IAHR 2017
37th IAHR
WORLD CONGRESS
13-18 August, 2017
Kuala Lumpur, Malaysia
Supported by Spain Water and IWHR, China

FUNCTION OF GOVERNANCE TO RIVER RESTORATION UNDER THE CLIMATE CHANGE

Lead Speaker: Suk Hwan JANG

PROGRESS OF RIVER RESTORATION TECHNOLOGIES AND PRACTICES IN CHINA

JINYONG ZHAO(1), ZHEREN DONG(2), WENQI PENG(3), BAOLIGAO BAIYIN(4) & JING ZHANG(5)

(1,2,3,4,5) China Institute of Water Resources and Hydropower Research, Beijing, China,
China River Restoration Network (CRRN),
zhaojy@iwhr.com

ABSTRACT

Along with the high-speed development of Chinese economy, many problems have occurred including the intensive exploitation of land, water shortage and deterioration of water environment, etc. In addition, there existed the problems of unordered and improper construction of hydraulic and hydroelectric projects. These problems have caused the persistent degradation of river habitat quality, the shrinkage of lake area, as well as the disappearance or degradation of natural wetlands. The progress of river restoration technologies and practices in China is briefly introduced herein in the aspects of national policies, fundamental research, as well as demonstration projects and guidelines. Ecologically influenced mechanism of water resources and hydropower engineering, plan and method of river restoration, health assessment of rivers, balancing reservoir regulation method of ecological protection as well as quantitative evaluation of ecological conditions of rivers are briefly introduced.

Keywords: River restoration; ecological influence mechanism; river health assessment; demonstration projects; guidelines.

1 INTRODUCTION

In China, the works related with river restoration included several stages. In 2004, the policy related to water ecosystem conservation and restoration was issued by the Ministry of Water Resources. Before 2004, river restoration was mainly carried out at local areas, especially areas with high-speed growth in economy, *e.g*. the eastern area or big cities. Since 2004, 14 national river restoration demonstration sites have been built step by step and a national river restoration plan of key rivers and lakes was issued in 2009. Since 2013, river restoration works were under the framework of national water ecosystem civilization city construction. However, it is necessary to realize that the tasks of river conservation will vary in different periods or at different stages (Dong et al., 2009), *e.g.* water pollution control should be put as top priority so that ecological restoration can be realized. Up to now, the following problems existed in different degrees and extent in China.

Among all 223 eco-flow control sections in China's major rivers and lakes, 167 have achieved excellent and good ecological basic flow satisfaction, accounting for 74.9% of all sections, most of which are located in the southern Yangtze River region, the Pearl River region and river regions in the southeast as well as the upstream regions of northern rivers, 46 have achieved poor and bad ecological basic flow satisfaction, accounting for 20.6% of all sections, most of which are located in the Liaohe region, Haihe region, Huaihe River region and the Yellow River (Zhu et al., 2015).

According to the recently completed evaluation of 8499 water function areas in the country's major rivers and lakes for the national water conservation plan, 4444 of such areas have not met the water quality requirements and water quality compliance rate is below 40% in Songhua River region, Liaohe region, Haihe region and Taihu Lake Basin. Among 168 lakes evaluated, nearly half have at least medium level eutrophication.

Among 217 evaluation units, 130 have achieved excellent and good wetland retention rates, most of which are distributed in the Songhua River region, the Yangtze River region and Pearl River region, 87 have got only medium and lower wetland retention rates. In terms of the Yellow River region, Haihe region and river regions in the northwest, about 70% of the units evaluated have got poor and bad wetland evaluation results.

The evaluation of 546 major aquatic habitats in the country shows that 206 among them have excellent and good habitat status, representing a percentage of 37.7%, which are mainly distributed in the Yangtze River, Pearl River and Songhua River; 186 have medium habitat status, representing a percentage of 34.1%; 154 have poor and bad habitat status, representing a percentage of 28.2%, which are mainly distributed in Yellow River and the Huaihe River Basin. The longitudinal connectivity assessment of major rivers showed that, due to reservoir dams, nearly half of the rivers have poor longitudinal connectivity (Zhu et al., 2015).

2 NATIONAL POLICIES

In the aspect of water ecosystem conservation and restoration, China started the planning and implementation of relevant works for water ecosystem conservation and restoration as early as in 2003, and

 / ISSN 1562-6865 (Online) - ISSN 1063-7710 (Print)

seminars and training courses on the same subject were successively held in Nanjing, Guilin and other places. In 2004, the Ministry of Water Resources issued the "Several Opinions on Water Ecosystem Conservation and Restoration, stating the guiding ideology, basic principles and objectives as well as the main contents of water ecosystem conservation and restoration; it is clearly stated in the National Medium and Long Term Science and Technology Development Plan (2006-2020) that it is required to develop technologies and countermeasures for protection and restoration of damaged ecological environment from the perspective of science and technology; since 2007, the Ministry of Water Resources has been engaged in the comprehensive planning for major rivers and important tributaries of the country. In December 2008, the Ministry of Water Resources approved the "Planning mission book for water ecosystem protection and restoration in major rivers and lakes" and started the planning for water ecosystem protection and restoration in such major rivers and lakes. Since 2010, the State Council approved the "National Water Resources Integrated Planning (2010-2030)", "National Ecological Protection and Construction Plan (2013-2020)";

In the aspect of water resources protection and ecological civilization construction, in February 2012, the State Council issued the "Opinions on the Implementation of the Strict Water Resources Management System". In November 2012, a report from the 18th National Congress suggested to "establish the concept of ecological civilization that respects nature, conforms to nature and protects nature." In January 2013, the Ministry of Water Resources issued an opinion on accelerating the construction of water ecological civilization. In October 2013, Ministry of Water Resources issued its "Guiding Opinions on Promoting the Connection of River and Reservoir Water Systems"; in March 2013, Ministry of Water Resources carried out declaration works for the first batch of water ecological civilization cities; in May 2014, the Ministry of Water Resources carried out declaration works for the second batch of water ecological civilization cities; in April 2016, the General Office of the State Council issued an opinion on improving the compensation mechanism for ecological protection.

In the aspect of water pollution control, in April 2015, the State Council issued the “plan of water pollution control”, in which the following goal was made. By 2020, the quality of water environment in China will be improved step by step, the pollution of important water bodies will be greatly reduced, the safety level of drinking water will be continuously improved, the groundwater over-exploitation will be strictly controlled, the trend of increasing groundwater pollution has been curbed, and the environmental quality of coastal waters will be improved under stable conditions. Also, the water ecological environment will be improved in the area of Beijing, Tianjin, Yangtze River Delta, Pearl River Delta and other regional areas. By 2030, the State Council strived to improve the overall water quality of the country by initiatively restoring water ecosystem functions. By the middle of this century, the ecological environment quality will be improved, and the ecosystem a realized virtuous cycle.

In the aspect of sponge city construction, the General Office of the State Council issued guiding opinions about spongy city construction in November 2015. Through the sponge city construction, the "infiltration, stagnation, storage, purification, utilization, draining" and other measures to minimize the impact of urban development and construction on the ecological environment will be implemented, such as 70% of the rainfall will be consumed and utilized in the local field. By 2020, more than 20% of the urban built-up area will meet the target requirements. By 2030, more than 80% of the urban built-up area will meet the target requirements.

3 FUNDAMENTAL RESEARCH

3.1 Study on ecologically influenced mechanism of water resources and hydropower engineering

(1) The holistic concept model of structure and function of river ecosystem was established for river ecosystem structure function. Based on current river ecosystem structure function concept and model, the Holistic Concept Model of Structure and Function of River Ecosystem (HCM for short) is advocated (Dong et al., 2010; Dong et al., 2014). The holistic concept model consists of four sub-models, comprising: (i) the 4-dimensional river continuum model; (ii) the coupled hydrological regime and ecological process model; (iii) the suitability model combining hydraulic conditions and biology life history traits; and (iv) a spatial heterogeneity of geomorphology and biocenosis diversity model. The holistic integration of the 4 sub-models basically includes the holistic features of the structure and function of river ecosystem. The large-scale development activities of human beings on rivers changed the natural environmental conditions, in which case, biological diversity of rivers was changed. HCM provides a theoretical frame for deeper research on the ecologically influenced mechanism by anthropogenic activities.

(2) Analysis on ecologically influenced mechanism of water resources and hydropower engineering.
Ecologically influenced mechanism of water resources and hydropower engineering is analyzed in the field of river continuity, water regime, landscape pattern and physicochemical property of water, etc. (Dong, 2013).
In the field of continuity, construction of dam on rivers causes non-continuity of rivers in a vertical direction, which makes continuum (Vannote et al., 1980) of natural rivers from source to estuary to become serial non-continuity (Ward and Stanford, 1983), and blocks species flow, material flow,

  / ISSN 1562-6865 (Online) - ISSN 1063-7710 (Print)

energy flow and information flow. Building of breakwaters against the flood constricts river channel and restrains flood during flood season from overflowing from both sides, in which case, a kind of side non-continuity feature of rivers was generated. Besides, waterproof embankment and bank protection structure block the exchange channel of surface water and underground water.

In the field of water regime, obvious wet season and dry season are seen during hydrological periods of natural rivers and floods during the wet season bears pulse characteristics. During running of dams, reservoir regulation is subjected to demands on flood control, power generation and water supply, etc., which makes inner runoff uniform, changes hydrological mode of change of natural rivers during wet season and dry season as well as growing conditions and rules of river biocenosis. When the flood takes place and how long-term the flood season lasts are vital for fish reproduction. In fact, flood pulse is a signal for fishes laying eggs (Wantzen et al., 2002; Middleton, 2002). Besides, uniform hydrological periods cause degradation of vegetation on flood plains and decrease in water birds.

In the field of landscape pattern, river regulation projects cause natural rivers to be channelized by human beings: sinuous rivers are cut-off as broken-line or straight; cross sections of rivers are changed into regular geometric cross sections; land construction by enclosing rivers and dam construction causes blockage of water system of rivers and lakes. Changes in landscape pattern causes a decrease in spatial heterogeneity as well as quantity and quality of habitats, which decreases diversity of biocenosis (Allan, 2004; Wang and Seelbach, 2006).

In the field of physicochemical property of water, after reservoirs restore water, flow speed of backwater influence area in reservoirs decreases, the assimilative capacity in areas near the bank and reservoirs drops, which increases the possibility of eutrophication in these areas. In addition, species in downstream areas are impacted on different levels, especially fish growth and reproduction, because of changes in thermocline and supersaturation of dissolved oxygen in reservoirs (Chen et al., 2009; Chen et al., 2009).

3.2 Plan and method of river restoration

Definition, objectives and tasks of ecological restoration of river were sorted out, and the concept of three-dimensional maintenance of river landform was put forward; a hierarchy system of ecological conditions of rivers was established; and a negative feedback, regulation and planning method based on adoptive management mode was perfected.

(1) Definition and objective of ecological restoration of rivers. Ecological restoration of rivers is defined as a series of ecological protection activities of accelerating river ecosystem restoration to a relatively natural condition, and improving ecological completeness and sustainability though engineering and non-engineering measures on the basis of relying fully on the self-restoration function of ecological system (Dong, 2007). During the revision of the Comprehensive planning of Yangtze river basin, the advanced concept and technological achievements in the research of ecological system locally and abroad were referenced (Chang et al., 2013).

(2) Comprehensive approach for classification of river systems and identification of ecological characteristics.

A comprehensive classification method for river ecosystems with full consideration of river formation, structure, controlling environmental factors and their ecological responses at different spatial scales including its period, system, series, type, pattern, habitat and biotic community was presented (Ni et al., 2011). The presented method was helpful to integrate the previous classifications of various kinds of rivers by describing their status and roles in the newly established classification system, revealing their relationship and appropriate scopes in practical applications, characterizing the major classifying abiotic factors in different spatial scales, evaluating biotic characteristics of different rivers, and guiding the forthcoming practices of river protection, environmental improvement and ecological rehabilitation.

(3) Establishing a hierarchy system of ecological condition of rivers. Objective of ecological restoration of rivers shall be on the basis of objective natural conditions rather than subjective figment. In addition, restoration objective is quantitative, able to be monitored and assessed rather than qualitative and abstract.

To realize the quantification of ecological restoration objective of rivers, the hierarchy system of ecological condition of rivers was put forward (Dong et al., 2013). First of all, define ecological condition before human's large scale development activities as a reference system, *i.e.* ideal condition of ecological restoration. Classify ecological conditions into 4 factors, *i.e.* organism quality, hydrology, physical chemistry and river landform, and each factor has several indexes. Rank ecological conditions, where the definitions are the highest rank and assigned respectively based on various indexes of the system; then, determine values of sub-item indexes of other ranks in accordance with deviation degrees of all indexes in ideal condition, in which case, the hierarchy system of ecological condition of rivers was created. Specific sub-item data of objective of ecological restoration planning was available via the hierarchy system.

(4) Task of ecological restoration of rivers. Ecological restoration of rivers includes 4 tasks, *i.e.* improvement of water quality, improvement of water regime, restoration of geomorphologic landscape of rivers, and maintenance and restoration of diversity of biocenosis. The final objective is to improve structure, function and process of ecological system of rivers, and to make it natural (Dong, 2005). On one hand, completeness of ecological system shall be taken into consideration and comprehensive rather than single restoration measures would be taken; on the other hand, the four types of tasks mentioned above shall be ranked pointedly and emphasis of restoration project will be confirmed through identification of key stress factors (Dong, 2006; 2009).

Summarization and creation points in any aspect of ecological restoration of rivers included:① If we improved water regime, we shall not only ensure instream flow, but also put emphasis on restoration and flood pulse during flow process to meet hydrological requirements in various stages of life history of organisms; ② natural water regime is the ideal condition of restoration of hydraulic condition; ③ Water regime may be described in 5 factors with ecological significance, *i.e.* flow, frequency, occasion of occurrence, duration and change rate of hydrologic conditions; ④ Improvement of spatial heterogeneity and complexity of habitat is the premise of maintaining biological diversity; ⑤“Three-dimensional restoration principle of river landform restoration”, *i.e.* vertical continuous restoration among the river channel, connective restoration of river channel alongside of water-flood plain, connective restoration of river-lake as well as restoration of water permeability and porosity of riverbed and bank slope; winding restoration of river form on the platform; diversity restoration of geometrical morphology of riverbed section on cross section (Dong, 2007; 2003; Dong et al., 2011; Dong et al., 2013).

(5) Negative feedback planning design method of ecological restoration of rivers. During ecological restoration of rivers, uncertainty during various types of natural processes and ecological factor of rivers imposes numerous risks on planning design and management of ecological restoration projects of rivers (Graf, 2008). To ensure ecological restoration projects of rivers were developed in accordance with expected objectives, adaptive management strategy was implemented in ecological restoration projects of rivers. Suggested negative feedback planning design method of ecological restoration of rivers, with the aid of information technologies of CIS and RS, etc., followed the method of repeated cycle in accordance with the process of “planning design-execution-management-supervision-assessment-adjustment”, in which case, the system continuously compared the control result and target discrepancy, which shrinks goal discrepancy in adjustment step by step, and finally the ecological restoration objective will be realized (Zhao et al., 2010).

3.3 Health assessment of rivers

River health is strictly speaking a kind of assessment tool in river management rather than a scientific concept.

(1) River health assessment technology. River health assessment technologies of America, Sweden, Australian, Britain, European Union and other countries and organizations are analyzed and summarized in the field of physics- chemistry assessment, quality assessment of organism habitat, hydraulic assessment and organism assessment, etc.

(2) Connotation of river health. Connotation of river health was completely explained nationwide as early as 2005, in which, several basis concepts were cleared and the function of river health assessment was pointed out: As a management tool, purpose of river health assessment is to assess ecological completeness and sustainability during long-term course of evolution under the dual actions of the force of nature and anthropogenic activities.

(3) Principle and method of river health assessment. In river health assessment, relationship between habitat factors and biotic factors as well as a reference system was established; 3 elements, *i.e.* hydraulic condition, water quality condition and quality of habitat were clarified; health assessment system, organism monitoring system and network were established for each river specifically.

(4) River health assessment index system. River health assessment is beneficial to improve decision-making capacity and promote integrated watershed management. The key point of making a technical standard on nationwide river health assessment not only covers basic ecological features of rivers nationwide, but also reflects characteristics of different drainage basins. Based on such ideas, all index system based on the nationwide health system assessment dominated ecological function regionalization (Zhang et al., 2010). One guideline, “River health assessment indicators, standards and methods (pilot work)” was issued by the Ministry of Water Resource, and is mainly utilized by the demonstration sites in the river basins around China (Peng, 2010).

3.4 Balancing reservoir regulation method of ecological protection

In December 2005, Dong Zheren and Gregory A. Thomas, the director of Natural Heritage Institute jointly initiated and held the “ecology seminar of reservoir regulation improvement and river restoration, in which, it was the first time introducing the concept of ecological reservoir regulation and expecting relevant researches. After the seminar, theoretical researches and practices of reservoir regulation method of ecological protection increased gradually (Dong et al., 2007).

Balancing of reservoir regulation method of ecological protection refers to improving the mode of reservoir regulation, partially restoring natural water regime, protecting and restoring ecological system of rivers in downstream of dams and realizing the win-win objective of flood control, interest booming and ecological protection on the premise of free from obvious impact as benefit from flood control and interest booming. 6 main steps of traditional reservoir regulation method are systematically summarized as follows: □ Assess influences of current reservoir regulations on river ecology; □ Clearly improve the ecological objective of reservoir regulation; □ Establish a quantitative model for water regime change and ecological responses; □ Establish an environmental water model of ecological protection objective; □ Make a technical plan for improvement of reservoir regulation; □ Carry out test for improvement of reservoir regulation based on negative feedback design method (Wang et al., 2013).

3.5 Quantitative evaluation of ecological conditions of rivers

Ecological study of rivers is a kind of interdisciplinary study. Vital emerging discipline is developed on basis of cross and integration of multiple disciples and river ecology, including ecological hydrology, ecological hydraulics and landscape ecology, etc. In such emerging disciplines, researches are carried out and a series of quantitative evaluation methods are developed in field of drainage basin, river section and landscape, etc. and based on relationships between water regime, hydro-dynamic conditions, landscape ecology and the like, which provides important scientific supports for development of eco-hydraulic engineering. The significant role is to change the ecological condition evaluation of rivers from qualitative description to quantitative evaluation calculated by a computer, so that the planning design in eco-hydraulic engineering is based on accurate data (Dong et al., 2009). At the same time, combination of such quantitative evaluation methods and hierarchy system of ecological conditions of rivers provided quantitative means for current condition analysis, objective setting, future prediction and so on, so as to make up for the shortage of qualitative analysis.

4 DEMONSTRATION PROJECTS AND GUIDELINES

4.1 Ruaral river-Xinjiangtang stream

4.1.1 Background of river restoration

Xinjiangtang stream is a plain river network, which usually has moderate flow velocity. Problems such as sedimentation, water and soil loss, shrinkage of water area, water quality deterioration are ubiquitous in Xinjiangtang stream. Moreover, navigation in the stream gradually faded away in recent years.

Bank erosion in Xinjiangtang stream is mainly due to surface soil erosion caused by rain wash and slope collapse caused by wave scour.

According to preliminary statistics, of the all river sludge (Figure 1), 60% comes from slope collapse, 30% is from surface soil loss and 10% is from decomposed plant material.

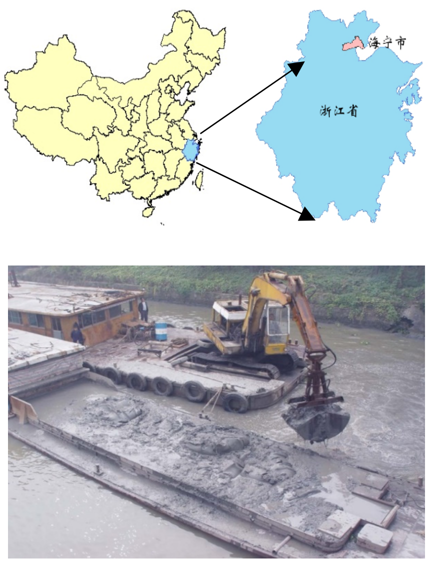


Figure 1. Xinjiangtang stream demonstration project.

4.1.2 Project planning and design

In combination with the implementation of a research program financed by the Ministry of Water Resources, from 2004 to 2005, China Institute of Water Resources and Hydropower Research was involved in the construction of a pilot project for the ecological restoration of Xinjiangtang stream in Haining County of Zhejiang Province by supplying technical consultation to local water sector.

The planning and design of Xinjingtang stream followed the concept of design with nature to achieve the multi-purposes.

Present platform morphological patterns are kept and only a few local modifications were conducted to meet special requirements. The natural meandering and width of the river channel were maintained. Floodplain and riparian wetlands were rehabilitated. Natural cross-section profile was preserved as much as possible. Compound or trapezoid cross section was adopted only in particular conditions.

4.1.3 The effects and current situation of river restoration

By the implementation of these comprehensive measures, the results of Xinjiangtang river restoration project corresponded with the primary design. The standard of flood control was improved; riverbank erosions were effectively controlled; water quality was improved; aquatic animals and riparian vegetation grew well (Figure 2) and the project budget was greatly saved.

By analysis and comparison with past river treatment achievement, the life cycle was about 10 to 20 years with the use of traditional river dredging only. However, river dredging together with slope protection through ecological engineering technology stabilized channel morphology effectively, and the life span was about 35 to 40 years which was nearly double the old life cycle according to preliminary analysis.

The future management should pay more attention to river dredging, which can save investment and the river training will embark on a more effective circle.

Figure 2. Riparian vegetation of Xinjiangtang stream.

4.2 Urban river-Zhuanhe River

4.2.1 Background of river restoration

The Zhuanhe River, a segment of the north-ring water system, connects the Summer Palace and the Chaoyang Park. Zhuanhe River is an urban river system. Zhuanhe River was covered up from 1975 to 1982, and the river training project started from 2002 to restore the original appearance of its history.

Along with the development of social economy and people's constant pursuit for a better living environment, people have put forward comprehensive requirements on the training of urban lake and river in many aspects including flood prevention, water quality improvement, ecology conservation and restoration as well as cultural landscape etc.

During the Tenth Five-year Plan period, Beijing focused on the training of water system in central urban and the investments were increased compared with the past years. In addition to traditional river training objectives, *i.e.* flood control and drainage, new objectives were added in the aspects of landscape and ecological rehabilitations in order to realize the harmonious coexistence of human and natural water.

4.2.2 Project planning and design

Its training followed the planning and design principles of maintaining its natural meandering and width. Stones and wood-like concrete piles, porous and pervious materials and live vegetation were applied for riverbank protection and erosion control.

The flood control standard was designed with 20 years-flood and checked with 100 years-flood. Wastewater discharge was under strict control and the water surface was expanded to 15-25m.

To develop tourism, the river was open to navigation. To this end, a new lock, 13 bridges, two docks, and a sluice have been completed.

  / ISSN 1562-6865 (Online) - ISSN 1063-7710 (Print)

4.2.3 The effect and current situation of river restoration

Six scenic spots including historical and cultural parks, ecological parks, water scenes with stacked stones, waterfront veranda, hydrophilic land and green channel were formed along the river.

By the principle of maintaining the current status of non-disturbance, the bridge built in the Liao Dynasty was restored.

As showed in Figure 3, after the river restoration of Zhuanhe River, the biological diversity was significantly improved, and the fish, frogs and other species came back to this river. Vegetation and human landscapes were recognized by the majority of the residents.

Figure 3. River restoration effect of Zhuanhe River.

4.3 Related guidelines

In the aspect of assessment, River health assessment indicators, standards and methods (for pilot work)" (BanZiYuan [2010] No. 484) were introduced, relevant standards were under preparation; *Guidelines for Assessment of Ecological Water Demand of Rivers and Lakes* (SL / Z479), *Ecological Risk Assessment Guidelines* (SL / 467), *Water Ecological Civilization Urban Construction Evaluation Guide* were promulgated.

In the aspect of planning, *Guidelines for Aquatic Ecological Protection and Restoration Planning*(SL709-2015), *Water Resources Protection Planning Rules* (SL613) were promulgated.

In the aspect of engineering, *Waterway and Hydropower Engineering Trail Design Guidelines* (SL609) has been promulgated, *Water Project Planning and Design Ecological Indicators System and Application Guidance* (ShuiZongHuanYi [2010] No. 248) were published; *Engineering Technical Guidelines for Ecological Protection and Restoration of Rivers and Lakes* was under preparation; *Embankment Engineering Design and Planning*(GB50286), *Design Code for River Regulation* (GB50707), *Engineering Technical Specifications for Channel Seepage*(SL18-91)were promulgated, however ecological restoration projects for rivers and lakes were yet to be clearly specified in the same.

In details, *Guidelines for Aquatic Ecological Protection and Restoration Planning*(SL709-2015) included a total of 11 chapters and 1 appendix(Guidelines for Aquatic Ecological Protection and Restoration Planning, SL709-2015), such as General Provisions, Terminology, Investigation and Evaluation of Current Situation, General Planning, Satisfaction of Ecological Water Demand, Water Quality Maintenance and Improvement, Landscape Protection and Restoration of Rivers and Lakes, Important Biological Habitat and Biodiversity Conservation, Important Regional Ecological Protection and Restoration, Ecological Monitoring and Comprehensive Management of Rivers and Lakes, Planning and Implementation Opinions and Effects Analysis and Appendix A Planning Evaluation Index System.

Apart from the above national guidelines, some areas also adapted river restoration guidelines based on the local real situation. In Zhejiang province, guideline of construction standard for river way (DB33/T614-2006) and technical code for ecological construction of river course (DB33/1038-2007) were issued. In Beijing, guidelines for planning of middle and small-sized river comprehensive regulation (DB11/T758-2010) were issued.

