. To preserve the water balance in the study area, this study assessed the water balance within consideration of scenarios and suggested smart water management system which can cover potential risks on current water distribution system.
3. Within the scenario of accident on water supply system, all potential water resources in the island have been calculated through the model developed through this study. As well as, designed capacity of WWTP and desalination plant could also add self-supply water resources.
4. The water balance in the study area was analyzed through estimation of water demand and available water resources in the study area. Although the study area is an island which the major water sources such as dams or national managed rivers are not connected to, water resources from rainfall-runoff through small streams, reservoirs and retention ponds were sufficient to cover water demand.
5. This study suggested simple and fundamental directions to apply smart water management technologies for the island region which can cover the water for non-drinking purposes at ordinary state. And the smart water management system was analyzed as being able to counter potential problems on water supply system which causes short-term water cutting off.

6. In terms of feasibility and economic impact of an accident on water distribution system, needless to say, it is necessary to make countermeasures to avoid the damages from water shortage and smart water management system can be one of the solutions.
7. For carrying out this study, new type of water balance assessment system has been developed through this study. As the existing model on water balance or water budget system try to judge water balance through the data or lumped system, this study tried to calculate overall water generated through rainfall, external water resources (i.e. metropolitan water distribution system), internal gray water and desalinated sea water so that the real water balance in whole domain as an administration area or an island can be evaluated.
8. The quantity of multi water source was calculated as meeting the water demand to cover a whole island. However some of multi water source cannot be considered as drinking water such as treated waste water in quality-wise. Therefore this study also suggested to use advanced water treatment technologies which produce non-drinking water at ordinary state and drinking water at emergency state.
9. Therefore, this study suggested the proportion of self-supply water as 40% for the study area and it can be enlarged through the advanced water treatment technologies.

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국문초록

물부족 위험을 고려한 지역 내 물수급 평가 연구

최근 한국뿐 아니라 전 세계적으로 반복되는 홍수, 가뭄 등 물 관련 재해에 의하여 거대한 경제적 타격을 동반한 극심한 피해가 발생하고 있다. 이를 위하여 현재 진행중인 스마트워터그리드 기술과 같은 해결방안을 통하여 이러한 문제가 완화될 것을 기대하고 있다. 이러한 기술들의 주요 골자는 다양한 유수지, 빗물저장시설 등 도시에 설치된 물관련 구조물들과 기타 더욱 다양한 시설물을 이용하여 홍수 발생 시 빗물을 모아 홍수 재해를 예방하고, 모여진 빗물은 가뭄을 대비하기 위한 새로운 수자원으로 활용되는 것이다. 또한, 정화된 오수, 지하수 및 담수화된 해수 등 역시 새로운 수자원으로 활용하여 부족한 용량을 채우는 것이다. 본 연구에서는 이러한 연구과정의 하나로 물수급 평가를 수행한다. 한국의 경우 대부분의 수자원이 하천에서 비롯되며, 본 연구에서 시범지역으로 활용하는 서해안 도서지역인 영종도의 경우 수십 킬로미터 밖에 있는 한강에서 물을 가져와 상수를 생산하고 이를 또 수 킬로미터를 이송하고, 일부 구간은 해저에 설치된 단일관로를 이용하여 물을 공급하고 있다. 고비용이며 또한 잠재적인 사고위험을 안고 있는 셈이다. 그러나 현재 상태에서는 섬 내부에서 발생하는 수자원을 활용하고 있지 않으며, 관로상 문제가 발생되는 경우 단수가 발생할 수 있는 실정이다.

본 연구에서는 물수급 정보, 즉, 수요량과 공급량에 대한 정보가 중요하며 이를 바탕으로 물이 부족한 지역을 파악할 수 있다는 점을 기반으로 지역 내에서

잠재적으로 활용 가능한 것으로 보이는 모든 수자원 발생 지점을 수리 및 수문학적인 방식으로 모의하여 수자원 활용 가능량을 계산하였다. 또한 발생 가능한 사고에 대하여 현실적인 시나리오를 적용하였고, 그 결과 섬에서 발생하는 수자원량은 양적인 측면에서는 섬 전체의 수요량을 충분히 공급할 수 있는 것으로 밝혀졌다. 수자원의 공급을 위해서는 반드시 수처리 시설이 함께 설치되어야 하며, 이를 평시에는 비음용 목적의 수자원 공급을 위하여 활용할 수 있도록 하고, 비상시에만 수처리 등급을 올려 음용수의 수준에 맞는 수량을 공급하도록 하면 비상시의 물공급에도 활용하고, 또한 평상시에도 적극 활용할 수 있는 것으로 나타났다.

이러한 연구 결과들을 바탕으로 기본적인 기술의 시범지역 적용 방안에 대하여 제시하였으며, 향후에는 이러한 연구 결과를 바탕으로 실증적인 개발 계획에 활용할 수 있도록 추가 연구를 수행해야 할 것이다.

핵심어: 물수지, 물수급, 스마트워터그리드, 도서지역, 기후변화