5 CONCLUSIONS

i. River restoration needs to start from the fundamental integrity of aquatic ecosystems, calling for a renewed awareness of the aquatic ecosystem, including hydrology, geomorphology, physical chemistry, biology and other basic process, as well as considering the sustainable development demand of human society. The objective of river restoration is restoring the structure and process of aquatic ecosystem, and the goal is to restore the ecosystem service function. In detail, river restoration includes 4 tasks, *i.e.* improvement of water quality, improvement of water regime, restoration of geomorphologic landscape of rivers, and maintenance and restoration of diversity of biocenosis. The final objective is to improve structure, function and process of ecological system of rivers, and to make it natural;

ii. In fundamental research, the correlation relationship between river habitat and river biology needs long-term monitoring data to provide the foundation for river restoration planning. Comprehensive standard system should be built as soon as possible to provide guidelines for river restoration practice, especially related with materials, facility, construction, monitoring and inspection etc.;

iii. River restoration in China should focus on eco-friendly hydraulic engineering, watershed management pattern transformation, and comprehensive management in ecological fragile zones.

REFERENCES

Allan, J.D. (2004). Landscape and Riverscapes: The Influence of Land Use on Stream Ecosystems. *Annual Review of Ecology and Systematics*, 35, 257-284.

Chen, Y.B., Peng, Q.D. & Liao, W.G. (2009). The Evolvement Study on Supersaturation of Dissolved Gas in the Middle Reaches of Yangtze River after the Three Gorges Project Running. *Journal of Hydroecology*. 2, 1-5.

Chang, J.B., Chen, X.J. & Qiao, Y. (2013). Ecological Principle and Its Realization in Comprehensive Planning of Yangtze River Basin. *Yangtze River*, 5, 15-17.

Chen, Y.C., Fu, J., Liu, Z.W., Cheng, X.J. & Zhu, D.J. (2009). Analysis of the Variety and Impact Factors of Dissolved Oxygen Downstream of Three Gorges Dam after the Impoundment. *Advances in Water Science*. 20(4), 526-530.

Dong, Z.R. (2003). Diversity of River Morphology and Diversity of Bio-Communities. *Journal of Hydraulic Engineering*, 11, 1-6.

Dong, Z.R. (2005). On the Design Principles of Eco-Hydraulic Engineering. *J. Hydraul. Eng.*, 35(10), 1-6.

Dong, Z.R. (2006). Matrix Method of Comprehensive Evaluation on Economic Benefits and Ecological Functions of Hydraulic Engineering. *Journal of Hydraulic Engineering*, 37(9), 1038-1043.

Dong, Z.R. (2007). Exploring Eco-Hydraulic Engineering. *China Engineering Science*, 9(1), 1-7

Dong, Z.R. (2007). Scale and Pattern for Ecological Restoration of River. *Journal of Hydraulic Engineering*, 37(12), 1476-1481.

Dong, Z.R., Sun, D.Y. & Zhao, J.Y. (2007). Multi-Objective Ecological Operation of Reservoirs. *Water Resources and Hydropower Engineering*, 38(1), 28-32.

Dong, Z.R. (2009). Framework of Research on Fluvial Ecosystem. *Journal of Hydraulic Engineering*, 40(2), 129-137.

Dong, Z.R., Sun, D.Y., Wang, J.N. & Zhao, J.Y. (2009). Progresses of Inter-Disciplines Related to River Ecology. *Water Resources and Hydropower Engineering*, 40(8), 36-43.

Dong, Z.R., Sun, D.Y., Zhao, J.Y. & Zhang, J. (2010). Holistic Conceptual Model for the Structure and Function of River Ecosystems. *Advances in Water Science*, 21(4), 550-559.

Dong, Z.R. (2013). *River Restoration*. China Water & Power Press, China.

Dong, Z.R., Wang, H.T., Zhao, J.Y., Zhang, J. & Wang, J. (2013). Eco-Survey and Planning Method for Rehabilitation of Connectivity of River-Lake Water System. *Journal of Materials Sciences & Technology*, 44(11), 8-.

Dong, Z.R., Zhang, A.J. & Zhang, J. (2013). Rating System of River Ecological Conditions and Its Applications. *Journal of Hydraulic Engineering*, 44(10), 1233-1248.

Dong, Z.R., Sun, D.Y., Zhao, J.Y. & Zhang, J. (2014). Progress and Prospect of Eco-Hydraulic Engineering. *Journal of Hydraulic Engineering*, 45(12), 1419-1426.

Dong, Z.R, Sun, D.Y., Zhang, J., Zhao, J.Y. & Zhai, Z.L. (2009) Progress of River Restoration in China, *Proceedings of 6th Asian River Restoration Networks*, Korea, 1-11.

Graf, W.L. (2008). *River Restoration: Managing the Uncertainty in Restoring Physical Habitat*. John Wiley & Sons, Inc., Chichester, UK, Chapter C2, 15-19.

Ministry of Water Resources (MWR). (2015). *Guidelines for Aquatic Ecological Protection and Restoration Planning (SL709-2015),* Ministry of Water Resources, China.

Middleton, B. (2002). *Flood Pulsing in Wetland Restoring the Nature Hydrological Balance*. John Wiley & Sons, Inc., New York, USA.

Ni, J.R. & Gao, X.W. (2011). Comprehensive Approach for Classification of River Systems and Identification of Ecological Characteristics I. Methodology. *Journal of Hydraulic Engineering*, 42(9), 1009-1016.

Peng, W.Q. (2010). Indicators, Standards and Methods of River Health Assessment (Pilot Work), No. 484, Ministry of Water Resources, China.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R. & Cushing, C.E. (1980). The River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Sciences*, 37(1), 130-137.

Wang, J.N., Dong, Z.R., Liao, W.G., Li, C., Feng, S., Luo, H. & Peng, Q. (2013). An Environmental Flow Assessment Method Based on the Relationships Between Flow and Ecological Response: A Case Study of the Three Gorges Reservoir and Its Downstream Reach. *Science China Technological Sciences*, 56(6), 1471-1484.

Wang, L.Z., Seelbach, P.W. & Hughes, R.M. (2006). Introduction to Landscape Influences on Stream Habitats and Biological Assemblages. *American Fisheries Society Symposium*, 48, 1-23.

Wantzen, K.M., Machado, F.A., Voss, M., Boriss, H. & Junk, W.J. (2002). Seasonal Isotopic Shifts in Fish of the Pantanal Wetland, Brazil. *Aquatic Sciences-Research Across Boundaries*, 64(3), 239-251.

Ward, J.V. & Stanford, J.A. (1983). *Dynamics of Lotic Ecosystems*. Ann Arbor Science, Chapter C2, 29-42.

Zhang, J., Dong, Z.R., Sun, D.Y. & Wang, J.N. (2010). Complete River Health Assessment Index System Based on Eco-Regional Method According to Dominant Ecological Functions. *Journal of Hydraulic Engineering*, 41(8), 883-892.

Zhao, J.Y., Dong, Z.R., Sun, D.Y. & Zhang, J. (2010). Negative Feedback Regulation Based Planning and Design Method for River Restoration. *Water Resources and Hydropower Engineering*, 9, 1-14.

Zhao, J.Y., Dong, Z.R., Zhai, Z.L. & Sun, D.Y. (2011). Evaluation Method for River Floodplain System Connectivity Based on Graph Theory. *Journal of Hydraulic Engineering*, 42(5), 537-543.

Zhu, D.S., Wang, X.H. & Zhang, J.Y. (2015). Approaches for Water Ecosystem Protection and Restoration. *China Water Resources*, 22, 9-12.

Proceedings of the 37th IAHR World Congress
August 13 – 18, 2017, Kuala Lumpur, Malaysia

HEIGHT DIFFERENCE FROM REGULAR WATER LEVEL AS INDICATOR FORECASTING VEGETATION AFTER CHANNEL EXCAVATION

DAISUKE NAITO(1), KENICHI KANENAWA(2), KAZUHISA FUKUNAGA(3), FUMIKO IMAMURA(4) & YUICHI KAYABA(5)

(1) Public interest incorporated foundation Japan Riverfront Research Center (1-17-24 Shinkawa, Chuo-ku, Tokyo 104-0033)
(2) Inspectors Office, Minister's Secretariat, Ministry of Land, Infrastructure, Transport and Tourism (2-1-3 Kasumigaseki, Chiyoda-ku, Tokyo 100-8918)
(3) River Division, Department of Public Works, Kagoshima Prefectural Government (10-1 Kamoikeshimmachi, Kagoshima, Kagoshima 890-8577)
(4) R&D Center, Nippon Koei Co., Ltd. (2304 Inarihara, Tsukuba, Ibaraki 300-1259)
(5) River Restoration Team, Public Works Research Institute (National Research and Development Agency) (1-6 Minamihara, Tsukuba, Ibaraki 305-8516)

ABSTRACT

Climate change is expected to not only increase the risk of flooding but also affect vegetation in river channels because of changes in river flooding pattern and flow regime. Channel excavation, which has been widely adopted for many rivers in the country as a development method for flood control, is also used as an approach to nature restoration that aims to restore natural bare land and swamp environments by excavating land area created by sandbars and is, therefore, considered an effective approach to both flood control and environmental preservation even under climate change. At present, however, there is an issue that sandbar excavation has failed to maintain vegetation as expected and resulted in the need of reforestation in some cases. Therefore, techniques are sought for forecasting vegetation after channel excavation. In this study, we have focused on two formation factors, i.e., the height difference from the regular water level and the distance from the water's edge, as forecast indicators, and organized their relationships with the distribution of vegetation in river channels across the country. As a result, it is found that the distribution characteristics of plant communities by height difference and distance from the water's edge vary according to segment and that vegetative distribution in low height difference zones where the height difference is not more than 1 m is different according to region. As a result of analysis focused on dominating plant communities after excavation, a closer relationship is found in segment 2-2 between the dominating plant communities in the low height difference zone where the height difference is not more than 1 m and the dominating plant communities after excavation. All of these results show that the height difference can serve as an indicator for forecasting vegetation after channel excavation.

Keywords: Vegetation in the channel; tree growth; channel excavation; height difference from the regular water level; distance from the water's edge.

1 INTRODUCTION

Channel excavation is widely adopted for rivers across the country as a method of development for flood control and is also used as an approach to nature restoration for natural bare land and swamp environments by excavating land area created by sandbars. However, there are some cases where bare land created by channel excavation is invaded by willow and other trees soon after completing the development measures and is consequently occupied by them. Since the risk of flooding due to climate change is expected to increase, it is important to forecast the vegetation that may form after channel excavation in order to excavate river channels effectively as a flood control measure and as an approach to nature restoration.

While knowledge has been accumulated about the impact of excavation and tree growth in individual rivers and sections, [1)2)] there are few studies focused on the overall trend and regionality concerning the relationships between the physical environment and plant communities in rivers across the country.[3)] In addition, no technology has been established to forecast with high accuracy plant communities that may form after channel excavation.

Therefore, in this study, we first grasp the distribution of plant communities in rivers across the country and analyze the relationships of plant communities and two factors of their formation, i.e., the height difference from the regular water level and the distance from the water's edge. We have also studied some excavation projects to analyze the relationships between the dominant plant communities with a height difference of under 1 m, excavation height, and the number and frequency of flooding events, and the dominant plant communities after excavation, in the segments where an excavation site is located.

  / ISSN 1562-6865 (Online) - ISSN 1063-7710 (Print)

2 CHARACTERISTICS OF PLANT COMMUNITIES IN RIVER CHANNELS IN TERMS OF DISTRIBUTION, HEIGHT DIFFERENCE, AND DISTANCE FROM THE WATER'S EDGE

2.1 Analytical method

We extracted and analyzed the information on plant communities in relation to the height difference from the regular water level ("height difference") and the distance from the water's edge ("distance from water's edge"), by overlapping the map of the Census of Rivers and Riparian Areas (vegetation mapping; "River Census Vegetation Map") with the map of the cross-section survey on GIS.

To analyze the information on rivers across the country, we used the River Census Vegetation Map of the 4th Census (2006-2010), the map of the cross-section survey, and milepost data. Categories of plant communities were integrated and set to 15 categories based on the 28 basic categories of plant communities used in the River Census. For the cross-section survey data, we used the data for which the difference between the survey year and the year of the relevant River Census was not more than two years. As the study subjects, we chose 174 rivers in 71 river systems, for which the aforementioned data set was available, and mainly analyzed segments 1, 2-1, and 2-2. For some of these rivers, data was available for part but not the whole river.

Regular water level that serves as the basis of the height difference was set to the lowest ground height among the intersections obtained by overlapping the water polygons on the River Census Vegetation Map with the cross-section survey data on GIS. This setting is based on the assumption that the water's edge indicated by the boundary line of water polygons is not greatly different from the edge at the regular water level, because periods of flooding and drought are usually avoided when conducting a survey for vegetation mapping.

The data used for analysis was obtained by plotting points at a 5 m pitch on the cross-section survey lines starting from the left and right banks of the river and extracting the plant community category, height difference, and distance from the water's edge at each point. Then, the distribution characteristics of plant communities were indicated by appearance rate based on the data obtained from each point. To be more specific, the appearance rate represents the ratio of the points of the applicable plant community category to the total number of points in a meshed area formed by a height difference of 1 m and a distance from water's edge of 10 m indicated on the two axes of height difference and distance from water's edge or in the area of a height difference under 1 m.

2.2 Outline of the characteristics of plant community distribution from the viewpoints of height difference and distance from water's edge

We plotted the information extracted by overlapping the vegetation map with the results of cross-section survey on the two axes of height difference and distance from water's edge, according to river and plant community category. Although the distribution of plots was different according to the river and cross-section profile, we confirmed the trend that distribution areas and density differ according to plant community category. Figure 1 provides some plant community categories with a lot of plots found in the Tone and Toyo Rivers.

In the Tone River, the distribution density of natural bare land, monocotyledons and willow trees is higher in the low height difference zones near the water's edge, while annual herbaceous plant communities, perennial herbs, artifacts, cultivated land, etc. are widely distributed in the horizontal direction where the height difference is large.

In the Toyo River, as seen in the Tone River, the distribution of monocotyledons and willow trees is concentrated in areas where the height difference is small and the distance from water's edge is short, while the distribution of bamboo trees is high in areas where the height difference is high and the distance from water's edge is large.

2.3 Difference in the distribution characteristics of river channel plant communities according to segment

We organized the characteristics of the height difference from the regular water level and the distance from the water's edge by the appearance rate and plant community category. Of the 174 rivers in 71 river systems analyzed in this study, the characteristics are described as follow, including examples, for 26 rivers in 21 river systems for which the data is available on a whole river basis.

In each segment, it was confirmed that the height difference from the regular water level and the distance from the water's edge for each plant community category were significantly different from the results of the Kruskal-Wallis test ($P < 0.05$)

i. Natural bare land

The distribution of natural bare land is limited to segments 1 and 2-1, where the height difference is approximately 4 m or below. The appearance rate is particularly high, more than 20%, in the area where the height difference is not more than 2 m (Fig. 2). For the distance from water's edge, the appearance rate is the highest at approx. 20-30% in the area of 0 to 10 m, and becomes lower as the distance increases, falling to 5-10% in an area of about 100 m from the water's edge (Fig. 3).

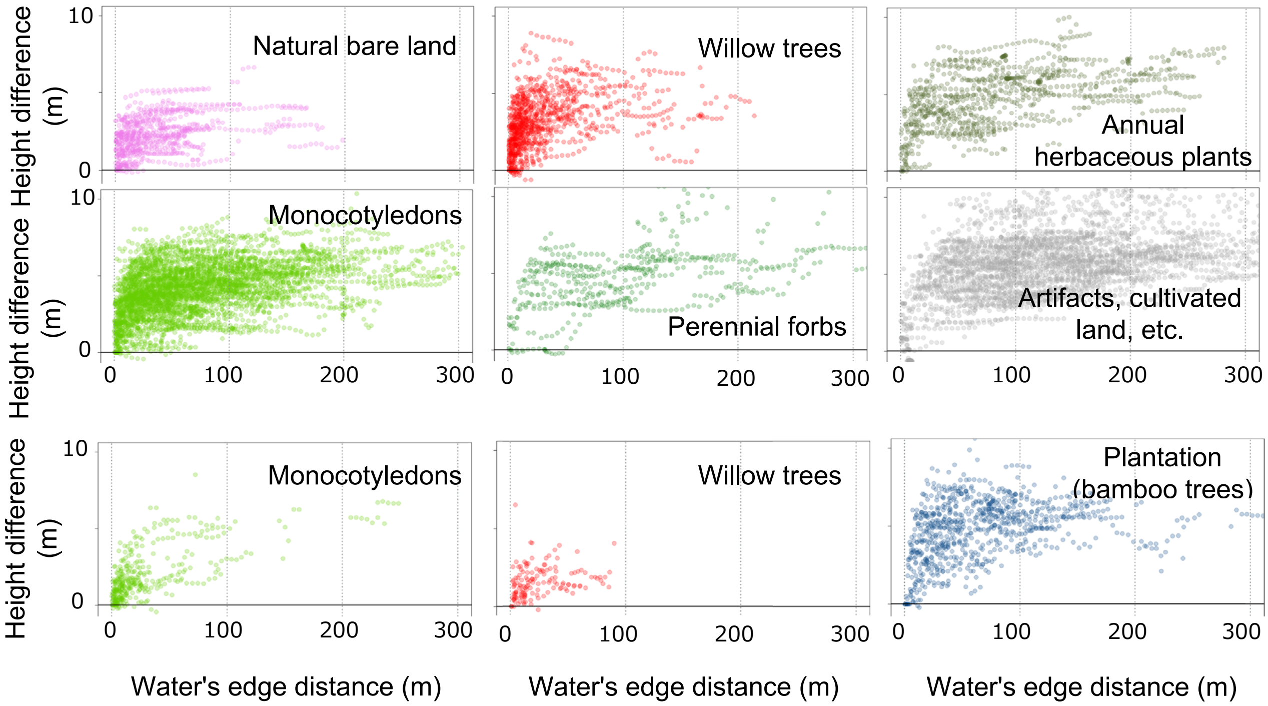


Figure 1. Distribution characteristics of plant communities on the two axes of height difference and water's edge distance (Upper two rows represent Tone River, and the bottom row, Toyo River)

ii. Annual herbaceous plant communities

These communities were widely found in height difference areas at an appearance rate of 5-10% in all segments. As the height difference decreases, the appearance rate goes up. The appearance rate is the highest in segment 2-2 and is higher than 10% where the height difference is not more than 2 m (Fig. 2). In terms of the distance from water's edge, the appearance rate shows little change in segments 1 and 2-1 from 0 to 100 m, while in segment 2-2, the appearance rate, which is the highest at approx. 15% at a distance of 0 to 10 m, becomes smaller as the distance from water's edge increases, and is lower than 5% in an area about 100 m from the water's edge (Fig. 3).

iii. Monocotyledon communities

In all the segments, as the height difference becomes smaller, the appearance rate goes up. In an area where the height difference is not more than 4 m, the appearance rate is approximately 0 to 20% (Fig. 2). As the distance from the water's edge becomes larger, the appearance rate also falls but with little change (Fig. 3).

iv. Willow trees

In segments 2-1 and 2-2, the appearance rate is high in the area where the height difference is not more than 4 m, and is particularly high, approx. 20 to 30%, in segment 2-1. In segment 1, the appearance rate is approx. 10% in the area where the height difference is not more than 2 m (Fig. 2). As the distance from water's edge becomes larger, the appearance rate falls (Fig. 3).

Figure 4 shows an example of the Ishikari River system. The main area where the appearance rate of willow trees is not less than 30% is located where the height difference is 0-9 m and the distance from water's edge is 0-150 m, and is concentrated in an area where the distance from water's edge is within 20 m for an area where the height difference is not less than 6 m.

v. Plantation (bamboo trees)

Figure 4 shows an example of the Yoshino River system. Most of the bamboo trees appeared in segment 2-1. The appearance rate is high, 30% or more, where the height difference is 6 m or more and the distance from water's edge is not more than 250 m, particularly not more than 100 m.

vi. Plantation (other)

The appearance rate of other planted vegetation, including Robiniapseudoacacia, is high in segment 1, and is about 10% where the height difference is 2-7 m. The appearance rate is low where the height difference is not more than 2 m (Fig. 2). As the distance from water's edge becomes larger, the appearance rate goes up (Fig. 3).

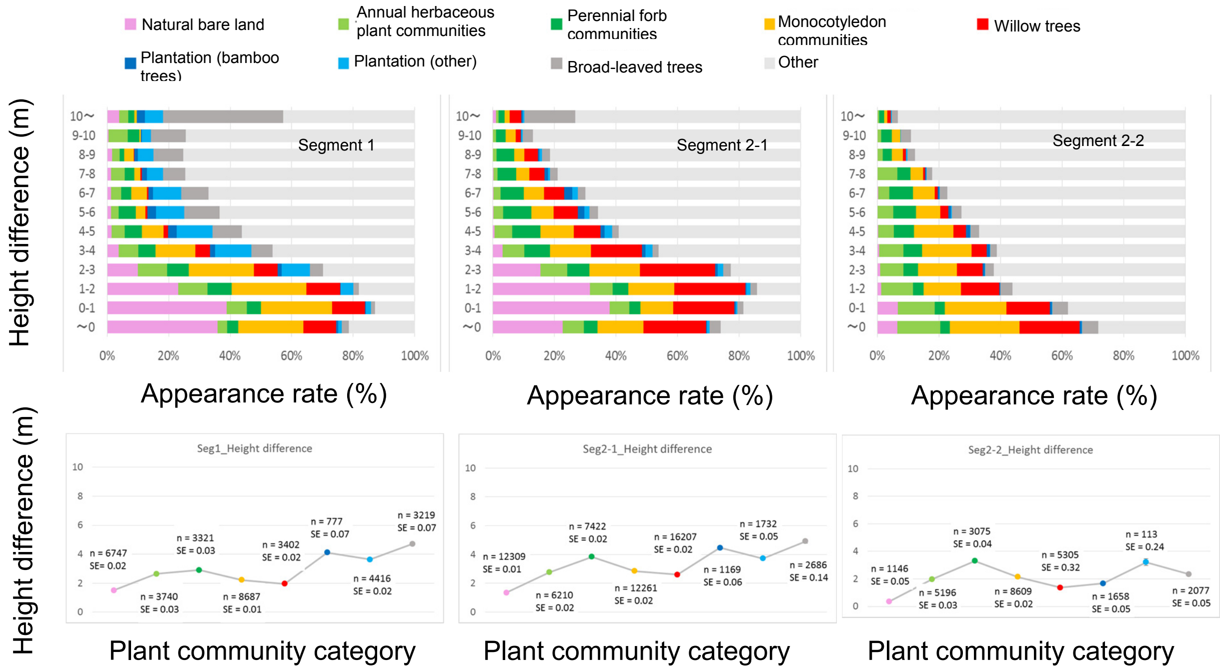


Figure 2. Distribution characteristics of plant communities by height difference (country-wide).

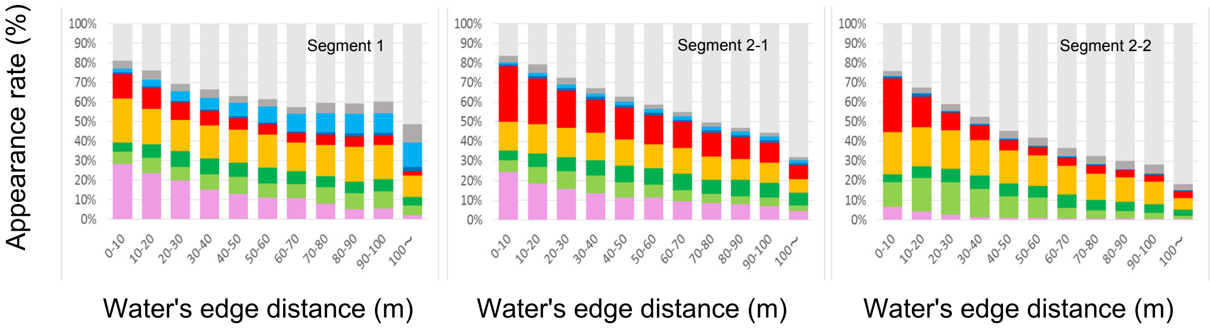


Figure 3. Distribution characteristics of plant communities by water's edge distance (country-wide).

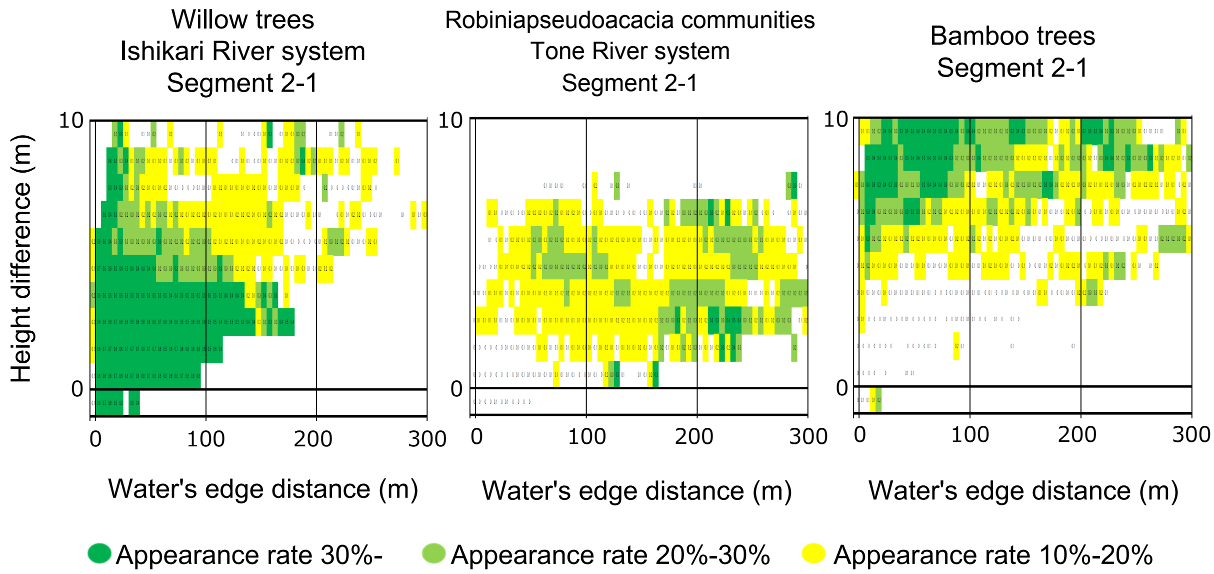


Figure 4. Example for distribution characteristics of plant communities by height difference and water's edge distance.

Figure 4 shows an example of the Tone River system. The appearance rate of other planted vegetation and Robiniapseudoacacia is high, 20% or more, in the area where the height difference is 2-8 m and the distance from water's edge is 150-300 m. Where the height difference is 1-2 m, there are still areas where the appearance rate is 30% or more, but where the height difference is under 1 m, there are only areas where the appearance rate is less than 10%.

2.4 Difference in the distribution characteristics of plant communities in low height-difference zones by region

We organized the appearance rates of plant communities within a height difference of under 1 m in segments 1, 2-1, and 2-2 of 174 rivers in 71 river systems across the country (Table 1), in order to clarify the distribution of plant communities in the areas of the regular water level, which is the standard level for excavation in many projects. Here, we described natural bare land, monocotyledon communities, and willow woods, for all of which the appearance rate is high, without consideration for artifacts, cultivated land, etc.

For natural bare land, the appearance rate is high in segments 1 and 2-1. Particularly, in segment 1, the average appearance rate is over 40% in rivers of the Tohoku, Hokuriku, and Chubu regions. In the Chubu region, the appearance rate is over 40% in segments 1, 2-1, and 2-2. In contrast, the appearance rate is under 20% in segments 1, 2-1 and 2-2 in Hokkaido, and in segments 1 and 2-1 in the Chugoku region (Fig. 5).

For monocotyledon communities, the appearance rate in Hokkaido is lower than those of rivers in other regions, under 5% in all segments. In the Hokuriku, Kinki, Chugoku, and Kyushu regions, the appearance rate is high, over 20%, in all segments. In the Tohoku region, the rate is over 20% in segment 2-2 (Fig. 5).

For willow trees, the appearance rate is high in Hokkaido, around 60% in all segments, showing a great difference from other regions, where the rate is under 20%. In contrast, the appearance rate is low, under 5%, in all segments of the Kyushu and Shikoku regions. Additionally, the appearance rate is higher in segment 2-1 in the Chugoku region and in segment 2-2 in the Hokuriku, Kanto, Chubu, and Kinki regions (Fig. 5).

Table 1. Target rivers and data points for analysis of plant communities with a height difference of under 1 m.

Regions	Number of river systems	Number of rivers	Data points		
			Segment 1	Segment 2-1	Segment 2-2
Hokkaido	5	15	13603	10615	10940
Tohoku	9	25	1679	44076	8301
Kanto	6	17	6931	4910	23048
Hokuriku	9	19	11743	8885	9675
Chubu	10	35	15161	19452	22417
Kinki	9	20	10160	13092	17232
Chugoku	10	18	3092	12184	14259
Shikoku	4	8	0	18530	5968
Kyushu	9	17	1054	7742	2226
Total	71	174	63423	139486	114066

Target rivers include those for which data was partially obtained.

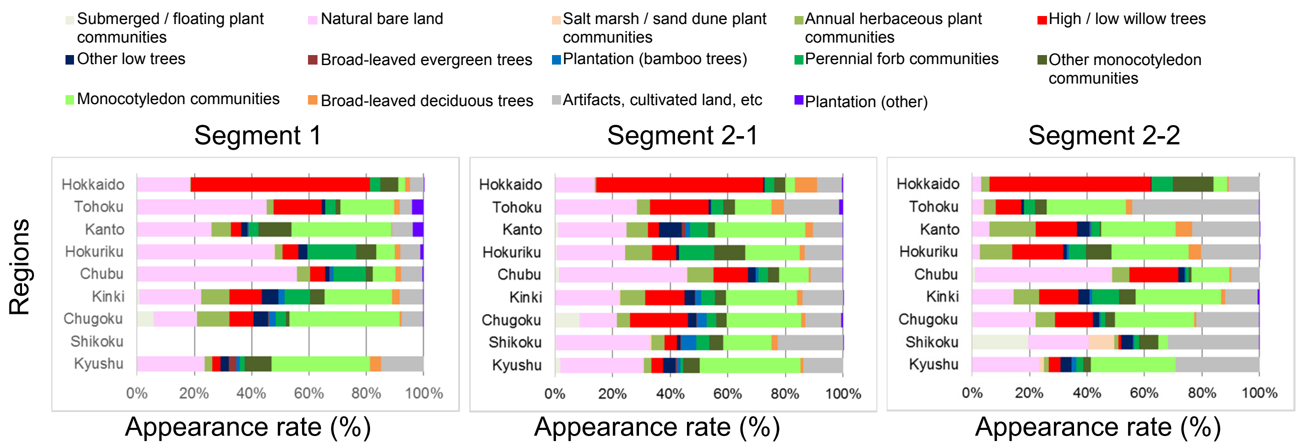


Figure 5. Plant community distribution with a height difference of under 1 m (by region).

3 RELATIONSHIPS BETWEEN THE DOMINANT PLANT COMMUNITIES AFTER EXCAVATION AND THE FACTORS OF THEIR FORMATION

We chose 48 projects in 23 rivers where five years or more had passed since excavation, to identify the dominant plant communities after excavation. We also organized the relationships between the excavation height and the number of flooding events exceeding the average annual maximum flow after excavation.

3.1 Analytical method

We studied excavation projects at 48 sites in 23 rivers to analyze the relationships between the dominant plant communities with a height difference of under 1 m, excavation height, and the number of flooding events, and the dominating vegetation communities after excavation, in segments where an excavation site was located, using the data on plant community categories, height difference, and distance from water's edge obtained in the same way as in section 2.1. Note that we analyzed three plant community categories, i.e., herbaceous communities, which were integrated into one category, natural bare land, and willow trees.

The dominant community vegetation within a height difference of under 1 m in each segment was organized based on the data of the fourth River Census Vegetation Map. As subjects of the analysis on changes in plant communities after excavation were selected projects for which five or more years had passed after excavation and necessary data could be obtained. For the year, shape, and height of excavation in each project, we obtained the data from each river office that undertook the relevant excavation projects. We also organized the number of flooding events exceeding the average annual maximum flow after excavation based on the data from the hydrology and water quality database.

3.2 Relationship with the dominant plant communities in low height-difference zones (under 1 m) of the segments where excavation sites were located

Table 2 shows the classifications of plant communities that dominated five or more years after excavation in each segment. The percentage of sites where willow trees dominated and grew is zero in segment 1, 26% in segment 2-1, and 39% in segment 2-2.

Table 3 organizes the relationships between the plant communities that dominated in an area within 1 m of height difference in the segments where an excavation site was located and the plant communities that dominated after excavation. As a result, in segment 2-1, when a herbaceous community dominates in an area within a height difference of under 1 m, the dominant plant community after excavation was the herbaceous community with a high probability of 80%, while no clear relationships were found in other dominant plant communities. In contrast, in segment 2-2, even if the dominant plant community in an area within a height difference of under 1 m was a herbaceous community, natural bare land, or willow trees, the same plant communities dominated after excavation with high probability. However, there was only one case where natural bare land dominated.

Table 2. Dominant plant communities after excavation.

Segment	Dominant plant communities after excavation	Number of excavated spots (Left) and ratio thereof to the total number in each segment (Right)	
1	2. Herbaceous communities	1	33%
	3. Natural bare land	2	67%
2-1	1. Willow trees	7	26%
	2. Herbaceous communities	14	52%
	3. Natural bare land	6	22%
2-2	1. Willow trees	7	39%
	2. Herbaceous communities	8	44%
	3. Natural bare land	2	11%
	4. Artificial bare land	1	6%

Table 3. Relationships between dominant plant communities with a height difference of under 1 m and dominant plant communities after excavation.

Segment	Dominant plant communities with a height difference of under 1 m	Number of applicable excavation projects	Dominant communities after excavation					
			Natural bare land		Herbaceous communities		Willow trees	
			Number of spots	Ratio	Number of spots	Ratio	Number of spots	Ratio
2-1	Natural bare land	8	2	25%	3	38%	3	38%
	Herbaceous communities	5	1	20%	4	80%	0	0%
	Willow trees	3	1	33%	2	67%	0	0%
2-2	Natural bare land	1	1	100%	0	0%	0	0%
	Herbaceous communities	6	0	0%	5	83%	1	17%
	Willow trees	7	1	14%	0	0%	6	86%

3.3 Relationships with the number and frequency of flooding events

Table 4 organizes the dominant plant communities, frequency of flooding events, and the number of flooding events, after excavation. In segment 2-1, the number of flooding events is high in sites where natural bare land formed after excavation, while in segment 2-2, the number is the lowest in sites where natural bare land formed and high where willow trees grew.

3.4 Relationship with excavation height

Table 5 organizes the dominant plant communities after excavation and excavation height. In both segments 2-1 and 2-2, there are no areas where willow trees dominated after excavation in projects where the excavation height was lower than the regular water level. However, the results of this study are not sufficient for determining the effect of excavation under the regular water level using willow trees as the control, since it was not confirmed in these projects that willow trees were the dominant plant community before excavation or the dominant plant community in the excavation area where the height difference was under 1 m in the relevant segment.

Table 4. Dominant plant communities after excavation and the number and frequency of flooding events.

Segment	Dominant plant communities after excavation	Number of flooding events	Frequency of flooding events (times/year)
1	2. Herbaceous communities	1.00	0.20
	3. Natural bare land	3.50	0.63
2-1	1. Willow trees	2.67	0.46
	2. Herbaceous communities	2.50	0.38
	3. Natural bare land	3.40	0.41
2-2	1. Willow trees	5.73	0.74
	2. Herbaceous communities	3.75	0.48
	3. Natural bare land	2.50	0.39
	4. Artificial bare land	2.00	0.33

Table 5. Dominant plant communities after excavation and excavation height.

Segment	Dominant plant communities after excavation	Higher than the regular water level	Regular water level	Lower than the regular water level
1	2. Herbaceous communities	1	0	0
	3. Natural bare land	2	0	0
2-1	1. Willow trees	4	1	0
	2. Herbaceous communities	10	0	3
	3. Natural bare land	2	1	3
2-2	1. Willow trees	4	2	0
	2. Herbaceous communities	2	2	4
	3. Natural bare land	1	0	1
	4. Artificial bare land	0	0	1

3.5 Other factors that affect changes in plant communities after excavation

From the results of this study, flooding is considered to have an effect on the formation of natural bare land since the average number of flooding events is higher in rivers where the dominant plant communities changed to natural bare land after excavation than in rivers where willow trees or herbaceous communities dominated (Fig. 4). However, the number / frequency of flooding events could not be the only factor since, looking at the rivers individually, there are cases where the number / frequency of flooding events is low in rivers where natural bare land dominated after excavation and inversely high in rivers where willow trees or herbaceous communities dominated.

This study adopted, as an indicator, only the number of flooding events over the average annual maximum flow, and excluded from the scope of analysis the scale of flooding, tractive force, corrosion by flooding, and impact of deposition on plant communities. Since it is clarified by some existing studies and a lot of projects that the loss of vegetation, deposition, etc. due to flooding affects the process of changes in plant communities [5)], it would be a challenge to organize the relationship with the invasion of willow trees using tractive force and topographic changes as indicators.

Additionally, the factors that affect changes in plant communities include external factors such as the bed material and frequency of submersion, and artificial factors such as the timing of excavation, topsoil treatment, and maintenance, in addition to the subjects of analysis in this study. Since these individual factors are expected to complexly affect changes in plant communities after excavation, it would be effective to advance statistical analysis in the future by increasing the number of examples, etc.

4 EFFECT OF EXCAVATION ON WILLOW TREES, ROBINIAPSEUDOACACIA COMMUNITIES, AND BAMBOO TREES, WHICH ARE THE MAIN TYPES OF TREE GROWTH

4.1 A case of excavation in the Toyo River

As a result of excavating a site in segment 2-1 in 2005 where bamboo trees dominated, the site is now, five years after the excavation, dominated by monocotyledon communities (Fig. 6). In the Toyo River system, the appearance rate of bamboo trees is high in an area where the height difference is over 3 m, and for annual herbaceous plant and monocotyledon communities in an area where the height difference is under 3 m. The height difference after excavation is under 3 m in many areas, which represents the height difference zone where monocotyledon communities are likely to dominate.

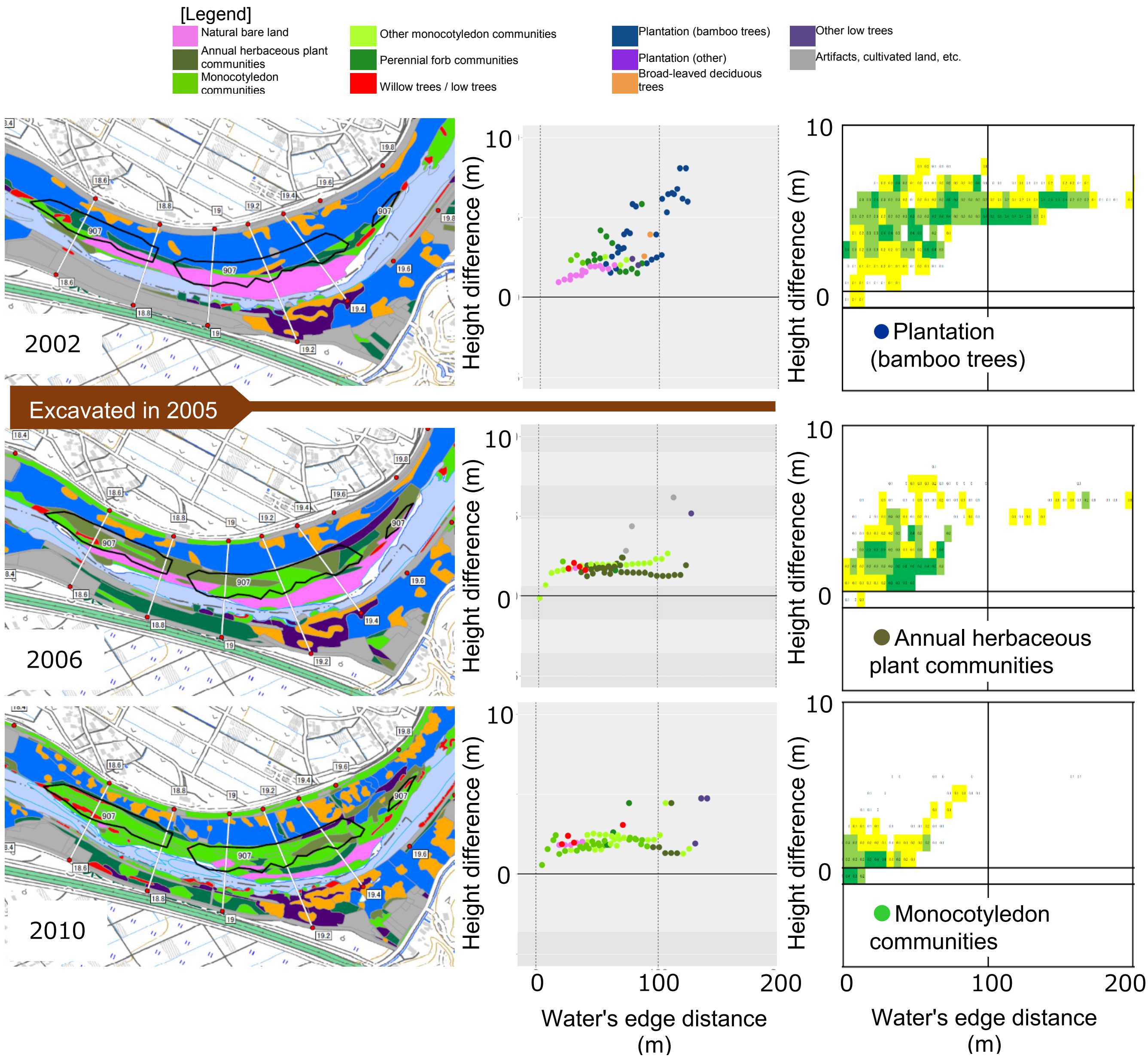


Figure 6. Excavation project of Toyo River Segment 2-1.
(Left: Changes in plant communities, Middle: Changes in plant communities on the cross section of excavation area, Right: Distribution characteristics of plant communities in Segment 2-1 [FY2006]).

4.2 A case of excavation in the Ibi River

As a result of excavating a site in segment 2-2 in 2005 where perennial forb communities dominated, natural bare land formed about two years after excavation across the entire site, but willow trees covered the site seven years after excavation (Fig. 7). In the Kiso River system, which includes the Ibi River, willow trees and natural bare land dominate where the height difference is under 1 m. Particularly, where the distance from water's edge is under 10 m, the appearance rate of willow trees is not less than 30% and, in many of these sites, willow trees are more dominant than natural bare land. The height difference after excavation is maintained mostly in the range of 0 to 1 m, which represents the height difference zone where willow trees are likely to dominate.

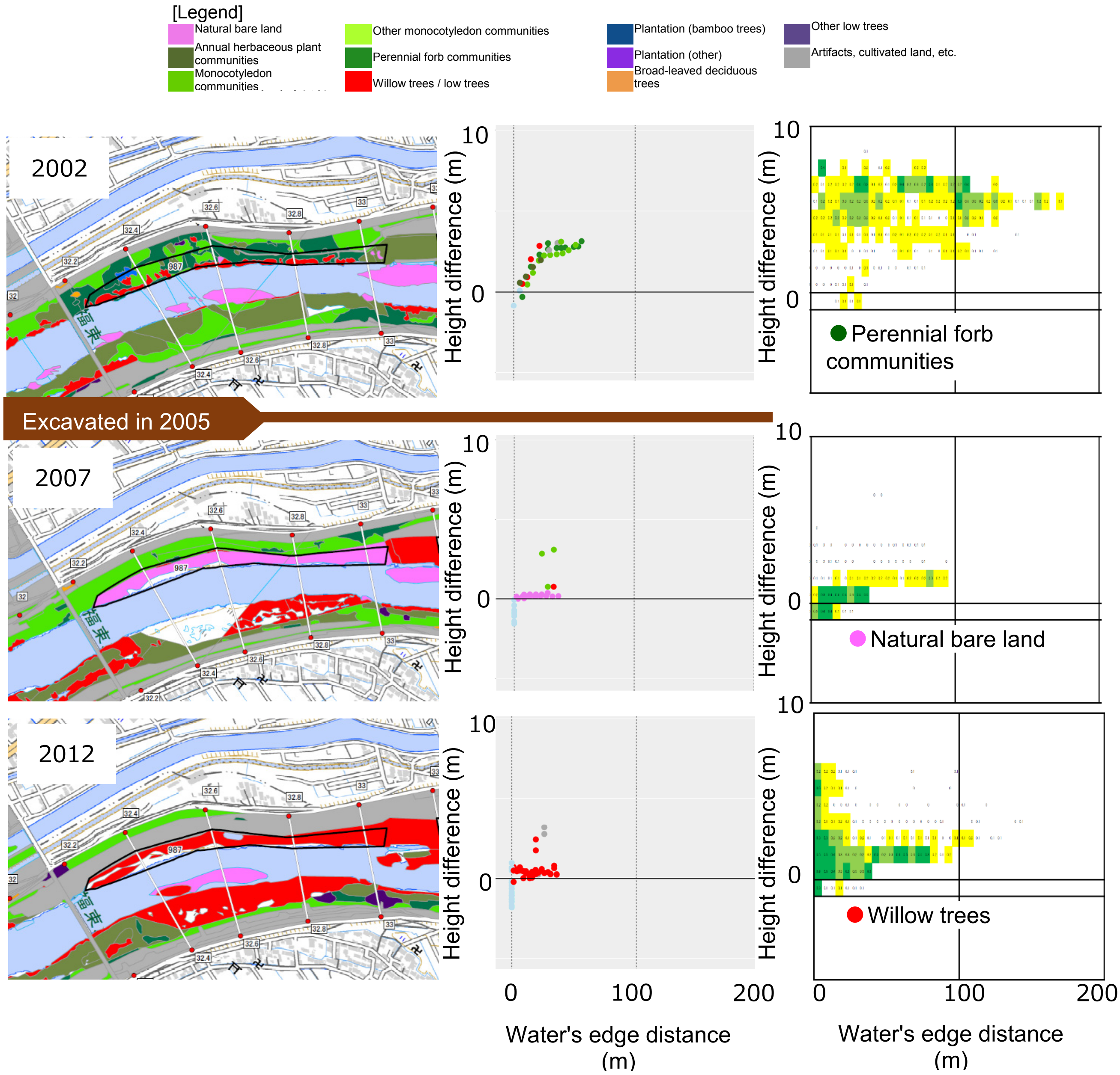


Figure 7. Excavation project of Ibi River Segment 2-2.
(Left: Changes in plant communities, Middle: Changes in plant communities on the cross section of excavation area, Right: Distribution characteristics of plant communities in Segment 2-2 [FY2007]).

4.3 Tree species considered effective for excavation

From the results of organizing data on rivers across the country, it was confirmed that distribution characteristics are different between willow trees, Robiniapseudoacacia communities, and bamboo trees (Fig. 2).

The appearance rate is high for Robiniapseudoacacia communities (confirmed in "Plantation (other)") where the height difference in segment 1 is over 3 m, and for bamboo trees where the height difference in segment 2-1 is over 6 m (Fig. 4). Thus, the distribution characteristics of plant communities suggest that excavation is an effective control measure to lower the height difference. Actually, in a case of excavation in the Toyo River, the bamboo trees in a high height-difference zone were replaced by plant communities where monocotyledon communities dominated as a result of excavation, which remained for over five years (Fig. 6)

In contrast, the appearance rate of willow trees is high in segments 2-1 and 2-2 where the height difference is under 2 m, which suggests that they are likely to invade after excavation (Fig. 2). Actually, for the sites where plant communities that survived five years or more after excavation, willow trees are dominant in 7 out of 27 sites in segment 2-1 and in 7 out of 18 sites in segment 2-2, and there are no sites where other tree communities dominate (Table 2). The aforementioned results suggest that excavation to a height equivalent to the regular water level is not sufficient as a measure to control willow trees.

It was also suggested that excavation to a height under the regular water level is effective towards controlling the invasion of willow trees, because there are no cases found in this study where willow trees dominated after excavation in projects where the excavation height was set under the regular water level (Table 5). However, since there are no sites where willow trees were dominant before excavation and there were not enough examples, it is necessary to collect and verify examples with the focus on the excavation sites where willow trees are dominant.

5 CONCLUSIONS

In this paper, we have organized the distribution characteristics of plant communities in rivers across the country with a focus on the two factors of height difference and distance from water's edge. We have also studied some excavation projects to analyze the relationships between the distribution characteristics of plant communities with a height difference of under 1 m, excavation height, and the characteristics of flooding with the plant communities after excavation, in the segments where excavation sites are located, and reached the following conclusions.

- The distribution characteristics of plant communities by the height difference and the distance from the water's edge are different according to region and segment.
- The distribution characteristics of willow trees, Robiniapseudoacacia communities, and bamboo trees, which are the main types of tree growth, are clearly different according to the height difference.
- Robiniapseudoacacia communities and bamboo trees can be controlled by cutting.
- In segment 2-2, the dominant plant communities after excavation may be related to the dominant plant communities where the height difference is under 1 m in the relevant segment.
- In segment 2-1, the average number of flooding events is high in rivers where natural bare land has dominated after excavation, which suggests that flooding may have an effect on the maintenance of natural bare land.

At present, no technology has been established that forecasts with high accuracy plant communities that form after channel excavation. The results of this study suggest that the dominant plant communities in the low height-difference zone are highly likely to continue to dominate after excavation in segment 2-2. It is, therefore, suggested that height difference is one of the main factors for plant community formation, which shows the possibility that height difference can be an indicator for forecasting vegetation after excavation. However, since there are other factors of vegetation formation, including the impact of flooding, surface soil, height of groundwater level, and alien plant communities, height difference alone carries uncertainty as a forecasting technique.

In the future, it is necessary to advance the clarification of the mechanism of plant community formation and to improve accuracy as a forecasting technique, by identifying the conditions under which the height difference and distance from the water's edge can be used in combination with test construction on the site, etc., to forecast plant community formation.

For what regards climate change, it is particularly important to clarify the response of vegetation to changes in the scale, frequency, and time of flooding, since changes in flooding patterns due to changes in precipitation patterns and changes in flooding due to changes in air temperature are likely to impact vegetation.

ACKNOWLEDGEMENTS

We sincerely appreciate the guidance and advice we have received from the people in the River Environment Division, Water and Disaster Management Bureau, MLIT in connection with this study.

Proceedings of the 37th IAHR World Congress
August 13 – 18, 2017, Kuala Lumpur, Malaysia

STUDY ON WATER QUALITY COUNTERMEASURES IN CONSIDERATION OF UNCERTAINTY IN LAKE AND RESERVOIR

DAIKI KAKINUMA [(1)] & TADASHI YAMADA [(2)]

[(1)] Graduate School of Science and Engineering, Chuo University, 1-13-27, Kasuga, Bunkyo-ku, Tokyo, 112-8851, Japan, kakinuma@civil.chuo-u.ac.jp
[(2)] Faculty of Science and Engineering, Chuo University, 1-13-27, Kasuga, Bunkyo-ku, Tokyo, 112-8851, Japan, yamada@civil.chuo-u.ac.jp

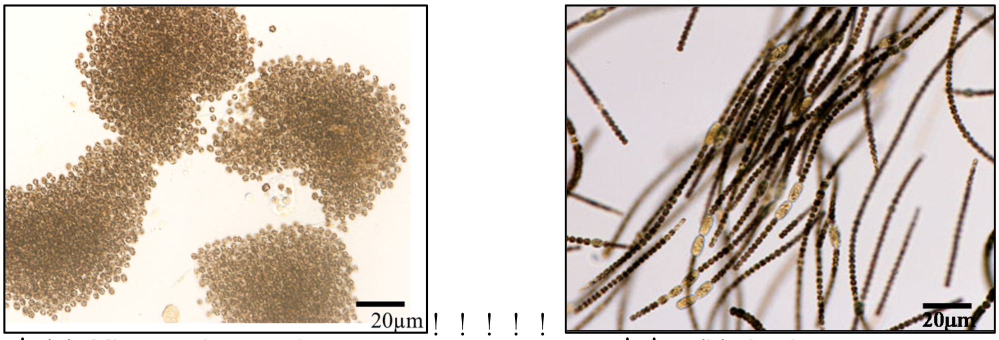
ABSTRACT

An alga bloom is one of the problems in lakes and reservoirs worldwide. The reason why blue-green algae become a problem is that odors such as 2-methylisoborneol and geosmin can be generated, and water body turns into light blue and leads to landscape deterioration at the time of decomposition. In addition, it can be harmful to livestock and human health due to its liver poison. Blue-green algae occur not only in lakes and reservoirs, but also in slow water flow rivers. Therefore, improvement of hydrophilicity and waterside is necessary, so river management considering water quality is very important at present. In this study, we assumed the environment has a lot of nutrients like nitrogen and phosphorous and propose a method to determine the volume of water conduction to prevent the occurrence of blue-green algae by numerical analysis and experiments. By adding a water conduction effect (referred to as washout effect) to the logistic equation, which describes the growth of an organism, the volume of water can be determined by the relation between the growth rate of algae and the rotation rate (Inverse of retention time). In other words, it is better to conduct water more quickly than the growth rate of blue-green algae. We investigated this relationship by indoor culture experiments with varying retention time and observation at Lake Tega-numa. Next, we proposed countermeasure for blue-green algae that contain uncertainty. The growth rate of algae uncertainty change depends on the light condition, water temperature, algae volume and cell condition. Thus, we proposed a new method that adds a washout effect term to a logistic equation and considering uncertainty into growth rate. We showed that it is possible to calculate the inflow discharge to flush out algae considering probability theory using new method.

Keywords: Closed water body; Washout effect; Growth rate; Rotation rate; Uncertainty.

1 INTRODUCTION

A water bloom is a phenomenon that water surface changes appreciably by increasing floating algae on lake or reservoir and gathering on the surface of the water. It is classified red tide and algal bloom (I. Ikushima., 1987). Red tide is caused by Cryptophyceae, Dinoflagellata and Blue-green algae is caused by Blue-green algae and Cyanobacteria (I. Somiya., 1997). Algal bloom generally exists on the water area (mainly closed water body) which has affluent nutrients taken by it. Figure 1 is Microcystis aeruginosa and Anabaena classified in Blue-green algae. Blue-green algae exude a toxin and offensive odors, and they have high planktonic and adaptability compared to the other algae. In particular, Blue-green algae is resistant to high water temperature and high solar radiation, and the optimum water temperature is higher than other algae (I. Ikushima., 1987; I. Somiya., 1997). They generate Geosmin and 2-MIB at the time of decomposition. In addition, some of them generate Arkanoid and Hepatotoxin Microcystin, which is the problem over the world because it is harmful to



(a) Microcystis aeruginosa (b) Anabaena

Figure 1. Blue green algae.

livestock, fish and human body. Blue-green algae occurs not only in lakes and reservoirs, but also in slow flowing rivers.

Two kinds of countermeasures to algal bloom have worked out in Japan, which are temporal countermeasures and fundamental countermeasures. Temporal countermeasures are plants purification to remove nutritive salt, dredging, and aeration to add oxygen and make a flow of water. Fundamental countermeasures are water conduction with river water or reclaimed wastewater to flush out Blue-green algae. This study focuses on water conduction, and proposed the method to determine the volume of water conduction in order to deter an increasing of algal bloom by adding term of flushing out to logistic equation, which expresses change of organism individual number, and discussed this term of flushing out theoretically by indoor culture experiments.

2 THEORY AND METHODS

2.1 Previous studies

Ecosystem and hydraulic model are generally used to express material circulation in water. In terms of structure of ecological model, it is calculated by using a number of variants such as Chlorophyll-a, COD, Nitrogen. And it also has a number of parameters which are estimated by dedicating much of time, cost, and effort. And for water conduction to improve water quality, volume of water conduction is computed by ecological model. Eq. [1] is the equation of chlorophyll-a in an ecosystem model, which has 6 terms meaning increase, inflow, outflow, respiration rate of phytoplankton, mortality rate of phytoplankton, and sedimentation. Of these terms, the most important one is the increase term expressed at Eq. [2]. Increase term can be estimated by multiplying max generating rate, nutritive salt (Inorganic Nitrogen, Inorganic Phosphorus) solar radiation, water temperature (J. L. Monod., 1942; J. H. Steel., 1962; R. W. Eppley,. 1972). In other words, by these given environment conditions express the increase of Glue-green algae. Discussing countermeasure of water pollution, the safest countermeasure and the most dangerous water quality condition (eutrophication) should be considered, and that condition is the max increase rate.

$$\frac{dC}{dt} = r(1-\varepsilon) - \frac{C \cdot q_{in}}{V} - \frac{C \cdot q_{out}}{V} - k_r C - k_d C - \frac{v_p C}{h} \qquad [1]$$

$$r = r_{\max}\left(\frac{N}{N+K_N}\frac{P}{P+K_P}\right)\frac{I}{I_{opt}}\exp\left(1-\frac{I}{I_{opt}}\right)\frac{T}{T_{opt}}\exp\left(1-\frac{T}{T_{opt}}\right)\cdot C \qquad [2]$$

$C(t)$ is the chlorophyll-a [mg L-1]. $N(t)$ is the Inorganic nitrogen [mg L-1]. $P(t)$ is the Inorganic phosphorus [mg L^{-1}]. $I(t)$ is the Light intensity [MJ $m^{-2}day^{-1}$]. $T(t)$ is the water temperature [°C]. V is the Volume [m^3]. h is the water depth [m]. $\varepsilon, K_r, K_d, q_{in}, q_{out}$ are parameters, which are decided by the observation and experiment. $r(t)$ is the growth rate [day^{-1}]. Growth rate decided by Maximum Growth rate of phytoplankton, Inorganic nutrients Phosphorous, Nitrogen, Light intensity and Water temperature. There are experimental formula.

2.2 Add the term of washout effect to logistic equation.

Eq. [3] is the logistic equation. This equation is the first Mathematical ecology model, and is still used at present. Eq. [4] is the logistic equation added the term of washout effect. Eq. [5] means when rotation rate is larger than growth rate, algae cannot increase themselves because they are flush out before they growth. This is the key point of this study. Figure 2 shows the fluctuation of number when growth rate is larger than rotation rate, and smaller case. Growth rate of algae is different in each species. Growth rate of Microcystis, which is the subject Blue-green algae of this study, is given with the width between 0.8-1.8 day^{-1} (N. Imamura., 1981; M. Takahashi et al., 1981; T. Iwai., 1960; N. Ohkubo et al., 1991). The reason why it has the width is the rate fluctuates according to many factors such as light environment condition, water temperature, condition of cell, and situation of sedimentation. In order to prove this relationship, theoretical discussions are conducted by culture experiment and observation.

$$\frac{dN}{dt} = rN\left(1-\frac{N}{K}\right) \qquad [3]$$

$N(t)$ is the number. K is the carrying capacity. This parameter shows the maximum that an algae can multiply in the environment.

! ! ! ! ! ! ! $$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) - C(t)\cdot Q(t)$$! [4]

$C(t)$ is the concentration. $Q(t)$ is the inflow [m^3 s^{-1}]. And volume is constant, Rotation rate (D) is the volume of water conduction divided volume. Eq. [4] can be written in the following form:

$$\frac{dC}{dt} = (r - D)\cdot C(t)\left(1 - \frac{C(t)}{K'}\right) \qquad \left(K' = \frac{r-D}{r}K\right) \quad [5]$$

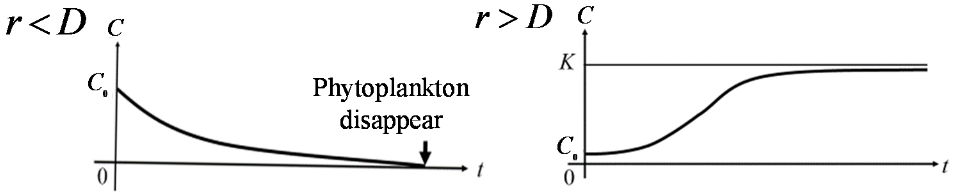


Figure 2. The relations of growth rate and rotation rate.

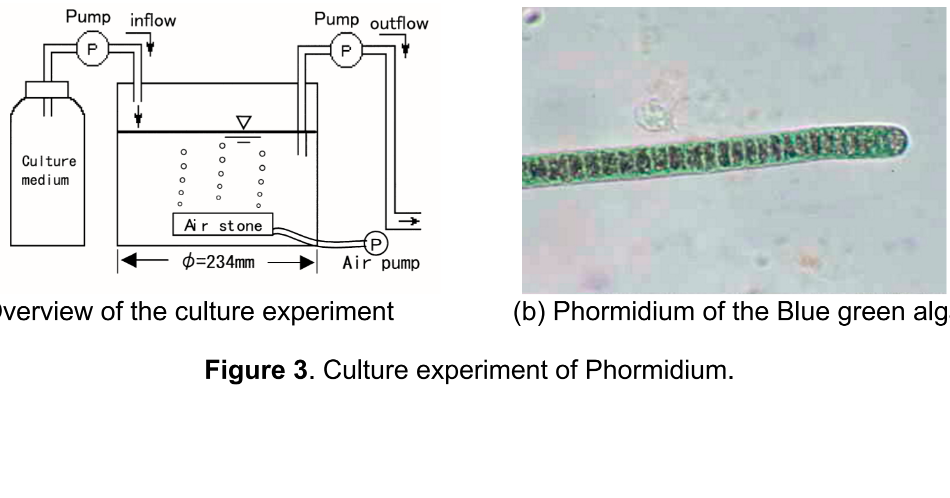
3 PROOF BY CULTURE EXPERIMENTS

3.1 Culture experiment overview

Generally, the method of culture of phytoplankton is the rotation culture that the object organism and broth are put into culture tank which is closed. On the other hand, continuous culture is the way to put broth continuously, and it is the closer case to actual situation of reservoirs and lakes.

Continuous culture are classified chemostat culture whose supply volume and supply rate are constant, and turbidstat culture whose supply volume are controlled to have the number of organism in culture tank to be constant (Y. Sudo., 1986). In order to the experiment condition be close to actual increase of Blue-green algae in reservoir, continuous chemostat culture which is complete mixing system and has constant light, water temperature, density of supply nutritive salt, and supply rate is adopted. The Phytoplankton used at the experiment is Phormidium, which is one of the Blue-green algae and the cause of the mold odor at reservoirs.

The condition of this experiment was that water temperature was 20 degree Celsius and illumination was 20 lux. White fluorescent lamp, air pump and air stone was used and culture tank was mixed state. Figure 3(a) shows the overview of the continuous culture experiment, and Figure 3(b) shows Phormidium which was used at the experiment. The condition of Residence time was adjusted by the supply rate of broth per time to it be 0.7, 1, 1.2, 2, 3, 5, 7, 10, 20 day^{-1}, and growth rate was estimated by the relationship between culture time and Chlorophyll-a density in culture tank. The flow of this experiment was that, at first, putting broth into the culture tank, and inoculating Phormidium which was the test algae in order for Chlorophyll-a density to be 1mg L^{-1}. After that, 2 or 3 days rotation culture was conducted, while observing the number of cell frequently, and changed over continuous culture experiment with supplying broth.



! ! !! (a) Overview of the culture experiment (b) Phormidium of the Blue green algae

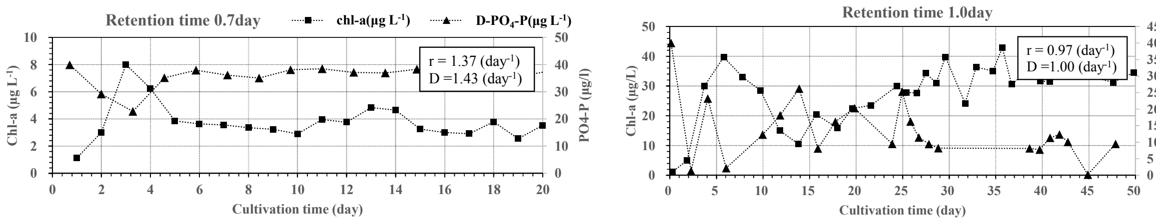
Figure 3. Culture experiment of Phormidium.

  / ISSN 1562-6865 (Online) - ISSN 1063-7710 (Print)

3.2 Result of experiment

Of the results of experiment, 0.7 and 1.0 days are shown (Figure 4). The growth rate and rotation rate were for 0.7 day: r=1.37, D=1.43, and for 1.0 day: 0.97, D=1.00. The growth rate calculated from the conservation equation of chlorophyll-a concentration in the culture tank.

Figure 4 shows the relationship obtained from the experiment between rotation rate and chlorophyll-a concentration that is the retention time. Generally, death rate and re-elution rate of the limiting substrate by decomposition are ignored under the favorable conditions for organisms to regenerate. However, under the unfavorable condition, for organisms to regenerate like increasing of stationary phase and death phase, death rate is regarded to be significant. As a result, the retention time condition is shorter than the retention time at which the algae volume is the maximum (retention time 3 day, rotation rate 0.33 day^{-1}); the growth rate becomes larger as the retention time is shorter, but the algae decreases as the retention time is shorter because algae outflows more than increase. Also, when the retention time is 20 or 40 days (0.05, 0.025 day^{-1}), we found that the algae decreases as the retention time is longer because of the death rate is faster than the growth of algae. This experiment proved that the relationship between growth rate and rotation rate is right.



! !! (a) Retention time 0.7 day‡ r=1.37↩ D=1.43 ! ! (b) Retention time 1.0 day‡ r=0.97, D=1.00

Figure 4. The results of the experiment.

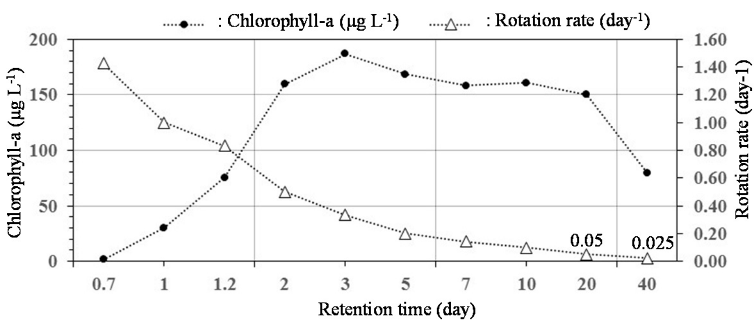


Figure 5. This figure is the experiments results. Horizontal axis is retention time, vertical axis are chlorophyll-a (μg L^{-1}) and rotation rate (day^{-1}). When retention time are 0.7, 1.0, 1.2 days algae cannot growth well because rotation rate higher than growth rate.

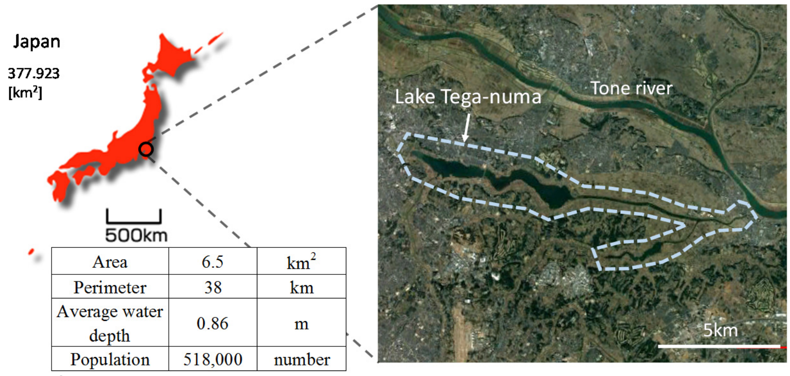
4 CASE OF LAKE TEGA-NUMA

4.1 Lake Tega-numa Overview

Overview of Lake Tega-numa is shown on Figure 6. Lake Tega-numa is the Lake located close to Tokyo. The area is 6.5 km^2 and averaged water depth is 0.86 m. From 1974 to 2001, this lake had the worst water quality in all the lakes in Japan. However, Thanks to some countermeasures and completion of Kita-Chiba water supply using Tone river water, since 1990s, water quality have been improving. This water supply project in Lake Tega-numa is one of the large-scale projects in Japan's water quality improvement project conducted by the country. This water conduit is an important facility for river management which is also used for urban water and prevention of inundation.

4.2 Fluctuation of Blue-green algae

Figure 7 shows the time series data of the amount of each algae, and it shows Blue-green algae decreased after water supply started. Increase of Blue-green algae in 2001 was due to the water conduction was stopped because of the risk of water disaster and irrigation. The rotation rate was changed from 0.07 day^{-1} to 0.12 day^{-1}. After water supply, Green algae also decreased and Diatoms was not changed much.



Area	6.5	km^2
Perimeter	38	km
Average water depth	0.86	m
Population	518,000	number

Figure 6. Topography of Lake Tega-numa and Tone river. Lake Tega-numa's water quality is the worst in Japan until 2001. And then after that the water quality improved by project using the water of the Tone river.

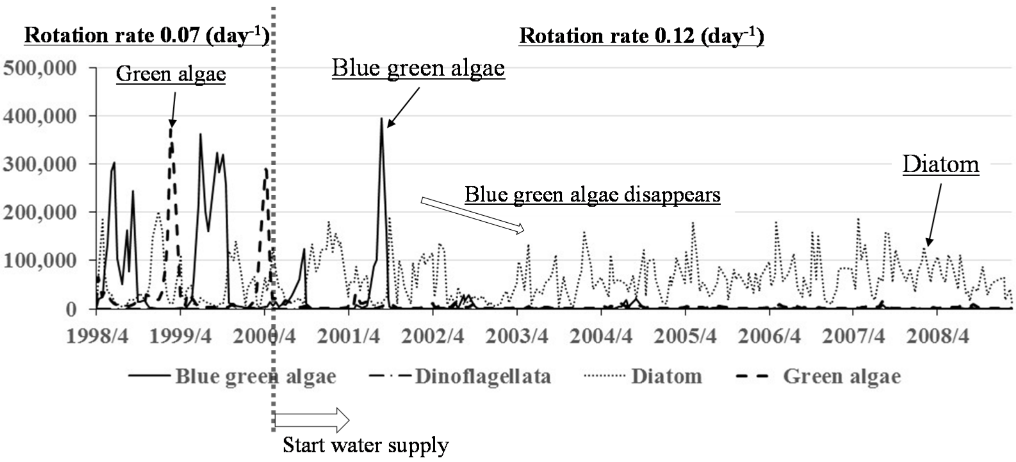


Figure 7. This Figure is observation results from 1998 to 2008 years of each algae in Lake Tega-numa. Horizontal axis is time, vertical axis are cell number. After the project, the rotation time changed 0.07 to 0.12 (day^{-1}), blue-green algae didn't occur after project, but diatom did not change.

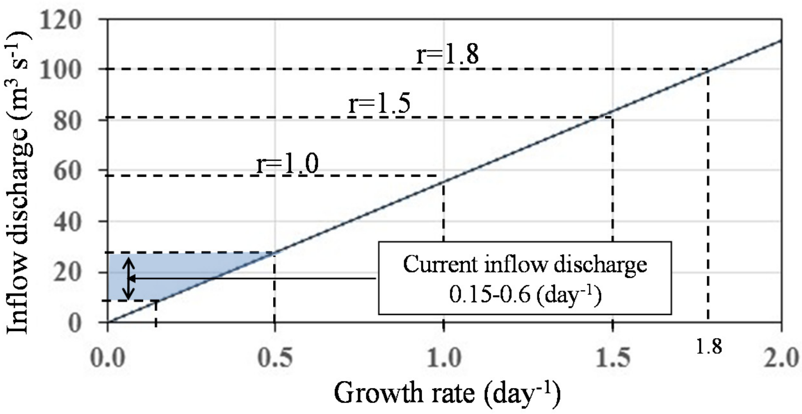


Figure 8. This Figure is the relation between inflow discharge and growth rate when Blue-green algae is removed in Lake Tega-Numa.

This is assumed because growth rate of Blue-green algae and Green algae is slow compared to Diatoms, and they are flush out before they regenerate. However, Blue-green algae are removed although rotation rate (0.12 day^{-1}) is slower than growth rate (0.15-1.5 day^{-1}).

This is the contradiction point against the theory. Figure 8 is the relation between inflow discharge and growth rate when Blue-green algae is removed in Lake Tega-Numa by using Eq. [4], which is explained in section 2. Growth rate is 0.15-1.8 day^{-1}, we use the average of 0.85 day^{-1}, and the volume of inflow discharge to flush out the growth rate, from 50 m^3 s^{-1} is needed. Averaged volume of inflow discharge of the present inflow discharge is from 20 to 30 m^3 s^{-1}, and it has the gap of about 20 m^3 s^{-1} when growth rate is 0.85 day^{-1}, or the gap of 50 m^3 s^{-1} when growth rate is 1.5 day^{-1}. The next section discusses this gap.

5 GRWOTH RATE CONSIDERING THE UNCERTAINTY

This section explains the reason of why the inflow discharge shown by equation at the section 2 and actual inflow discharge in Lake Tega-Numa is different by considering two kinds of uncertainty. The first is the fluctuation factor by site of observatory. It is generally impossible to observe a value that is spaciously dense and the value at certain site is regarded as representative value. However, in fact a value has variability according to a site, and even at the same site, the same value cannot be observed according to observation time and the way of observation. The second is the uncertainty of growth rate of algae due to internal and external factor. A growth rate of algae is variable depending on light condition and water temperature. In addition, volume of algae and condition of sell also bring about an uncertainty. This study focuses on the latter one. Phenomena including uncertainty in mathematical ecology are widely recognized (H. Haario et al., 2009; H. Harasawa. 1985; E. Teramoto et al., 1997). However, few studies have focused on the water quality improvement countermeasures while considering the uncertainty. Therefore, in this study, we investigated the theory that adds uncertain components to the growth rate in logistic equation with washout effect. As the first step in proposing countermeasures that include uncertainty, based on the case of Lake Tega-numa.

The following equation:

$$\frac{dC}{dt} = (r(t) - D)\cdot C(t)\left(1 - \frac{C(t)}{K'}\right) \qquad \left(K' = \frac{r-D}{r}K\right) \tag{6}$$

This is exactly the purpose of analyzing cell number or concentration. The blue line in Figure 9 shows a basic solution of Eq. [6].

Next, we are going to introduce the stochastic differential equation theory into rainfall-runoff process based on work of K. Yoshimi and T. Yamada (2016). The Ito's stochastic differential equation and the Fokker-Planck equation of rainfall-runoff process considering the uncertainty of rainfall intensity will be suggested. Therefore, we apply this suggestion to the ecosystem model. Eq. [7] is a first order ordinary differential equation about C, and it can be written in the following form:

$$dC = (r(t) - D)\cdot C(t)\left(1 - \frac{C(t)}{K'}\right)dt \tag{7}$$

r(t) is the growth rate. However, in a practical problem, it is very difficult to know the instantaneous value of growth rate, so we divided the r(t) into two parts: an average value between a small period of time, and a random part represents the difference between the instantaneous value and the average value:

$$r(t) = \bar{r}(t) + r'(t) \tag{8}$$

Substituting Eq. [8] into Eq. [9], we get:

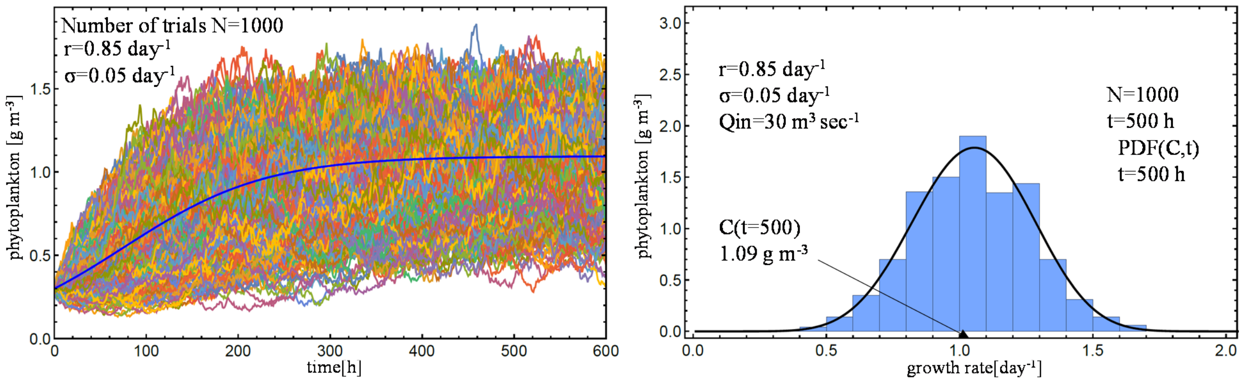
$$dC = (\bar{r}(t)\cdot A - D)\cdot C(t)dt + C(t)\cdot A\cdot r' dw \qquad \left(A = 1 - \frac{C}{K}\right) \tag{9}$$

Eq. [9] has the same form as Ito's stochastic differential equation. σ is the standard division of r'(t) and w(t) is the standard Winner process. It had been shown that Eq. [9] is equivalent to the following Fokker-Planck equation.

$$\frac{\partial P(C,t)}{\partial t} = -\frac{\partial(\bar{r}(t)\cdot A - D)\cdot C\cdot P(C,t)}{\partial C} + \frac{1}{2}\frac{\partial^2 (C\cdot A\cdot r')^2\cdot P(C,t)}{\partial C^2} \tag{10}$$

Eq. [10] is an equation about the time development of the probability density function of the concentration rate. By solving the Fokker-Planck equation numerically, the time evolution of the distribution of concentration rate C can be known. Figure 9(b) shows what information you can get by solving the Fokker-Planck equation.

Figure 9(a) shows the solutions of the deterministic method and stochastic method. Compare that can be known. Figure 9(d) showed the comparison between the result of random test and the Fokker-Planck equation. The histogram of C at t=500h matches the distribution calculated by Fokker-Planck equation very well.



(a) (b)

Figure 9. Solutions of the stochastic differential equation and the Fokker-Planck equation. (a) is the deterministic solution and the 1000 times random test consider the randomness of growth rate result. (b) is the PDF and the histogram of the random test at time 500 hour.

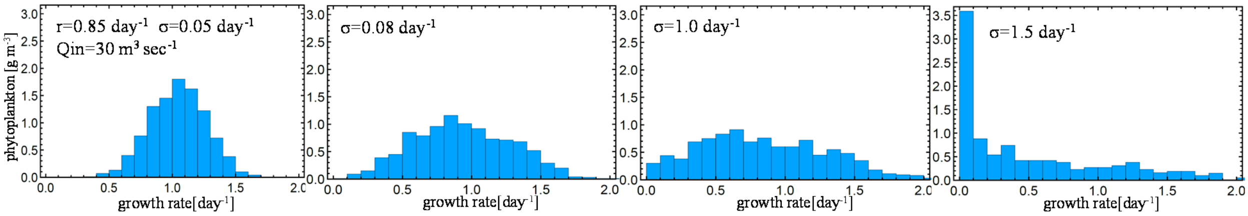


Figure 10. The histogram of the random test at time 500 hour when σ is changed.

Figure 10 shows a histogram when σ is increased (0.08, 1.0, 1.5 day-1). The larger the σ is, the fluctuation range becomes large. And, when σ is 1.0 day^{-1}, it means that the algae concentration sometimes becomes 0. Therefore, it is the reason why the calculation result and the actual inflow discharge are not same in section 4.2. By considering uncertainty, algae may disappear even with actual inflow discharge. As mentioned above, we presented the inflow discharge for improving the blue-green algae calculated by considering probability theory. Future issues, to further improve accuracy, we will study σ and an average value of growth rate carefully.

6 CONCLUSIONS

This study was made to propose countermeasures focused on the blue-green algae that causes odors and degradation in the aquatic environment. We assumed the environment has a lot of nutrients like nitrogen and phosphorous and propose a countermeasure for improving blue-green algae by numerical analysis and experiments. We took washout effect into account in logistic equation and prooved the relation of growth rate and rotation rate from culture experiment and observation. Using the water to flash out plays an important role on controlling of algae's growth. If rotation rate is higher than maximum growth rate, algae's growth can be controlled during experiment and observation. We proposed a new method that adds a washout effect term to a logistic equation and consider uncertainty into growth rate. We showed that it is possible to calculate the inflow discharge to flush out algae considering probability theory using the new method.

REFERENCES

Ikushima, I. (1987). Generation Mechanism and Its Control of The Algal Bloom. *Tokai university press, Japan, Tokyo*, 1-10.

Somiya, I. & Tsuno. H. (1997). *Water Environment Basic Science*. Corona Publishing Co., Ltd. Japan, Tokyo, 150.

Ministry of the Environment Government of Japan (2007*). Introduction of the environmental water,* Ministry of the Environment Government of Japan

Monod, J.L. (1942). Recherches Sur La Croissance des Cultures Bacteriennes. *Molecular Biology*.

Steel, J.H. (1962). Environmental Control of Photosynthesis in The Sea. *Limnology and Oceanography*. Volume 7, Issue 2, 137-150.

Eppley, R. W. (1972). Temperature and Phytoplankton Growth in The Sea. *Fish. Bull*, *70*(4), 1063-1085.

Imamura, N. (1981). Studies on The Water Blooms in Lake Kasumigaura. *Proceedings-International Association of Theoretical and Applied Limnology*, 21, 652-658.

Takahashi, M. & Ichimura, S. (1981). Nutrient Characteristics of Lake Water and Outbreaks of Blue-Green Algae in Lake Kasumigaura. *Environmental science*. B93-R12-2.

Iwai, T. (1960). Distribution of Microcystis in A Farming Pond, In Particular The Effects of Salinity, Water Temperature, Nutrient Salt On Growth. *Rep. Fac. Fish., Pref. Univ. Mie* 3(3): 741-757

Ohkubo, N., Yagi, O. & Okada, M. (1991). Effects of Temperature and Illumination on The Growth of Blue-Green Alga Microcystis Viridis. *The Japanese Society of Limnology*. 52(4), 255-261.

Sudo, Y., Okada, M. & Inamori, Y. (1986). *Microbial ecology Ⅰ*- Microbial population variation and interaction-. Kyoritsu Shuppan Co., Ltd. Japan, Tokyo, 64-81.

Ministry of Land, Kanto Regional Development Bureau of Japan (2014). *Kitachiba conduit project, Outline of periodic report.* Ministry of Land, Kanto Regional Development Bureau of Japan.

Haario, H., Kalachev, L., & Laine, M. (2009). Reduced Models of Algae Growth. *Bulletin of mathematical biology*, 71(7), 1626-1648.

Harasawa, H. (1985). Study on Stochastic Prediction of Algal Dynamics In Lake. *PhD Thesis*, Kyoto University. doi: 10.14989/doctor.r5741.

Teramoto, E., Kawasaki, K., Shigesada, N., Nakajima, H., Higashi, M. & Yamamura, N. (1997). *Mathematical Ecology*. Asakura Publishing Co., Ltd. Japan, Tokyo, 43-54.

Yoshimi, K. & Yamada, T. (2016). A New Theoretical Framework of Uncertainty Estimation in Rainfall-Runoff Process Based on The Theory of Stochastic Process. *Annual journal of Hydraulic Engineering. JSCE*, 60, 1225-1230.

Proceedings of the 37th IAHR World Congress
August 13 – 18, 2017, Kuala Lumpur, Malaysia

TEMPORAL STREAMATE CHARACTERISTICS OF WATER LEVELS AND RIVER STORAGE EFFECT IN A RIVER HAVING SUDDEN CONTRACTION

ICHIU KOISHI(1) & TADASHI YAMADA(2)

(1) Graduate School of Science and Engineering, Chuo University, 1-13-27, Kasuga, Bunkyo-ku, Tokyo, 112-8851, Japan,
ichiu@civil.chuo-u.ac.jp

(2) Faculty of Science and Engineering, Chuo University, 1-13-27, Kasuga, Bunkyo-ku, Tokyo, 112-8851, Japan,
yamada@civil.chuo-u.ac.jp

ABSTRACT

One of the problems in flood control is the backwater in upstream direction which occurs when the river channel suddenly contracts. It is very important to understand the water surface profile in such river channels under the maximum possible flow considering the effect of climate change. In the present study, the following two works have been accomplished: 1) using numerical simulation technics to quantitatively evaluate the water surface profile in river channel which includes sudden contraction; 2) using Yamada's theory to study the backwater-curve transitions considering the changing of cross-section area of the river channel. An example of the result of the present study indicates that a discontinuous water surface profile is formed at the contraction part of the channel. The flow at the downstream side of the contraction part is supercritical flow and the water level at the upstream side has been dam-up about 3m. The regime diagram of the water surface profile in the river channel, which has sudden contraction suggested by Yamada, shows that the result of numerical simulation agrees with this regime diagram very well. Furthermore, the original theory of Yamada considers the shape of the cross-section of river channels as rectangle for simplicity. The present study extends Yamada's theory to any kind of cross-section shapes. In addition, the storage effect of the unsteady and non-uniform flow caused by the non-uniformity of the river channel has also been studied. Using numerical simulation, we can calculate how much quantity that is stored in the dam-up part at the upstream side and evaluate the effect of lowering the water level at downstream side.

Keywords: Unsteady flow; non-uniform flow; flood flow; regime shift; river storage effect.

1 INTRODUCTION

One of the problems in flood control is the backwater in upstream direction which occurs when the river channel suddenly contracts. In general, there are still many unknown phenomena about the water flow in undeveloped river channel. The situation of these river channels can be very complicated, for example, there may be sudden expansion or contraction along the river channel, or the river channel can be quite meandering. In this case, it is very important to understand the water surface profile in such river channels under the maximum possible flow considered the effect of climate change.

This study aims to elucidate the influence of the longitudinal and cross sectional shape of river channel on water flow and water surface profile when maximum possible flow considered the effect of climate change flows in undeveloped rivers such as mountainous rivers. Therefore, in this paper, we grasp qualitatively and quantitatively the water surface profile of the unsteady flow (non-uniform flow) flowing through a rectangular water channel changing only the width, using numerical calculation, taking the problem to be simple. Also, in this study, we showed a phenomenon (river storage effect), in which the discharge is stored in the upstream side of the contraction part when the flow state changes in the contraction part. Furthermore, the present study had extended Yamada's theory to any kind of cross-section shapes, and the limit of occurrence of dam-up of the water level and the river storage effect is shown theoretically.

2 NUMERICAL EXPERIMENT OF UNSTEADY FLOW IN A RIVER HAVING SUDDEN CONTRACTION

2.1 Basic equations and numerical methods for one-dimensional unsteady flow

In this paper, one-dimensional analysis is used. Continuous equations and momentum equations of one-dimensional unsteady flow are shown below:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad [1]$$

  / ISSN 1562-6865 (Online) - ISSN 1063-7710 (Print)

$$\frac{\partial Q}{\partial t}+\frac{\partial(\alpha v Q)}{\partial x}=-gA\frac{\partial(h+z)}{\partial x}-\frac{gn^2 Q|Q|}{AR^{4/3}} \quad [2]$$

where h is Water depth [m], A is cross-sectional area of the flow [m^2], R is Hydraulic radius [m], Q is discharge [m^3/s], v is the mean velocity of the cross-sectional area [m/s], α is momentum coefficients, g is gravitational acceleration [m/s^2], z is elevation [m], and n is Manning's coefficient of roughness [m$^{-1/3}$s]. The resistance law is evaluated using the Manning's law. The finite difference method is used for the discretization method. The time differential is discretized by forward difference and the spatial differential by central difference. Only the advection term of Eq. [2] was up winded.

2.2 Conditions of the calculation

For numerical experiments, a uniform rectangular cross section channel with a slope of 1/1000, an extension of 20 km, and Manning's n = 0.02 was set assuming a mountainous river. In addition, the width of the river was 100 m (uniform), and an arbitrary pulse shape narrowed part with a reduction rate of width of 10 to 60 % was set at 10 km from the downstream end. Here, the reduction rate of width is defined as the ratio of the width of the contraction portion to the width before the contraction is subtracted from 1.

In this research, we conducted the following 4 cases of numerical experiments. Case 1: in the uniform width channel, as the initial condition, equal water depth and flow velocity are uniformly given to the river channel, a constant flow rate is passed from the upstream side, instantaneously the contraction part appears in the central part of the river, and the time change of the water surface profile during the experiment is observed. Case 2: experiment of uniformly giving equal water depth and velocity to the river as the initial condition in the constricted river, giving a discharge hydrograph from upstream, and observing the time change of the water surface profile. Case 3: the same experiment as in Case 1, in which the water level at the downstream end is set as a constant value and the water level is given to the reference height of the altitude as the initial condition. Case 4: same experiment as in Case 2, but under the same initial condition as Case 3. In Cases 3 and 4, it is assumed that the water level is dam-up of by the dam at the downstream end.

2.3 Results of numerical experiment and its consideration

Numerical calculation results of Case 1 and Case 4 are shown in Figure 1(a) and 1(b) as numerical experiment results. In Case 1, a constant discharge of 4000 m^3/s was flowed from the upstream side, and the calculation time was 1 hour, which is sufficient to form a steady-state water surface profile. Figure 1 (a) shows the calculated water level at 3 minutes, 10 minutes, 1 hour (steady state) and the critical water level at the steady state from the momentary appearance of the contraction part with the reduction rate of width of 50 %. After the contraction part appears, a bore is generated upstream of the contraction part, the critical water level is taken at the center of the contraction part, and the flow becomes supercritical flow at the downstream side of the contraction part. In the downstream, hydraulic jump occurs, the flow becomes a subcritical flow, connects to the downstream water level, and forms a steady-state water surface profile, that is, a non-uniform flow surface profile, accompanied by a shock wave propagating downstream. The control section appears at the most contraction part. The non-uniform flow water surface profile in the river having sudden contraction becomes supercritical flow at the narrowed part when at least the width narrows by half or more.

In Case 4, a mountain type discharge hydrograph with a base flow of 100 m^3/s and a peak of 5000 m^3/s after 5 hours is the given upstream, and the calculation time is 17 hours which is sufficient for the downstream end flow hydrograph to attenuate and become the base flow. Figure 1(b) shows the calculation result when the reduction rate of width is 60 %. The water level after 4 hours from Figure 1(b) is a water surface profile convex downward in the contraction part, and the flow is subcritical flow in all sections. However, as the discharge increases, the water level above the contraction section falls below the critical water level and the water level on the upstream side of the contraction section rises. Then, a discontinuous water surface profile is formed with the contraction portion as the boundary. Here, in the experiment of Case 4 given the discharge hydrograph, a bore like Case 1 cannot be confirmed on the upstream side of the contraction part, but in this Case 4, the infinite small bore momentarily propagates upstream. Therefore, it can be interpreted that the water level rises on the upstream side of the contraction. Compared to the peak water level in a similar experiment in a uniform width channel, it is understood that the water level at the upstream side has been dam-up about 3m. In the numerical experiment of Case 4, since the water level at the downstream end is dam-up, as long as the discharge does not exceed a certain threshold value, a water surface profile which is convex downward is formed in the contraction part. However, when the discharge exceeds a certain threshold value, that is, when the water level falls below the critical water level at the contraction part, the water level on the upstream side of the contraction part suddenly rises. This suggests the possibility of causing large damage on the upstream side of the contraction part.

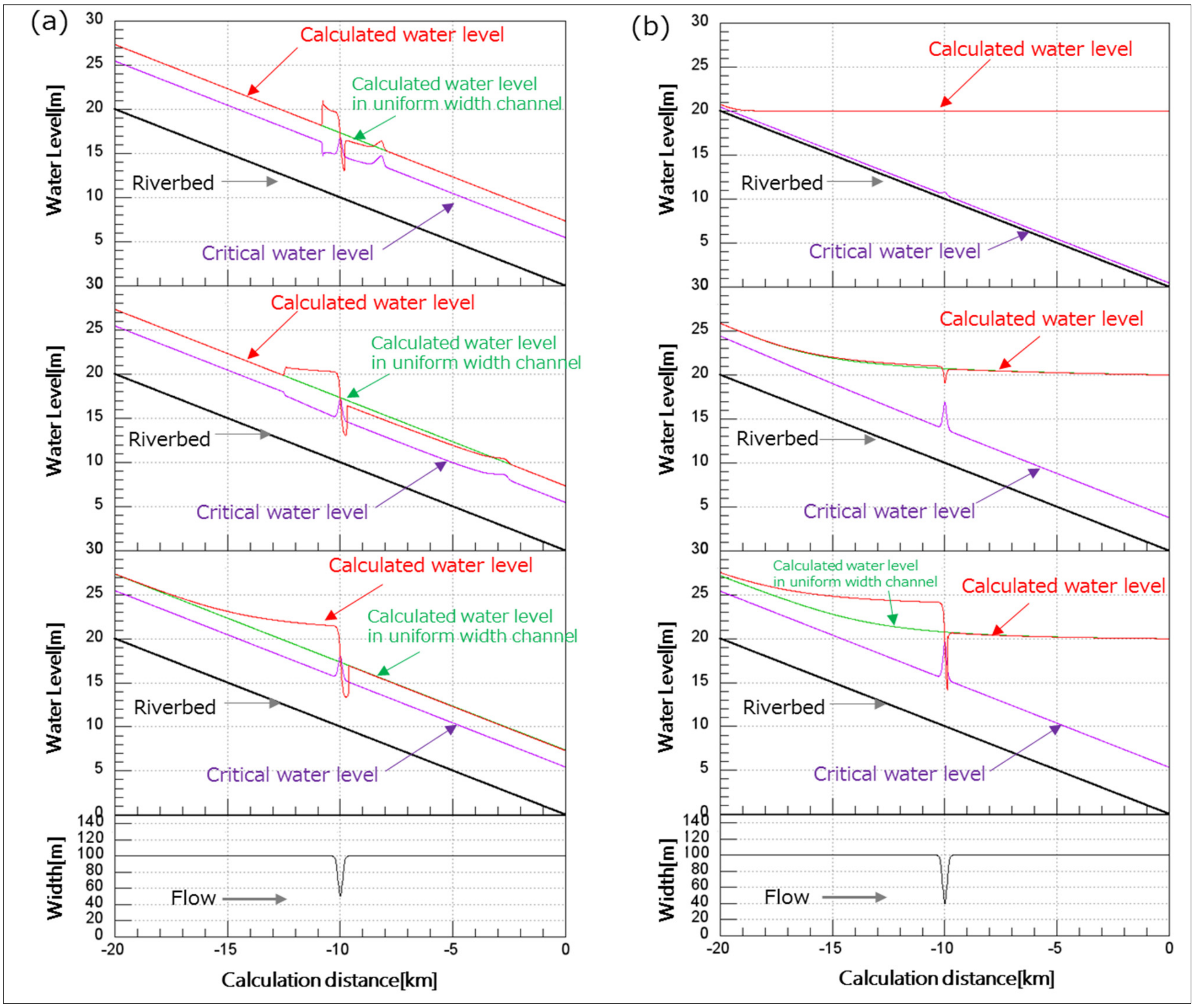


Figure 1(a). Numerical calculation results of Case 1. **Figure 1(b)**. Numerical calculation results of Case 4.

From the above, it was found that backwater can occur in the upstream direction from the contraction part when a large discharge flows in a river channel having a sudden contraction. In addition, when the water level at the downstream end is dam-up by a dam or the like, the dam-up phenomenon of the water level does not occur until the discharge exceeds a certain threshold value.

3 RIVER STORAGE EFFECT IN A RIVER HAVING SUDDEN CONTRACTION

Figure 2 shows an image of the bore in the numerical experiment of Case 1 shown in Figure 1(a). Here, the cross section 0 shows a section where no bore occurs, the section 1 shows the cross section at the front of the bore, the section c shows the control section, Q_0 and Q_1, Q_c, h_0 and h_1, h_c are discharges and the water depth. At this time, the discharge Q_c in the control section is not determined by the upstream discharge but is a theoretically uniquely determined discharge from the critical water depth h_c. Since the discharge Q_1 in the cross section 1 coincides with the discharge Q_c in the control section by the continuous condition and the section can be regarded as stationary, *Bernoulli*'s theorem is held in the section of the cross section 1 and the section c. Because the velocity of the section c is faster than the cross section 1, the water depth of cross section 1 can be dam-up from *Bernoulli*'s theorem. However, in cross section 0, since it originally flowed at the uniform water depth, a discontinuous surface of the water level is generated. At this time, the discharge of the cross section 1 and the cross-section c are smaller than the discharge of the cross section 0, and this relationship is as shown in the Eq. [3]. The situation where this relational expression holds is called the river storage effect of the discharge in a river having sudden contraction. Since the above explanation is based on the theory neglecting the influence of the frictional force, the dam-up of the water level is a phenomenon that can occur irrespective of the presence or absence of frictional resistance.

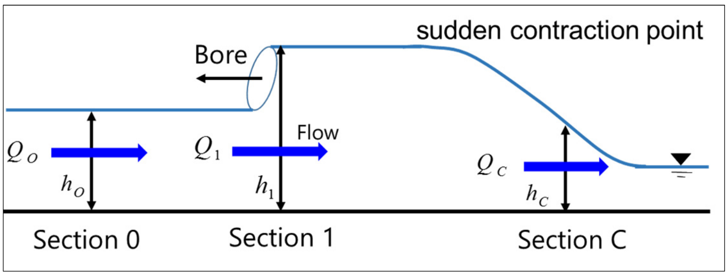


Figure 2. An image of the bore in the numerical experiment of Case 1.

$$Q_0 > Q_1 = Q_c \qquad [3]$$

Figure 3(a) is a longitudinal distribution of the discharge in the numerical experiment of Case 1 shown in Figure 1(a). Figure 3(b) is the maximum discharge storage rate of the contraction section when changing the reduction ratio of width from 0 to 50 %, and the maximum water depth decrease rate at -5 km point on the downstream side of the contraction part is due to river storage effect in the numerical experiment of Case 1.

Here, the maximum discharge storage rate is obtained by dividing the difference between the initial discharge and the lowest discharge at the contraction point by the initial discharge, the maximum water depth decrease rate is obtained by dividing the difference between the initial water depth and the lowest water depth at the -5 km point by the initial water depth. In Figure 3(a), the discharge at 3 minutes from the momentary appearance of the contraction part is reduced by about 1500 m^3/s, centering on the contraction section. And the decrease of the discharge is transmitted upstream and downward with time, mainly decreasing the discharge of the downstream around the contraction section and returning to the constant discharge of the original steady state after sufficient time has passed. Also, in Figure 3(b), the maximum discharge storage rate and the maximum water depth decrease rate on the downstream side of the contraction section increase nonlinearly as the river width narrows. When the reduction ratio of width is 50%, the maximum discharge storage rate is 36% and the maximum water depth decrease rate is 10%.

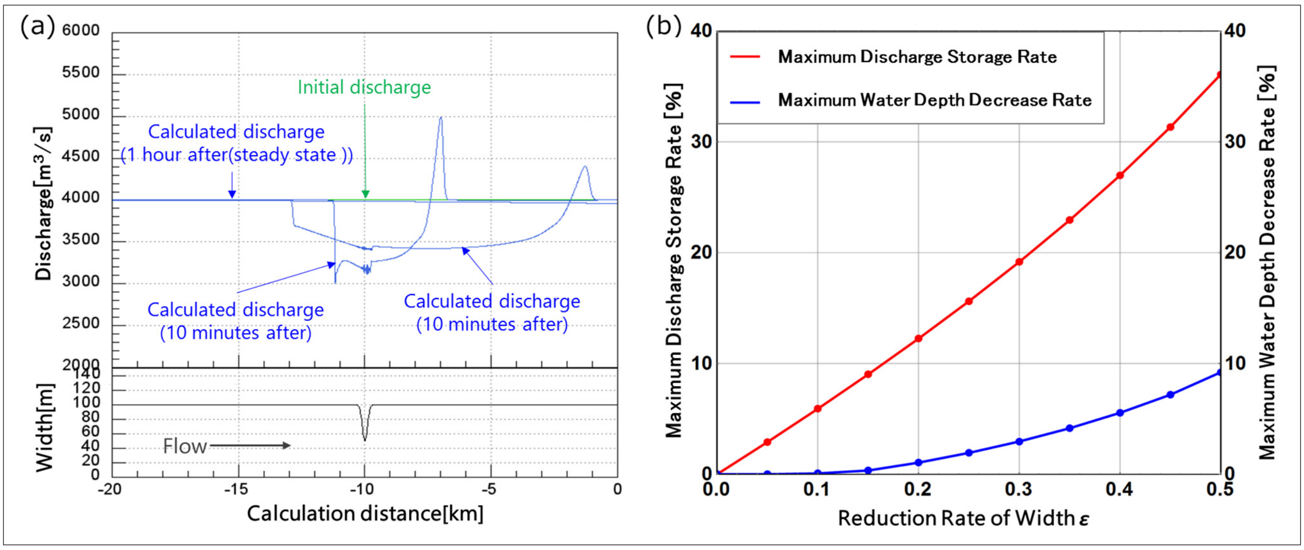


Figure 3(a). Longitudinal distribution of the discharge in the numerical experiment of Case 1.
Figure 3(b). The maximum discharge storage rate of the contraction section when changing the reduction ratio of width to 0 to 50 %, and the maximum water depth decrease rate at -5 km point on the downstream side of the contraction part in the numerical experiment of Case 1.

Figure 4(a) shows the time series of the discharge in the numerical experiment of Case 2, while Figure 4(b) shows the maximum discharge storage rate of the contraction section when changing the reduction ratio of width from 0 to 50 %, and the maximum water depth decrease rate at -5 km point on the downstream side of the contraction part due to river storage effect in the numerical experiment of Case 2. The vertical axis of Figure 4(a) shows the discharge and the horizontal axis shows the time, which is a comparison of the time series of the discharge when there is not the contraction section and the discharge when there is the contraction section.

When comparing the peak discharge, the difference in peak discharge between when there is no contraction section and when there is some is about 2.5% at maximum. Also, the time when the peak discharge appeared is delayed in the case where the contraction part is present.

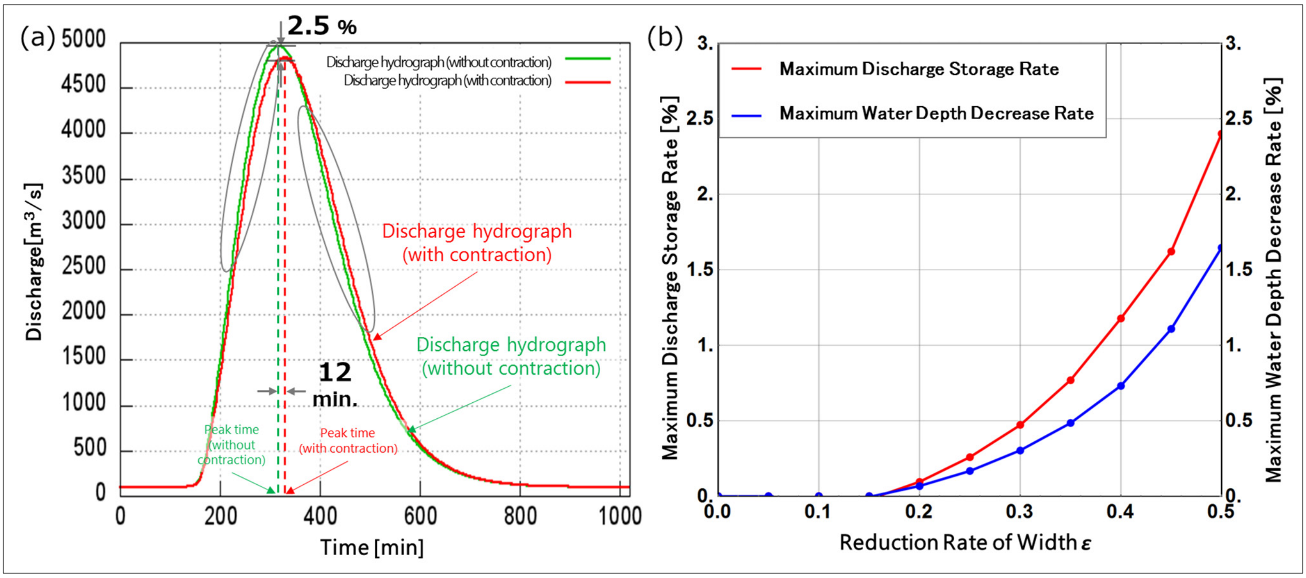


Figure 4(a). The time series of the discharge in the numerical experiment of Case 2.
Figure 4(b). The maximum discharge storage rate of the contraction section when changing the reduction ratio of width from 0 to 50 %, and the maximum water depth decrease rate at -5 km point on the downstream side of the contraction part in the numerical experiment of Case 2.

When drawing an *H* - *Q* curve at this point, the curve became a loop when there was no contraction part, whereas when there was a contraction part, it became one curve. The reason for this is that the water level is at the critical water level on the constricted part, which also shows that the discharge that can flow in the contracted part is restricted. Therefore, the following three things can be said from the above: 1: if there is a constricted part in the river, the discharge is stored upstream of the contraction part and the water level is dam-up; 2: the appearance time of the peak discharge is delayed; 3: Since the discharge decreases downstream of the contraction section, the water level drops. In addition, as shown in Figure 4(b), the maximum discharge storage rate and the maximum water depth decrease rate on the downstream side of the contraction section increase nonlinearly as the river width narrows, similarly to Figure 3(b), and if the reduction rate of width is 50 %, the maximum discharge storage rate is about 2.5% and the maximum water depth decrease rate is about 1.6%.

The river storage effect and the dam-up of the water level are the phenomena caused by the water level being the critical water level at the contraction section. Generally, the river storage effect is that the flood hydrograph given upstream is deformed, while the flood flow flows down a river from a certain point in the upstream to a certain point, causing a reduction in the peak discharge and a delay in the flood flow. Although this is a word indicating the phenomenon, this study quantitatively shows that the existence of the contraction section in the river has the effect of storing the discharge.

4 A PROPOSAL ON THE THEORY ON WATER SURFACE PROFILE TRANSITION IN GENERAL CROSS SECTION OF A RIVER

4.1 Comparison with Yamada's theory and numerical experiment results

Yamada and colleagues have conducted theoretical analysis and experimental study on the water surface profile, its transition and resistance law for a rectangular open channel with a contraction section and a riverbed convex section. Figure 5 is plots of numerical experiment results on a regime diagram of water surface profile in open channel with contraction part derived by Yamada et al. (1986). In the numerical experiments of Case 1 to 4 shown in Section 2, numerical calculation results obtained by variously changing the reduction ratio of width ε and the discharge given to the upstream end. The point indicated by the black circle ● in the Figure 5 is the numerical experimental condition, where the dam-up of the water level occurred, while the white circle ○ is the numerical experimental condition without the dam-up of the water level. In spite of numerical experiments considering bottom friction, the numerical experiment result agrees with this regime diagram very well. From this, it can be said that the Yamada's theory shows the occurrence limits of the dam-up of the water level and the river storage effect on the contraction section of the river.

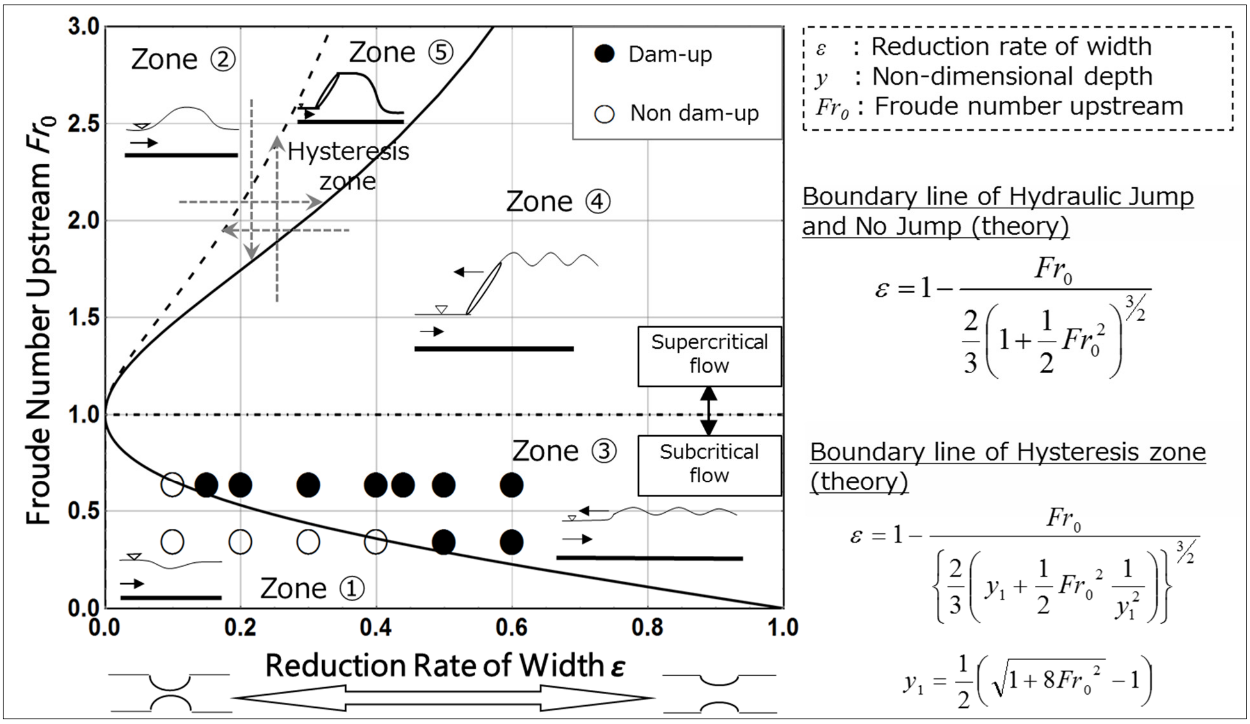


Figure 5. Plots of numerical experiment results on a regime diagram of water surface profile in open channel with contraction part derived by Yamada et al. (1986).

4.2 Determination of water level in general cross-sectional shape of a river

Next, in this research, we extend Yamada's theory on water surface transition to a theory that can be applied to general rivers having complicated river cross-sectional shapes. Therefore, we first propose a method for determining the water level in a general river cross section shape. Considered is steady and frictionless flow. Then, the following Eq. [4] is obtained by the continuous equation (Q = Const.) and the *Bernoulli*'s theorem. And Eq. [5] is obtained by rearranging the cross-sectional area of the flow $A(H)$ from Eq. [4].

$$\frac{1}{2g}\frac{Q^2}{A(H)^2}+H=T_0 \qquad [4]$$

$$A(H)=\frac{Q}{\sqrt{2g}\sqrt{T_0-H}} \qquad [5]$$

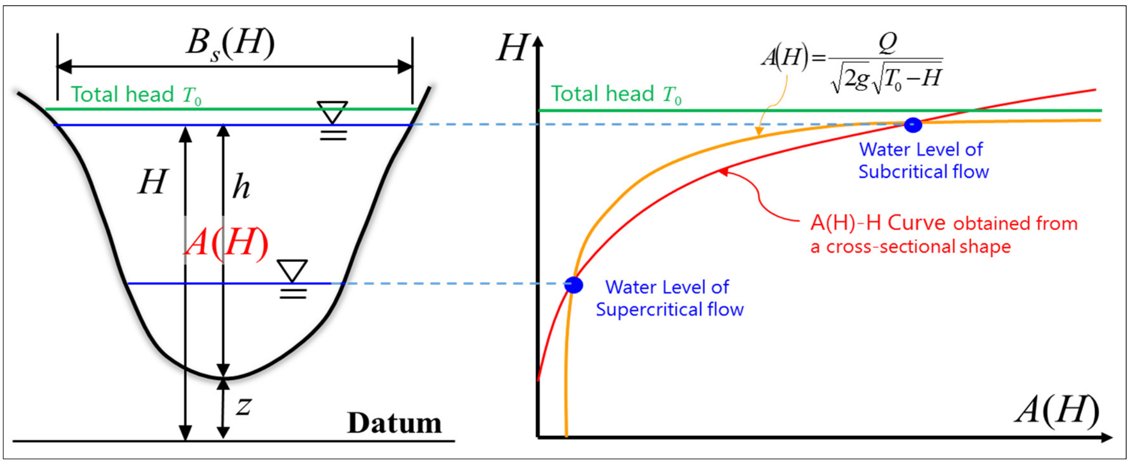


Figure 6. Diagram of a water level determination method in a general cross section.

where, H is Water level [m], A is cross-sectional area of the flow [m^2], Q is discharge [m^3/s], g is gravitational acceleration [m/s^2], T_0 is total head [m]. On the other hand, if an arbitrary sectional shape is given, the cross-sectional area of the flow A for a certain water level H can be uniquely determined. This is called the $A(H)$ -H

curve obtained from the cross-sectional shape. Figure 6 is a diagram of a water level determination method in a general cross section. Then, the point where the $A(H)$ -H curve obtained from the cross-sectional shape and the Eq. [5] intersect is the water level of the subcritical flow and the supercritical flow. Therefore, the water level can be obtained by giving the total head T_0 and the discharge Q, $A(H)$ -H curve. If the $A(H)$ -H curve does not intersect with the Eq. [5], it means that Bernoulli's theorem is failing, and energy loss occurs at this point. In other words, bore and dam-up of water level are occurring.

4.3 Extended Yamada's theory to any kind of cross-section shapes

In the case of a rectangular cross section, in which the cross-sectional area of the flow A is proportional to the water depth h or the water level H, a cubic equation on the water depth h or the cross-sectional area of the flow A is obtained from the Eq. [5], which obtained from *Bernoulli*'s theorem and the $A(H)$ -H curve of the rectangular cross sectional shape. In this study, we introduce a hydraulic depth $D(H)$ and substitute a rectangular cross section for an arbitrary cross section. Then we derived a cubic equation on the hydraulic depth $D(H)$ shown in Eq. [6].

$$D^3-(T_0-z_m)D^2+\frac{Q^2}{2gB_s^2}=0 \qquad [6]$$

where, $D(H)$ is hydraulic depth [m], B_s is water surface width [m], and z_m is mean riverbed [m]. The hydraulic depth $D(H)$ is defined as the cross-sectional area of the flow A divided by water surface width B_s, and mean riverbed z_m is defined as a riverbed when it is replaced with a rectangular cross section. Furthermore, to non-dimensionalization, we divide Eq. [5] by the water depth D_0 on the upstream side. Then, a cubic equation having 3 parameters of the Froude number Fr_0 on the upstream side with respect to the dimensionless hydraulic depth D', the reduction ratio of water surface width ε, and the dimensionless mean riverbed η is obtained.

$$D'^3-\left\{1+\frac{1}{2}Fr_0^2-\eta\right\}D'^2+\frac{1}{2}Fr_0^2\frac{1}{(1-\varepsilon)^2}=0 \qquad [7]$$

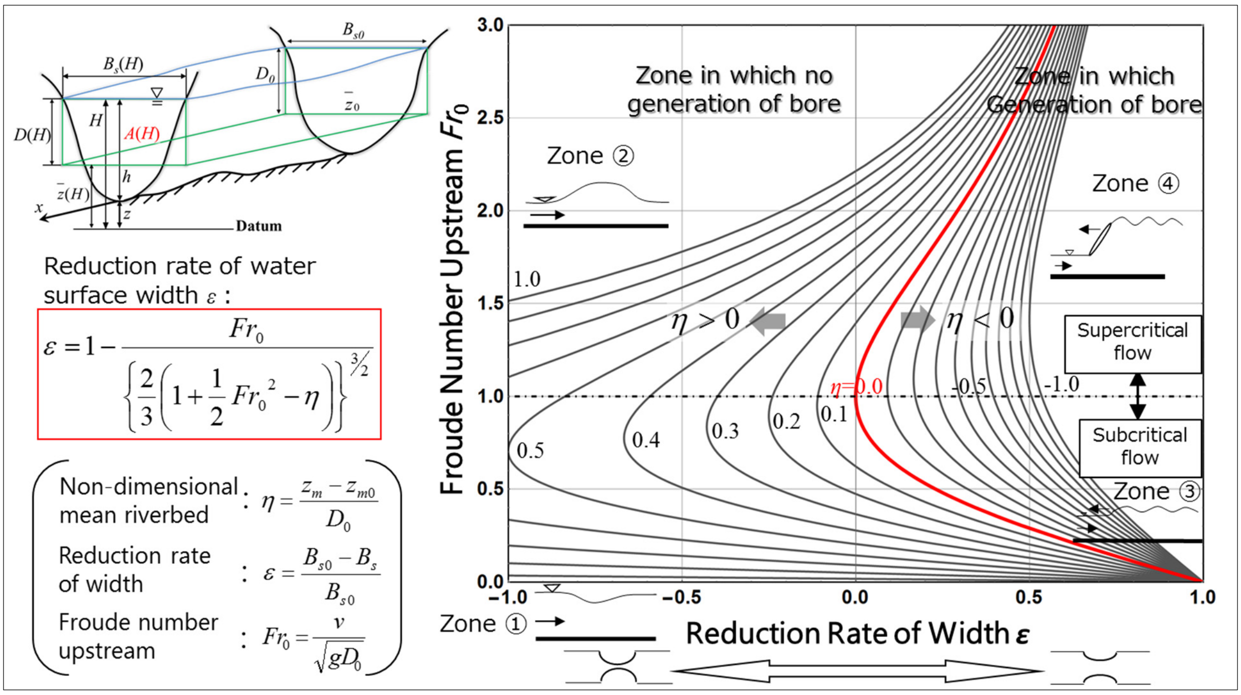


Figure 7. Regime diagram of the water surface profile transition showing the Eq. [7] in which the value of the dimensionless mean riverbed η is varied.

where, $D' = D/D_0$ is the dimensionless hydraulic depth [m], $Fr_0 = v/\sqrt{gD_0}$ is Froude number upstream, $\varepsilon = (B_{s0}-B_s)/B_{s0}$ is the reduction ratio of water surface width, and $\eta = (z_m - z_{m0})/D_0$ is the dimensionless mean riverbed. By deriving the discriminant of Eq. [6] using the Cardano's formula and arranging it for ε, we can derive the limit condition where the real solution of the hydraulic depth D can exist.

$$\varepsilon = 1 - \frac{Fr_0}{\left\{\frac{2}{3}\left(1 + \frac{1}{2}Fr_0^{\ 2} - \eta\right)\right\}^{3/2}} \qquad [8]$$

Figure 7 is the regime diagram of the water surface profile transition showing the Eq. [7], in which the value of the dimensionless mean riverbed η is varied. The red line in the Figure 7, which is the original theory of Yamada, shows the occurrence limits of the bore and hydraulic jump when η = 0, that is, when there is no difference in mean riverbed from the upstream. When η > 0, the limit line is distorted to the left, and when η < 0, the limit line is distorted to the right. In other words, when the mean riverbed is higher than that on the upstream side, the occurrence area of the hydraulic bore and hydraulic jump becomes large, so it is easy to occur the dam-up and the river storage effect.

5 CONCLUSIONS

This study aims to elucidate the influence of the longitudinal and cross sectional shape of river channel on water flow and water surface profile when maximum possible flow considered the effect of climate change flows in undeveloped rivers such as mountainous rivers. Therefore, in this paper, we grasp qualitatively and quantitatively the water surface profile of the unsteady flow (non-uniform flow) flowing through a rectangular water channel changing only the width, using numerical calculation, taking the problem simple. Also, in this study, we showed a phenomenon (river storage effect) in which the discharge is stored in the upstream side of the contraction part when the flow state changes in the contraction part. Furthermore, the present study had extended Yamada’s theory to any kind of cross-section shapes, and the limit of occurrence of dam-up of the water level and the river storage effect is shown theoretically. The results can be summarized as follows:

1. We showed qualitatively and quantitatively by numerical calculation that the existence of the contraction part of the river has the effect of raising the water level;
2. In this study, we newly presented a phenomenon (= river storage effect) in which the discharge is stored upstream of the contraction part when the flow state transits in the contraction part of the river;
3. We extended the Yamada 's theory on the transformation of water surface profile to the theory that can adapt to the any kind of cross-section shapes, and theoretically showed the limit of occurrence of the damming of the water level and the effect of the storage of the river way.

REFERENCES

Tadashi, Y., Masayuki, I. & Yoshihiro, M. (1986). Studies on the Transition of Subcritical Flow, Supercritical Flow, Chutes & Pools and the Resistance Law, Annual *Journal of Hydraulic Engineering, JSCE*, 30, 73-78.

Proceedings of the 37th IAHR World Congress
August 13 – 18, 2017, Kuala Lumpur, Malaysia

RUNOFF ANALYSIS CONSIDERING THE UNCERTAINTY OF RAINFALL INTENSITY BASED ON STOCHASTIC DIFFERENTIAL EQUATION

DAIWEI CHENG [(1)] & TADASHI YAMADA [(2)]

[(1)] Graduate School of Science and Engineering, Chuo-University , Tokyo, Japan
davidchengchina@gmail.com
[(2)] Faculty of Science and Engineering, Chuo-University , Tokyo, Japan
yamada@civil.chuo-u.ac.jp

ABSTRACT

In 1974, M. Hino had firstly introduced the Kalman filter in forecasting the rainfall-runoff process which considered the uncertainty of the process. Since then a lot of research have been done considering the uncertainty effects in rainfall-runoff process. However, most of research are based on filtering theory and statistical methods which cannot recognize the physical meaning of the uncertainty. On the other hand, recently, K. Yoshimi and T. Yamada (2016) have tried to use the stochastic differential equation to study the uncertainty of runoff rate due to the random fluctuation in rainfall. And this can be used in the prediction of rainfall-runoff process which not only provides a range of prediction interval but also gives a clear physical explanation to the uncertainty of the process. The present study, which is based on K. Yoshimi and T. Yamada (2016)'s work, aims at directly using the theory to practical problems, and discusses how to decide the parameters of the new theory.

Keywords: Stochastic differential equation; rainfall-runoff; the Fokker-Planck equation; uncertainty.

1 INTRODUCTION

Rainfall-runoff process has been considered as the central issue of hydrology. However, because of the scale of the catchment area, it is almost impossible to apply first principles of physics directly to simulate the rainfall-runoff process. But still, people want to predict the process deterministically. Thus, many models had been suggested and some of them had achieved a very high accuracy and been widely used in runoff forecast and flood control.

However, when models consider only the large-scale effects of the system, the subscale effects have been ignored and will cause prediction errors. The most common way to deal with the problem is to develop more detailed models which can consider smaller scale effects of the system. For example, the basic concept of distributed hydrologic models is trying to divide the basin into small pieces, so that it can incorporate a variety of spatial-varying land characteristics. But recently research had pointed out that uncertainty in the high-resolution observation of precipitation and model parameters may diminish potential gains in prediction accuracy achieved by accounting for the inherent spatial variability. Besides, there are also observation errors that can cost prediction error when using those models.

Based on that, it can be known that there is a limit in detailing models. Or, there might be some fundamental flaws that cannot be overcome when we considered the rainfall-runoff process as a deterministic process. Another way of considering the subscale effects is to think the rainfall-runoff process as a stochastic process. Filtering theory plays a very important role in identifying and forecasting stochastic process. In 1974, M. Hino had first introduced Kalman filter in rainfall-runoff process, the main problem of Kalman filter is that it has two basic assumptions: 1) the system is linear, and 2) the distribution of physical quantity in the stochastic process is normal distribution. Generally, rainfall-runoff process does not agree with the two assumptions very well.

Thus, new filters have been suggested and applied in rainfall-runoff process. Filters for nonlinear systems can be classified into two groups: 1) to linearize the nonlinear system, such as extended Kalman filter or Unscented Kalman filter; 2) sampling methods, such as ensemble Kalman filter and particle filter. However, these filters have their own limits also. On the other hand, in mid-1940, Ito. K (1946) developed a mathematical fundamental of stochastic differential equation which is an essential way of describing stochastic process. He showed that the time development of the probability density function of a random variable in stochastic process is controlled by the famous Fokker-Planck equation which was originally used to describe the Brownian motion. This work provides a new way of how to consider uncertainty in systems

Recently, K. Yoshimi and T. Yamada (2016) have tried to use Ito. K's stochastic differential equation theory to study the uncertainty of runoff rate caused by the random fluctuation in rainfall intensity. Unlike the filtering theory, stochastic differential equation is able to recognize the physical meaning of the random external force very well, so that it is possible to consider the effect of a specific source of randomness. Besides, the theory has less assumptions than all the filters that have been mentioned above; the theory should be able to be used in a nonlinear system, and filters can be more or less considered as a simplification of the theory.

K. Yoshimi and T. Yamada's work (2016) have actually opened a new way of modeling rainfall-runoff process because all the physical models that were built before are deterministic. On the contract, the theory was built on the basic concept that due to the incompleteness of information and the chaotic characteristics of a nonlinear system, the time development of a physical system cannot be decided deterministically. The effect of uncertainty should be considered seriously. The theory is also different from filtering theory, because it was built under a well-tested physical model which makes all the terms in the control equation to have specific physical meanings.

The present study is based on K. Yoshimi and T. Yamada's work (2016), aimed at finding a way to apply the theory in practical problem. In order to do so, the following works had been done: 1) review K. Yoshimi and T. Yamada's theory (2016) briefly, 2) apply it to Kusaki dam basin, 3) discuss the meaning of the results and compared it to the results of extended Kalman filter, and 4) discuss how to decide the parameters in the theory.

2 Deterministic rainfall-runoff models

Among plenty of rainfall-runoff models, the present study has chosen the model suggested by T. Yamada (2003) for 3 reasons: 1) the parameters in the model all have their physical meanings. It provided a possibility of identifying the physical source of uncertainty; 2) it has been verified that the model works well in mountain watershed area; and 3) the form of the model is relatively simple so it can be written into a form as Ito's stochastic equation.

T. Yamada (2003) considered a mountain watershed as a single modelized slope. By applying the continuous equation and momentum equation to the slope, he suggested the following equation:

$$\frac{dq}{dt} = \alpha q^{\beta}(r(t) - q) \qquad [1]$$

α, β are parameters which are decided by the characteristics of the catchment area. $q(t)$ is the runoff rate[mm/h]. $r(t)$ is the rainfall intensity[mm/h]. One can calculate $q(t)$ with a given $r(t)$, this is exactly the purpose of analyzing rainfall-runoff process. The blue line in Fig.1 shows a basic solution of equation [1].

Next, we are going to apply the model in Kusaki dam basin in Japan and see if the model can represent the rainfall-runoff process well. Kusaki dam is a very important dam in Tonegawa river, which is the largest river in Japan. The area of the basin controlled by Kusaki dam is about 254 km2

The parameters are decided by experience and the past rainfall events. We used 22 large rainfall events from 1978 to 2013 to identify the parameters. The values of the parameters are $\alpha = 0.047$, and $\beta = 0.4$. The results of the deterministic simulation are shown in Fig. 1. We chose 6 rainfall events as examples to put into the figures. It can be told that the results basically agree with the observations. But in some cases, such as the 1990-9-19 and 1982-07-31 rainfall events, the difference of peak runoff rate between the simulation and observation is relatively large.

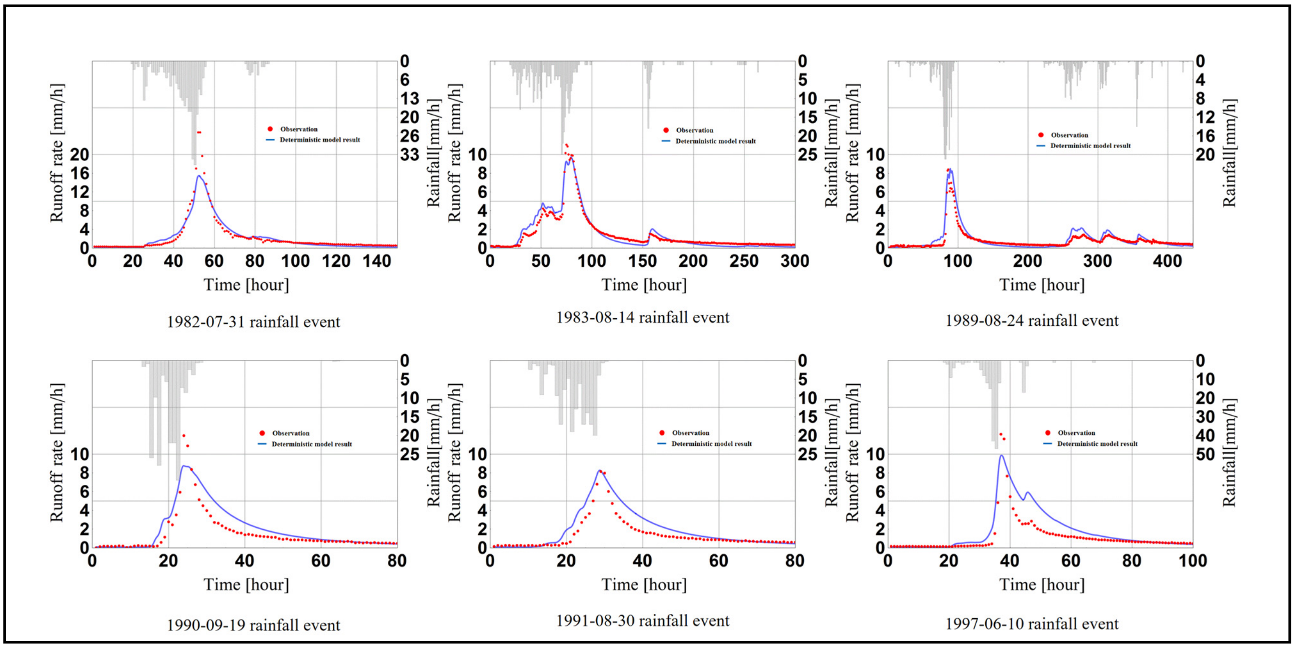


Figure 1. Deterministic simulation results by using T. Yamada's ranfall-runoff models in Kusaki dam river basin.

Generally speaking, the difference between the simulation and observation is called error. The word “error” seems to imply that those differences came out only because something wrong has been done. The final aim of deterministic simulation is to make the 3 error” become 0. And the way to evaluate a model is to find out whether the “error” is small enough. Also, the basic concept of parameter estimation is to find the optimal value that can give the smallest “error”.

However, regarding the previous discussion, we knew that it is almost impossible to do the simulation or prediction on a large-scale physical system deterministically such as rainfall-runoff process. So, here we would rather call the difference between the simulation and observation “prediction uncertainty” or “simulation uncertainty” than “error”, because we believe that the prediction uncertainty is caused by the incompleteness of information and the physical uncertainty of the system. One thing that the present study has achieved is to apply the stochastic differential equation theory to quantify these uncertainties.

3 Rainfall-runoff process considering the uncertainty of rainfall

Next, we are going to introduce the stochastic differential equation theory into rainfall-runoff process based on K. Yoshimi and T. Yamada’s work (2016). The Ito’s stochastic differential equation and the Fokker-Planck equation of rainfall-runoff process considering the uncertainty of rainfall intensity will be suggested.

Eq. [1] is a first order ordinary differential equation about q; it can be written in the following form:

$$dq = \alpha q^{\beta}(r(t) - q)dt \qquad [2]$$

$r(t)$ is the rainfall intensity. However, in a practical problem, it is very difficult to know the instantaneous value of rainfall intensity, so we divided $r(t)$ into two parts: an average value between a small period of time, and a random part represents the difference between the instantaneous value and the average value:

$$r(t) = \bar{r}(t) + r'(t) \qquad [3]$$

Substituting Eq. [3] into Eq. [2], we get:

$$dq = \alpha q^{\beta}(\bar{r}(t) - q)dt + \alpha q^{\beta} r' dt \qquad [4]$$

According to Ito’s stochastic differential equation theory, Eq. (4) can be written in the following form:

$$dq = \alpha q^{\beta}(\bar{r}(t) - q)dt + \alpha q^{\beta}\sigma\sqrt{T_L}dw \qquad [5]$$

Eq. [5] has the same form as Ito’s stochastic differential equation. T_L is the period of time that $r'(t)$ and $r'(t+T_L)$ can be considered as independent. σ is the standard division of $r'(t)$ and $w(t)$ is the standard Winner process. It had been shown by Ito. K that Eq. [5] is equivalent to the following Fokker-Planck equation.

$$\frac{\partial P(q,t)}{\partial t} = -\frac{\partial \alpha q^{\beta}(\bar{r}(t) - q)P(q,t)}{\partial q} + \frac{1}{2}\frac{\partial^2\left(\alpha q^{\beta}\sigma\sqrt{T_L}\right)^2 P(q,t)}{\partial q^2} \qquad [6]$$

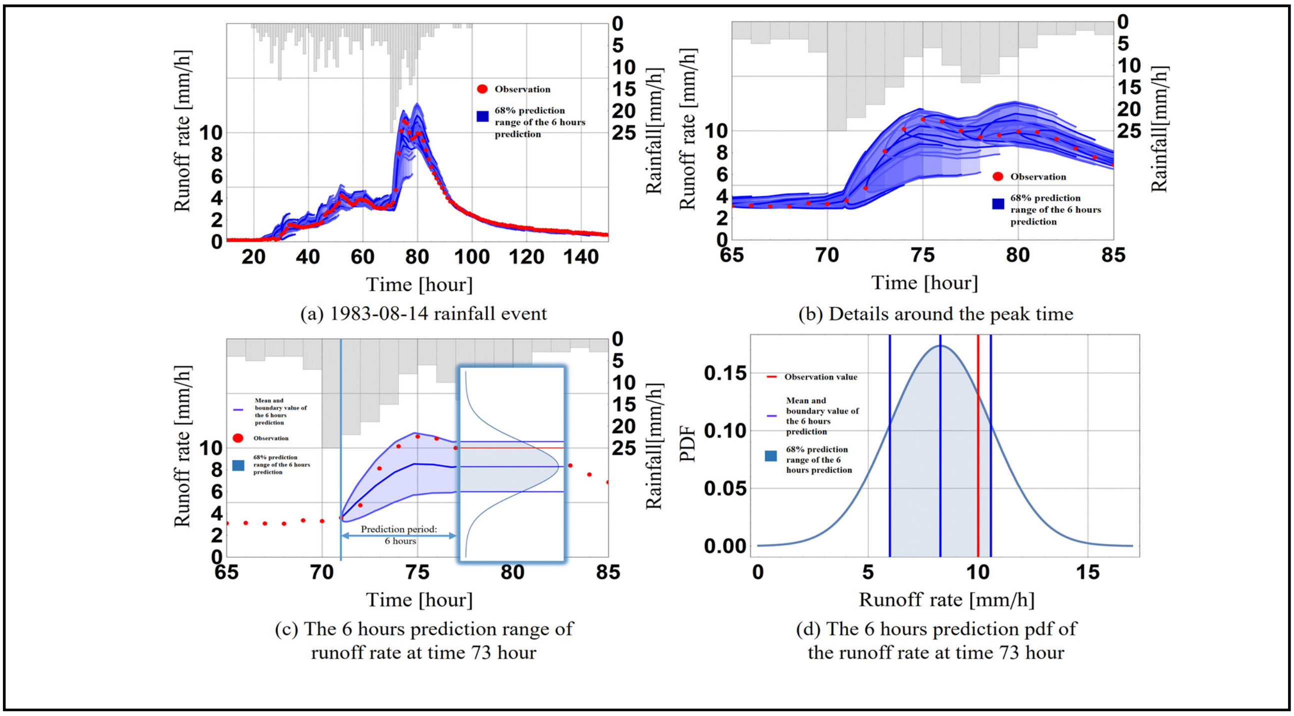
Eq. [6] is an equation about the time development of the probability density function of the runoff rate. By solving the Fokker-Planck equation numerically, the time evolution of the distribution of runoff rate q can be known.

4 Rainfall-runoff forecasting considering the uncertainty of rainfall

As discussed above, deterministic models have their limitations because of the following two fundamental reasons:1) when it comes to practical problems with the large scale like rainfall-runoff process, it is almost impossible to get the complete information of the system, deterministic models can not consider the effect of the incompleteness of information; 2) when you detail the models in order to get a more accurate result, it will raise the nonlinearity of the model and makes it more sensitive to the initial and boundary condition and the parameters.

Hence, a more reasonable way to think of it is to admit the incompleteness of information and the imperfection of models, and take them into account. In the present study, we use equation [6] to consider the rainfall-runoff process under uncertain rainfall. Of course, the probability density function calculated by equation [6] will be affected by the important parameter $\sigma\sqrt{T_L}$. We will discuss how to decide it latter.

Fig. 2 shows the result of the simulation based on stochastic differential equation theory using 1983-08-14 rainfall event as an example. Firstly, the Fig. 2(a) gives a general image of the simulation, it shows that unlike the deterministic way, the simulation has a range, it shows that all of the observations are mostly included in the range. Secondly, the Fig. 2(b) shows the detail of the simulation around the peak of the flood. It can be seen that the prediction range are overlapping in the figure. In order to explain how the range be calculated, we have to see the Fig.2(c). The start point is at time 73 hour just before the peak runoff rate coming.



(a) 1983-08-14 rainfall event
(b) Details around the peak time
(c) The 6 hours prediction range of runoff rate at time 73 hour
(d) The 6 hours prediction pdf of the runoff rate at time 73 hour

Figure 2. Simulation result of the 1983-08-14 rainfall event using stochastic differential equation method

Using the observation value at the start point we can get the initial distribution of the runoff rate which $\delta(\mathrm{q}-\mathrm{q}_{ob})$. $\delta(\mathrm{q}-\mathrm{q}_{ob})$ is the Dirac delta function, which is a very special probability density function meaning that the probability of q=q_{ob} is 100%. It can also be understood as the translate function between deterministic value and random variables. In filtering theory, the observation error has been considered, which means even with the observation value, the distribution at certain point cannot be set as Dirac delta function. In the present study, we did not consider the observation error in order to make the case simpler.

The next step is to solve the Fokker-Planck equation with the initial distribution. The solution will be the time evolution of the probability density function (PDF) of runoff rate which is $P(q,t)$. Fig. 2(d) shows the function of $P(q,t=79hour)$ with starting point at time 73 hour. The time point 79 hour is 6 hours after the starting point. The three blue lines are: the upper and lower boundary of the prediction range, and the mean value of the prediction. In this case, the PDF of runoff rate is very close to normal distribution, so the prediction range is set to be plus and minus one standard division σ away from the mean value, which means the possibility of observation value finally end up in the range will be about 68%.

Back to Fig. 2(c), we can see the time evolution of the prediction range from time 73 hour to time 79 hour. It can also be seen as the time evolution of $P(q,t)$ because the prediction range are calculated by $P(q,t)$. The prediction range at the starting point time 73 hour is just a point because we used the observation value at the start point and made the uncertainty to be 0, which is the same meaning as using Dirac delta function as initial condition. Then, the prediction range is going larger and larger because of the uncertainty of the system. In the present study, we assumed that the only source of system uncertainty is the uncertainty of rainfall intensity. The assumption may not be completely justified in all cases, but it really simplified the situation. The other sources of uncertainty will be concerned further in the study.

By using the above-mentioned calculation with the start point at every time point with observation value in the rainfall event, you can get the overall prediction range of the rainfall event which is shown in Fig. 2(a). The reason that we choose the prediction period to be 6 hours is that the Japan meteorological agency provides a 6 hours period of prediction rainfall data during a rainfall event. Although this calculation is not precisely a “prediction”, it is very close to a real-time prediction when you replace the observed rainfall with the prediction rainfall.

5 Diffusion coefficient of the uncertainty of rainfall

As mentioned above, the diffusion parameter $\sigma\sqrt{T_L}$ will affect the prediction range a lot. The $\sigma\sqrt{T_L}$ can be decided by examining the rainfall data since the parameter’s physical meaning is the randomness of the rainfall intensity.

However, to decide $\sigma\sqrt{T_L}$ by rainfall observation, temporal high- resolution series is required. Also, it related to the time period of averaging the rainfall, since the random part of rainfall $r'(t)$ is the difference between the real rainfall $r(t)$ and the timely averaged rainfall $\bar{r}(t)$.

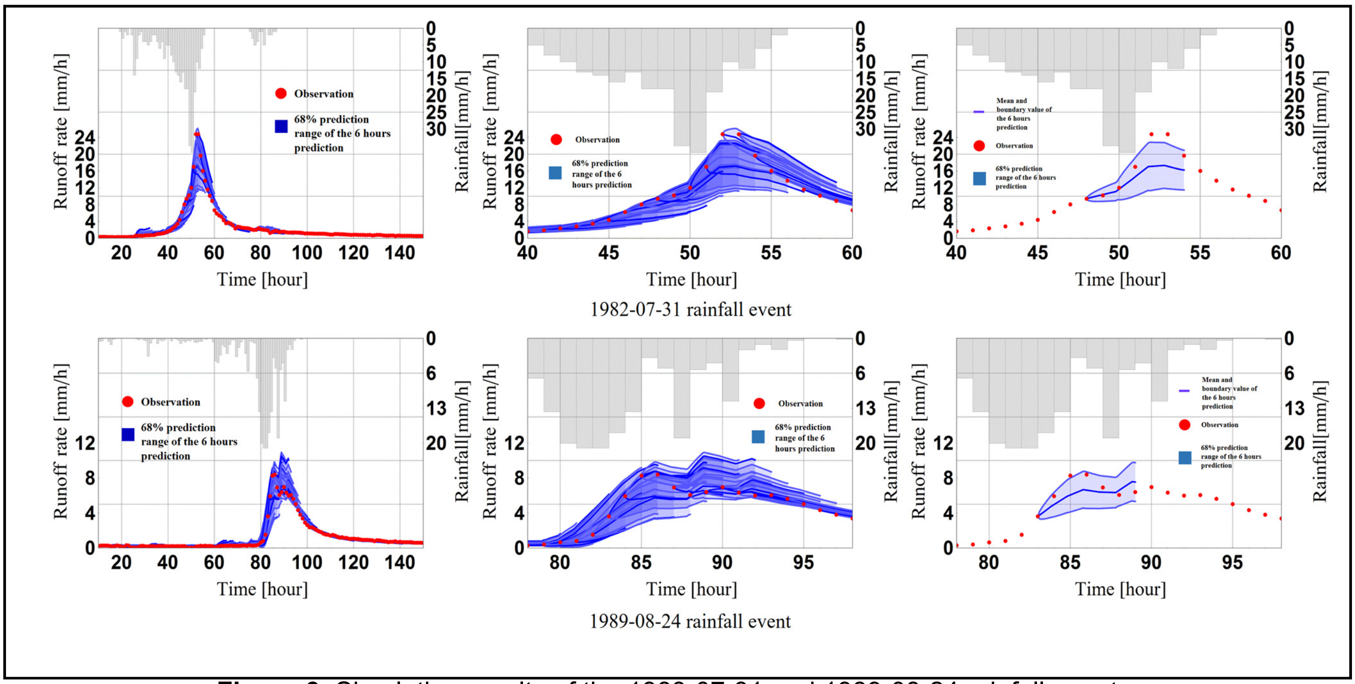


Figure 3. Simulation results of the 1983-07-31 and 1989-08-24 rainfall events using stochastic differential equation method

In filtering theory, the parameters which describe the system noise, are decided by statistical methods. One of the most common ways is the maximum likelihood estimation (MLE). While in deterministic simulations, parameters are often set to minimized residual sum of squares.

$$RSS = \frac{1}{n}\sum_{i=1}^{n}(q_{sim} - q_{ob})^2 \qquad [7]$$

But when you consider the uncertainty of a system, the meaning of residual changed, you can no longer use RSS to estimate the parameters. Instead, the maximum likelihood method is using the following thought of the estimate the parameters. For a given parameters set $(\alpha, \beta, \sigma\sqrt{T_L})$, one can calculate the PDF of runoff rate q at any certain time, and we refer it as $P(q, t, \alpha, \beta, \sigma\sqrt{T_L})$. At a certain time point t_i with observation value, one can calculate the probability density of observation value which is $P(q_{ob}(t_i), t_i, \alpha, \beta, \sigma\sqrt{T_L})$.

To use the method of maximum likelihood, one has to consider the joint density function for all observations. For an independent and identically distributed sample, this joint density function is

$$\prod_{i=1}^{n} P(q_{ob}(t_i), t_i, \alpha, \beta, \sigma\sqrt{T_L}) \qquad [8]$$

The basic thought of MLE is to find the parameters $(\alpha, \beta, \sigma\sqrt{T_L})$, of which maximize the joint density function. Usually, it is often more convenient to work with the natural logarithm of the likelihood function.

$$\sum_{i=1}^{n} ln\, P(q_{ob}(t_i), t_i, \alpha, \beta, \sigma\sqrt{T_L}) \qquad [9]$$

Furthermore, for the cases we discussed in the present study, we add the following 2 restrictions: 1) the parameters α, and β are decided by the deterministic simulation, so there is only one parameter needed to be decided which is $\sigma\sqrt{T_L}$; and 2) since $\sigma\sqrt{T_L}$ represents the randomness of $r'(t)$, it is reasonable to assume that $\sigma\sqrt{T_L}$ is not a constant but a function to $\bar{r}(t)$. In the present study, we assumed that $\sigma\sqrt{T_L}$ has the following form.

$$\sigma\sqrt{T_L} = \sigma_{Coff} \cdot \bar{r}(t) \qquad [10]$$

Considered are the two restrictions that the problem is simplified to find the σ_{Coff} which maximizes the joint density function [9]. Using 22 large rainfall events in Kusaki dam basin from 1978 to 2013, we can estimate that the value of σ_{Coff} should be 0.78. And all the simulations are based on that value. More results are shown in Fig.3.

6 COMPARISON TO THE FILTERING THEORY

In 1974, M. Hino first applied Kalman filter in rainfall-runoff process to consider the uncertainty of the system. Next, we will compare the extended Kalman filter to the present study.

First of all, in order to deal with nonlinear systems, the original Kalman filter must be extended to extend Kalman filter. The prediction step of extended Kalman filter is

$$q_{t+1} = f(q_t) \qquad [11]$$

$$\sigma_q{}^2(t+1) = \left(\frac{\partial f}{\partial q}\right)^2 \cdot \sigma_q{}^2(t) + \sigma_{noise}{}^2 \qquad [12]$$

$f(q)$ is the function which updates the system, $\sigma_q{}^2$ is the variance of runoff rate q, and $\sigma_{noise}{}^2$ is the variance of system noise. When compared equation [11] and [12] to the Fokker-Planck equation, we can summarize the difference as follows: 1) the Fokker-Planck equation calculates directly the time development of the PDF of q, while the extended Kalman filter only calculates the time development of the mean value and variance of q; and 2) the Fokker-Planck equation can be written in the form of Ito's stochastic equation, which has perfect correspondence relationship to the deterministic model, while the extended Kalman filter is written in temporal discrete form that is not directly corresponded to the deterministic model. So, one cannot find the physical meaning of $\sigma_{noise}{}^2$, and $\sigma_{noise}{}^2$ in the Kalman filter is not the same as the $\sigma\sqrt{T_L}$ in the Fokker-Planck equation.

Fig.4 shows the result of the extended Kalman filter. We can tell from Fig. 4 that there are some problems when using extended Kalman filter. The prediction range is almost the same through time. it is understandable because $\sigma_{noise}{}^2$ does not change through time. But it does not agree with the physical phenomena very well. When there are no rainfall or little rainfall, the runoff rate is almost certain to be 0 while the result of Kalman filter showed that the variance does not change much though time. Moreover, in order to fit the values where the runoff rate q is low, the prediction range is not large enough to cover the observations at the peak time.

It is true that one can assume $\sigma_{noise}{}^2$ changes though time, but it still cannot give any physical explanation of $\sigma_{noise}{}^2$. Besides, it becomes a much more difficult problem to identify $\sigma_{noise}{}^2$ when you assume it changes though time.

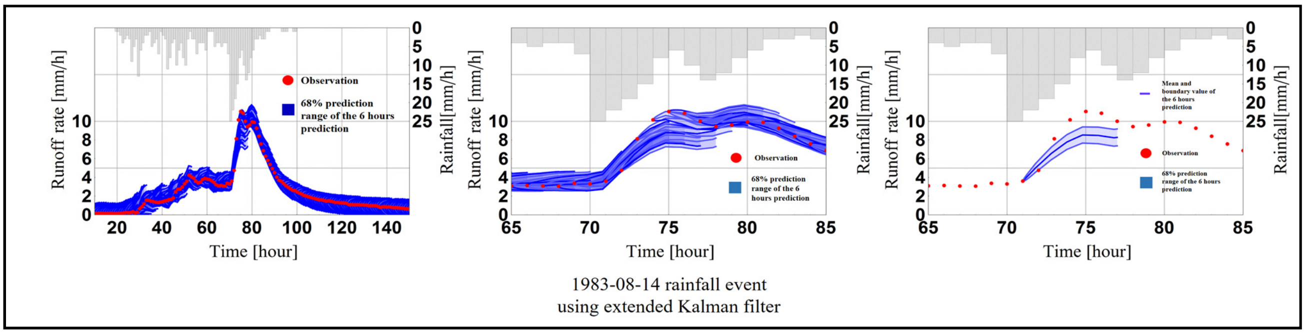


Figure 4. Simulation results of the 1983-08-14 rainfall event using extended Kalman filter. It is the same rainfall event shown in Fig. 2 and all legends remain the same meanings

7 CONCLUSIONS

The present study suggested a new way of analyzing the rainfall-runoff process under uncertain information which is by using Ito. K's stochastic differential equation theory.

There are two benefits of doing so which is: 1) unlike the traditional deterministic method, it can quantify the effect of uncertain information and get a prediction range of the system; and 2) the stochastic differential equation is corresponded to the original deterministic model which makes it possible to give physical explanation of the system noise.

The new method had been applied to Kusaki dam basin. By comparing the result to the extended Kalman filter, it can be concluded that: 1) the prediction range of extended Kalman filter does not change through time which does not match the physical truth very well; 2) the prediction range of the new method changes through time depending on $\alpha q(t)^{\beta} r'$ and that makes it close to the past experience; and 3) last but not the least, the new method also gives the system noise a physical explanation which is the random fluctuation of rainfall intensity.

In order to further verifying the new method, the following work must to be done: 1) identify the parameter $\sigma\sqrt{T_L}$ from both the rainfall data and runoff data, to see if the physical explanation of $\sigma\sqrt{T_L}$ given by the new method is right; and 2) compare the new method to other advanced filters such as particle filter or ensemble Kalman filter.

REFERENCES

M. Hino (1947). Prediction of hydrologic system by Kalman filtering. *Journal of JSCE*, 221, 39-47.

Itô. K. (1946). On a Stochastic Integral Equation. *Proceedings of the Japan Academy*, 22(1-4), 32-35.

K. Yoshimi, & T.Yamada (2016), A New Theoretical Framework of Uncertainty Estimation in Rainfall-Runoff Process Based on The Theory of Stochastic Process. *Annual journal of Hydraulic Engineering, JSCE*, 60, 1225-1230.

T. Yamada (2003). Studies on Nonlinear Runoff in Mountainous Basins. *Journal of JSCE*, 47, 259-264.

A. H. Weerts, G.Y.H. El Serafy (2006). Particle filtering and Ensemble Kalman Filtering for State Updating with Hydrological Conceptual Rainfall-Runoff Models. *Water Resources Research,* 42, W09403.

T. M. Carpenter, K. P. Georgakakos (2006). Intercomparision of Lumped Versus Distributed Hydrologic Model Ensemble Simulations on Operational Forecast Scales. *Journal of Hydrology*, 329, 174–185.

A NONSTATIONARY TRIVARIATE DROUGHT FREQUENCY MODEL FOR ESTIMATING DROUGHT RISK IN A CHANGING CLIMATE

JIN-YOUNG KIM(1), HYUN-HAN KWON(2), JIN-GUK KIM(3) & SUK-HWAN JANG(4)

(1,2,3) Department of Civil Engineering at Chonbuk National University, South Korea
jinyoungkim@jbnu.ac.kr; hkwon@jbnu.ac.kr; jg.kim@jbnu.ac.kr
(4) Department of Civil Engineering at Daejin University, South Korea
drjang@daejin.ac.kr

ABSTRACT

Drought can be defined as an extended period of precipitation deficiency and is often driven by natural climate variability. Drought frequency analysis has been typically based on univariate approach. However, extreme events of interest in hydrologic design show multivariate dependencies that may be described by a set of dependent random variables. In particular, drought events are generally characterized by three dependent attributes: drought duration, severity and intensity. It has been reported that the univariate models often underestimate drought risk compared to the multivariate models. Therefore, the univariate model may not be appropriate for complex hydrological events. Various studies have been conducted to estimate the joint or conditional probability of extreme events using multivariate joint distributions. In this regard, this study aims to propose a novel approach to estimate the parameters of the copula function and their uncertainty within the Bayesian framework. The proposed nonstationary trivariate drought frequency model is used to estimate drought risk in South Korea. As an experimental study, we evaluated the stationary and time-varying joint return periods of the drought duration and severity for both the historical runs and future projection using GCM model output. It is clearly identified that the climate model shows a limited capability to accurately model the underlying probabilities in the drought variables, which could lead to misinterpretation for climate variability associated drought patterns in the future.

Keywords: Trivariate Copula; Bayesian; Climate change scenarios; uncertainty; return period.

1 INTRODUCTION

Meteorological drought can be defined as an extended period of deficient precipitation. A number of univariate drought frequency methods have been developed and applied to estimate return periods of droughts (Engeland et al., 2004; Sadri and Burn, 2012). Extreme drought events are particularly of interest from a hydrologic design perspective. Modeling the multivariate dependence has been recognized as necessary for hydrologic risk estimation (Hao and Singh, 2012; Shiau, 2006), especially for assessing risks associated with climate change and variability. For drought risk analyses, hydrologists are interested in how joint return periods or joint likelihoods for drought duration and severity could be estimated to understand their mutual dependences on drought risk. Several studies have been conducted to estimate the joint or conditional probability of extreme events with multivariate joint distributions (Favre et al., 2004; Hao and Singh, 2013). A major difficulty in estimating the multivariate joint density function for drought risk analyses is that the marginal distributions of the variables of interest (e.g. duration, severity and intensity) are often different. Copula functions are initially introduced by (Sklar, 1959) and they provide the flexibility to identify and fit a dependence structure to variables that have different marginal distributions.

In these reasons, this study developed a trivariate copula function based drought frequency analysis model to better evaluate the recent 2014-2015 drought event in South Korea. The bivariate frequency analysis for the drought duration and severity has been routinely applied. However, the recent drought patterns show that the intensity can be regarded as an important factor which is being characterized by short duration and severe intensity. In this context, this study developed the trivariate copula function approach to incorporate the trivariate drought characteristics into the frequency analysis.

2 COPULA FUNCTION OVERVIEW

A copula is a multivariate probability function to describe interdependence among multivariate random variables (Sklar, 1959). Copulas are very useful for multidimensional hydrologic applications because they allow us to model joint functions by estimating copulas and marginal distributions separately. The copula has been widely used for multivariate analysis of hydrologic variables because of its flexibility and power to establish a joint probability function with the different marginals.

Suppose we have m-dimensional random variables *($X_1, X_2, \ldots, X_m$)* and their maginal *CDFs (i.e. $F_i(x) = p[X_i \le x]$)* are continuous. The random variables can be transformed into uniformly distributed marginal distributions by applying the marginal CDFs to the random variables as in Eq.1:

$$(U_1, U_2, \ldots, U_m) = (F_1(X_1), F_2(X_2), \ldots, F_m(X_m)) \tag{1}$$

The copula of random variables is then defined as a joint CDF (Eq.2).

$$C(u_1, u_2, \ldots, u_m) = p[U_1 \le u_1, U_2 \le u_2, \ldots, U_m \le u_m] \tag{2}$$

The marginal CDF (Fi) describes underlying marginal distribution of variable i, while the copula function C describes the dependency structure between the random variables *($X_1, X_2, \ldots, X_m$)*. A main advantage of the copula approach is that the reverse of the above steps can be applied to efficiently simulate multivariate random samples. Specifically, the required multivariate random variables can be sampled from a uniformly distributed random vector *($U_1, U_2, \ldots, U_m$)* (Eq.3)

$$(X_1, X_2, \ldots, X_m) = F_1^{-1}(U_1), F_2^{-1}(U_2), \ldots, F_m^{-1}(U_m) \tag{3}$$

where F_i^{-1} is the quantile function (or inverse CDF) of the marginal distribution can be expressed as Eq. 4.

$$C(u_1, u_2, \ldots, u_m) = p[X_1 \le F_1^{-1}(u_1), X_2 \le F_2^{-1}(u_2), \ldots, X_m \le F_m^{-1}(u_m)] \tag{4}$$

This study aims to estimate return period of drought variables (e.g. drought duration, severity and intensity) based on bivariate and trivariate copula functions. The drought variables are defined by the run theory (Yevjevich, 1967), which has been widely used for characterizing different aspects of drought as shown in Figure 1.

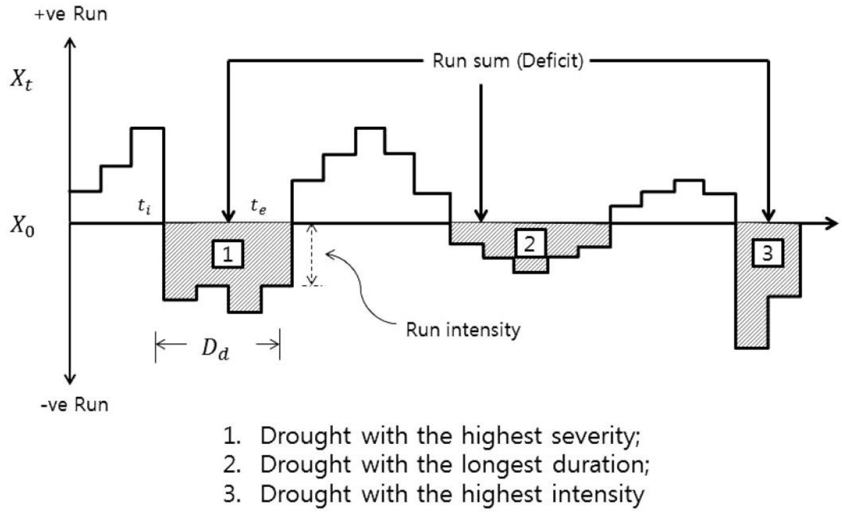


Figure 1. The identified drought duration, severity and intensity by run theory.

The univariate return period of a certain drought severity (Shiau and Shen, 2001) T_{DS} and drought duration (Shiau, 2006) T_{DD} can be estimated as follows:

$$T_{DS} = \frac{E(L)}{P(S \ge s)} = \frac{E(L)}{1 - F_S(s)} \tag{5}$$

$$T_{DD} = \frac{E(L)}{P(D \ge d)} = \frac{E(L)}{1 - F_D(d)} \tag{6}$$

where, *E(L)* is the expected drought interval time, *s* and *d* denote drought severity and drought duration, and F_S and F_D are represented cumulative distributions of the drought severity and duration, respectively.

Shiau (2006) proposed joint return periods for the bivariate frequency analysis. The joint drought duration and severity return periods can be defined in two cases: return period for $D \geq d$ and $S \geq s$ (T_{DDS}) and return period for $D \geq d$ or $S \geq s$ (T'_{DDS}).

$$T_{DDS} = \frac{E(L)}{P(D \geq d, S \geq s)} = \frac{E(L)}{1 - F_D(d) - F_S(s) + C(F_D(d), F_S(s))} \tag{7}$$

$$T'_{DDS} = \frac{E(L)}{P(D \geq d \text{ or } S \geq s)} = \frac{E(L)}{1 - C(F_D(d), F_S(s))} \tag{8}$$

where, $C(F_D(d),F_S(s))$ represents the joint probability between the drought duration and severity. This study further developed the trivariate frequency analysis, and its joint return period can be defined as follows:

$$T_{DDSI} = \frac{E(L)}{P(D \geq d, S \geq s, I \geq i)} = \frac{E(L)}{1 - F_D(d) - F_S(s) - F_I(i) + C(F_D(d), F_S(s)) + C(F_D(d), F_I(i)) + C(F_S(s), F_I(i)) - C(F_D(d), F_S(s), F_I(i))} \tag{9}$$

$$T'_{DDSI} = \frac{E(L)}{P(D \geq d \text{ or } S \geq s \text{or } I \geq i)} = \frac{E(L)}{1 - C(F_D(d), F_S(s), F_I(i))} \tag{10}$$

where, $C(F_D(d),F_S(s))$, $C(F_D(d),F_I(i))$ and $C(F_S(s),F_I(i))$ are the joint probability between a pair of variables (D,S,F) of interest. In addition, $C(F_D(d),F_S(s),F_I(i))$ is the joint probability of the three variables considered in this study. A conceptual diagram for the estimation of copula parameters in a multivariate setting is represented in figure 2.

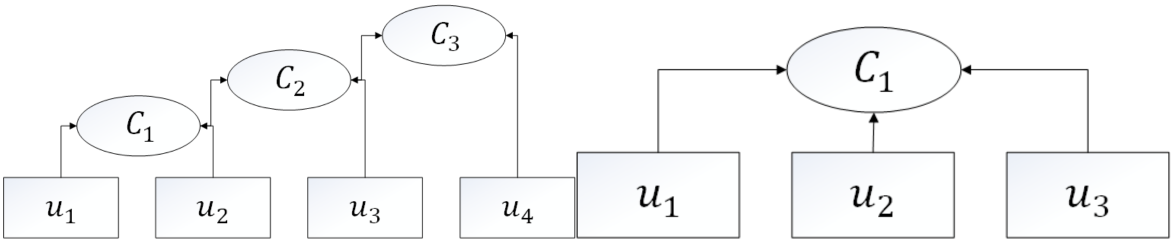


Figure 2. A schematic representation for the estimation of trivariate joint probability. The left panel indicates the Archimedean copula functions based joint probability estimation while the right panel indicates the meta-elliptical copula function based approach.

3 THE RESULT OF TRIVARIATE DROUGHT FREQUENCY ANALYSIS

3.1 Watershed and Precipitation Data

In this study, the Han River watershed (in figure 3) is considered as a case study due to the recent extreme drought conditions in the area and importance of the watershed from a water security perspective (i.e. the watershed is the primary water supply for the Seoul metropolitan area). The Han River is the second largest tributary including Seoul and is the main source of water supply to the central part of South Korea. The watershed size is occupied about 23% of the national territory that is 26,355 km^2, excluding the Imjin River watershed, and its length is about 482 km. The annual average discharge of watershed is about 613m^3/s. In this reason, this study was selected for a case study which was analyzed for drought. The monthly precipitation data of eighteen weather stations (in Figure 3 and Table 1) at the Han River watershed was obtained from the Korea Meteorological Administration(KMA, http://web.kma.go.kr) , spanning the period is 1974-2014.

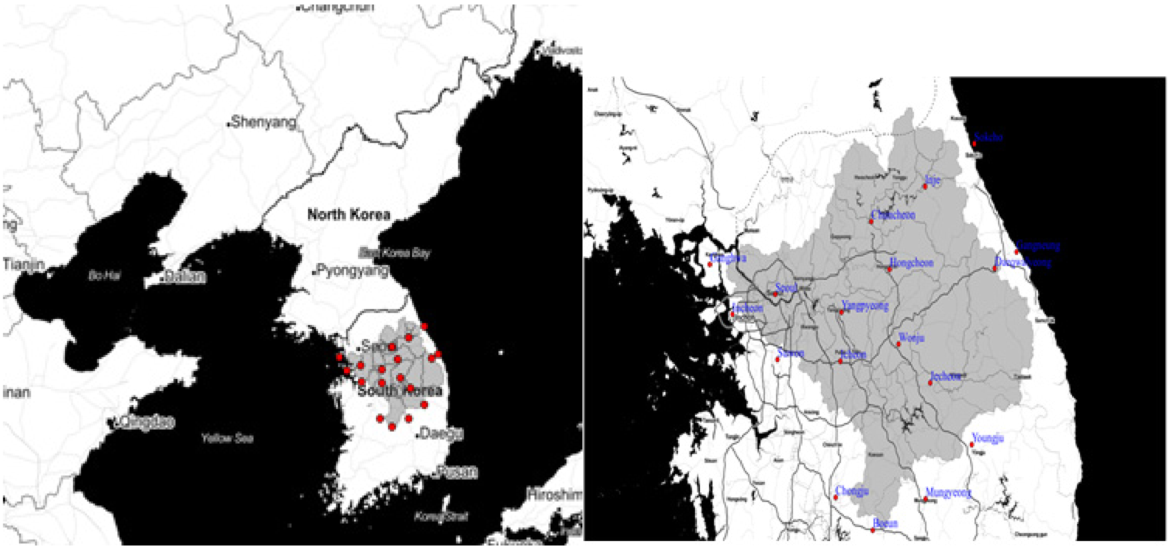


Figure 3. A map is showed the Han River watershed along with weather stations(red filled circle)

Table 1. Weather stations used in this study

Station	Latitude(°)	Longitude(°)	Altitude(m)
Suwon	37.2723	126.9853	34
Sokcho	38.2509	128.5647	18
Gangneung	37.7515	128.8910	26
Yeongju	36.8719	128.5170	211
Mungyeong	36.6273	128.1488	171
Boeun	36.4876	127.7341	175
Cheongju	36.6392	127.4407	57
Daegwallyeong	37.6771	128.7183	773
Jecheon	37.1593	128.1943	264
Wonju	37.3376	127.9466	149
Icheon	37.2640	127.4842	78
Yangpyeong	37.4886	127.4945	48
Inje	38.0599	128.1671	200
Chuncheon	37.9026	127.7357	78
Hongcheon	37.6836	127.8804	141
Seoul	37.5714	126.9658	86
Ganghwa	37.7074	126.4463	47
Incheon	37.4776	126.6244	68

3.2 Results of drought frequency analysis

The bivariate drought frequency analysis based on the drought duration and severity has been widely developed and applied over the last decades. In this study, the drought intensity is additionally included for the estimation of joint return periods. Three drought variables extracted from Seoul station are shown in Figure 4, as a representative case study. As shown in Figure 4, the drought intensity for the 2014-2015 years is exceptionally high. The Log-normal, Gamma and Gamma distribution are selected as marginal distributions for the drought duration, severity and intensity, respectively.

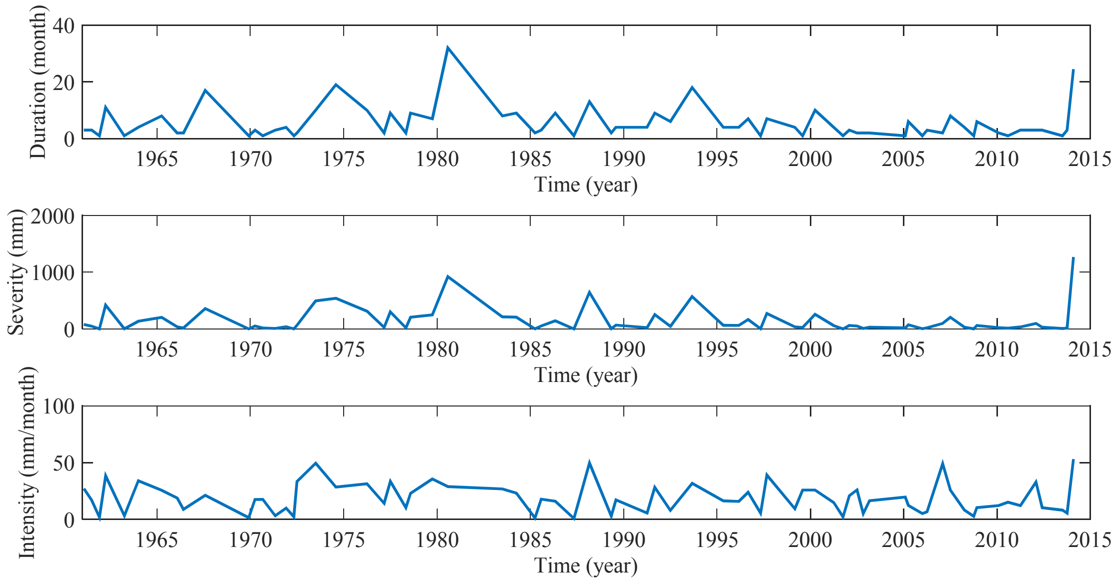


Figure 4. The drought variables are used in this study for Seoul station

Table 2. The table indicated BIC value of each distributions.

Drought variable	Distribution	BIC
Duration	**Log normal**	**370.9302**
	Log logistic	375.0777
	Exponential	380.7142
	Gamma	381.8993
	Weibull	383.8809
	Normal	450.6571
	Extreme	505.1580
Severity	**Gamma**	**818.3143**
	Weibull	821.7076
	Log logistic	820.6706
	Exponential	837.8622
	Inverse gaussian	840.2267
	Normal	962.6028
	Extreme	1023.1410
Intensity	**Gamma**	**547.7647**
	Weibull	549.7865
	Exponential	553.0873
	Log logistic	562.7535
	Normal	565.8007
	Inverse gaussian	574.0500
	Extreme	587.9190

Table 3. The correlation matrix indicated for all drought variables.

Correlation coefficient	Duration	Severity	Intensity
Duraton	1.000	0.926	0.560
Severity	0.926	1.000	0.704
Intensity	0.560	0.704	1.000

In this study, the Log-likelihood value was used to select the best copula function, as summarized in Table 4. The selected copula functions for Seoul station are the Gumbel, Gumbel and Frank copula for different combinations of drought variables.

Table 4. The estimated log-likelihood between the drought variables.

Variables	Clayton	Frank	Gumbel	•
1) Duration & Severity	48.0972	57.7230	**62.7928**	3.6300
2) Duration & Intensity	14.8194	17.5215	**17.7652**	1.7459
3) Severity & Intensity	44.0731	**45.6612**	38.3132	10.1869

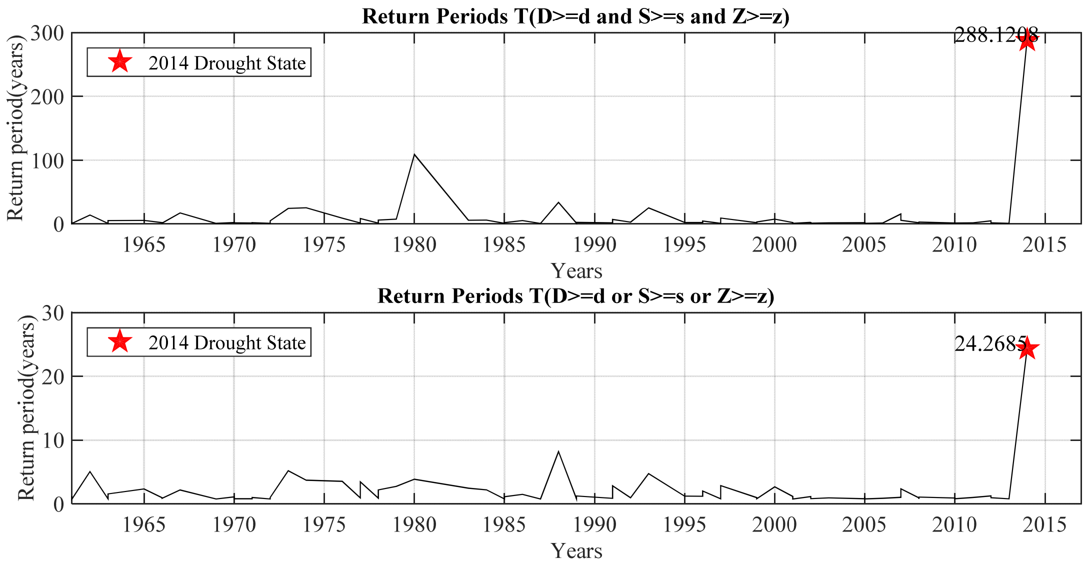


Figure 5. The result shows return period using trivariate copula function of Gumbel. The red stars indicates the drought state for the 2014-2015 drought event.

Table 5. The table indicates the return period using Gumbel trivariate copula function.

Year	And year				Year	And year			
	Duration & Severity	Duration & Intensity	Severity & Intensity	Trivariate		Duration & Severity	Duration & Intensity	Severity & Intensity	Trivariate
1961	1.851	3.820	3.564	3.308	**1988**	**22.462**	**31.699**	**31.807**	**33.918**
1962	10.357	13.824	12.387	13.945	1989	1.944	2.486	2.020	2.352
1963	2.607	6.631	6.123	5.322	1991	5.683	7.280	5.582	6.993
1965	4.585	5.875	4.383	5.573	1992	2.702	2.821	1.421	2.804
1966	1.304	2.060	1.982	1.951	1993	21.877	22.036	17.464	25.176
1967	16.234	17.159	7.578	17.282	1995	1.923	2.407	1.933	2.291
1969	0.835	0.833	0.813	0.845	1996	3.761	4.882	3.663	4.581
1970	1.588	2.182	1.938	2.054	1997	5.340	11.266	10.037	9.217
1971	1.801	1.973	1.396	1.946	1999	1.793	1.945	1.354	1.923
1972	1.609	5.781	5.659	4.918	2000	6.331	7.554	5.321	7.446
1973	12.994	28.161	26.27	24.322	2001	1.889	2.282	1.791	2.194
1974	22.903	23.625	15.456	25.293	2002	1.671	2.599	2.36	2.38
1976	7.159	9.143	7.354	8.978	2003	1.260	1.800	1.722	1.732
1977	6.459	9.137	7.636	8.556	2005	2.757	3.022	1.800	2.973
1978	5.173	6.150	4.138	5.991	2006	1.401	1.482	1.123	1.478
1979	4.866	8.882	7.729	7.526	2007	1.979	22.692	22.471	15.621
1980	**104.996**	**104.04**	**54.88**	**108.965**	2008	2.729	2.923	1.629	2.891
1983	4.692	6.152	4.703	5.798	2010	1.187	1.457	1.37	1.436
1984	5.182	6.171	4.167	6.010	2011	1.477	1.736	1.457	1.695
1985	1.594	2.21	1.967	2.076	2012	2.044	5.809	5.513	4.749
1986	4.826	5.302	2.782	5.228	2013	1.388	1.442	1.056	1.442
1987	0.826	0.823	0.790	0.830	**2014**	**142.568**	**66.677**	**144.575**	**288.121**

4 CONCLUSIONS

A copula-based multivariate frequency analysis was employed to model the dependence in drought duration, severity and intensity. Copula-based multivariate models have been widely applied to hydrologic frequency analyses, however, reliable estimation of the parameters is often a challenging task in the multivariate setting, due to limited data available. Moreover, uncertainties associated with the model parameters in copula-based frequency models are not often properly. We have developed and tested a trivariate copula approach for drought frequency analysis. The proposed model was applied to estimate joint return periods on a network of eighteen weather stations in the Han River watershed in South Korea.

The trivariate frequency analysis is more realistically reflected than bivariate frequency analysis, because the recent drought patterns showed that the intensity can be regarded as an important factor. Also, the result of bivariate frequency analysis was underestimated. It will occur to make the management difficult when the extreme drought phenomenon arises. Thus, this study recommends trivariate drought variable to analyze the drought frequency analysis for reality reflection. Finally, this proposed model can be notified the reasonable drought return period value for drought monitoring or management.

ACKNOWLEDGEMENTS

This study was supported by a Grant (KMIPA2015-6190) from See-AT of Korea Meteorological Industry Promotion Agency.

REFERENCES

Chen, L., Singh, V.P., Guo, S., Mishra, A.K. & Gou, J. (2013). Drougth Analysis Based on Copulas. *Journal of Hydrologic Engineering,* Vol. 18(7), 797-808.

Engeland, K., Hisdal, H. & Frigessi, A. (2004). Practical Extreme Value Modelling of Hydrological Floods and Droughts: A Case Study. *Extremes*, 7(1), 5-30.

Hao, Z. & Singh, V. (2012). Entropy- Copula Method for Single- Site Monthly Streamflow Simulation. *Water Resour Res*, 48(6).

Hao, Z. & Singh, V. (2013). Modeling Multisite Streamflow Dependence with Maximum Entropy Copula. *Water Resour Res*, 49(10), 7139-7143.

Kwon, H.-H. & Lall, U. (2016). A Copula-Based Nonstationary Frequency Analysis for the 2012-2015 Drought In California. *Water Resources Research*, doi:10.1002/2016WR018959.

Requena, A. L., Mediero O. & Marcos, L. G. (2013). A Bivariate Return Period Based on Copulas for Hydrologic Dam Design: Accounting for Reservoir Routing in Risk Estimation. *Hydrology and Earth System Sciences*, Vol. 17(8), 3023-3038.

Sadri, S., and Burn, D. (2012). Nonparametric Methods for Drought Severity Estimation at Ungauged Sites. *Water Resour Res*, 48(12).

Salvadori, G. & C. Michele (2004). Frequency Analysis Via Copulas: Theoretical Aspects and Applications to Hydrological Events. *Water Resources Research*, 40(12).

Shiau, J.T. & Shen, H.W. (2001). Recurrence Analysis of Hydrologic Droughts of Differing Severity. *Journal of Water Resources Planning and Management.*

Shiau, J.T. (2006). Fitting Drought Duration and Severity with Two-Dimensional Copulas. *Water resources management*, 20(5), 795-815.

Sklar, M. (1959). *Fonctions De Répartition a N Dimensions et Leurs Marges*. Université Paris 8.

Yevjevich, V. (1967). On Objective Approach to Derinitions and Investigations of Continental Hydrologic Droughts. *Hydrology Paper*, No. 23, Colorado State University, Fort Collins, 4-18.

APPENDIX

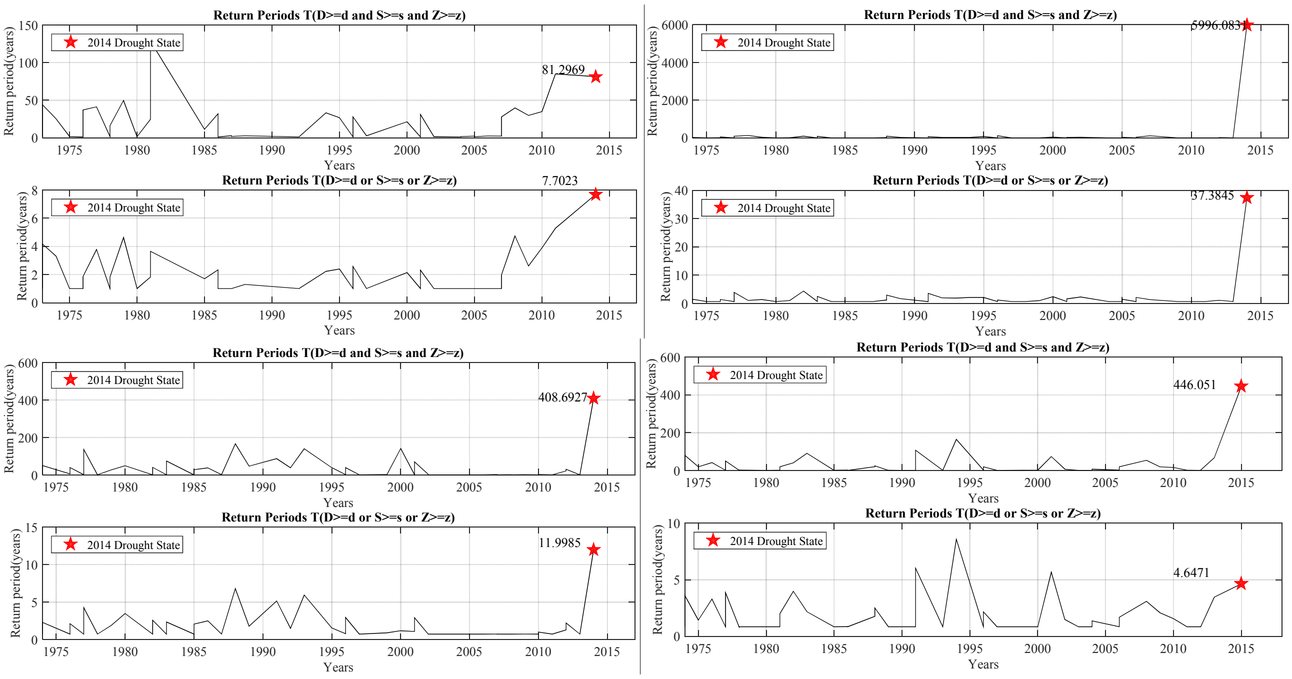


Figure A. The result showed return period using trivariate copula function of Gumbel (Daegwallyeong (Northeast), Ganghwa(Northwest), Inje(Southeast) and Boeun(Southwest)). The red stars indicated the drought state for the 2014-2015 drought event.

ASSESSMENT OF ACUTE IMPACT OF HIGH SEDIMENT CONCENTRATION ON YELLOW RIVER CARP

FENGRAN XU(1), BAOLIGAO BAIYIN (2), XINGRU CHEN(3) & HUANHUAN DENG(4)

(1,2,3) State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, China,
baiyinblg@hotmail.com; xufengran@126.com
(4) Zhejiang Provincial Key Laboratory of Watershed Science and Health Risk, Wenzhou, China,
(4) School of Public Health and Management, Wenzhou University, Wenzhou, China

ABSTRACT

To reduce reservoir sedimentation and deliver sediment to the downstream rivers, sediment flushing has been conducted annually by multi-reservoir operations along the Yellow River since 2002. Deceased fishes often appear during the period of reservoir sediment flushing. To explore the quantitative impact of suspended sediment on carp (*Cyprinus carpio*), suspended sediment concentration-exposure duration model (SEV model) was applied. In 2009, it was assessed to have no lethal effect during the sediment flushing of Xiaolangdi Reservoir. While in 2010, the fish mortality rate is assessed to be less than 20%. With data from experiments that have carps exposed in different sediment concentrations, it is analyzed that the SEV model tends to underestimate the acute impact of high sediment concentration (>25kg/m^3). By refitting the regression model with experimental data, SEV model was revised to evaluate the impact of sediment on carp in the Yellow River. This research could promote further understanding of quantitative principles of impact of sediment on fishes, and provide scientific basis for river sediment management and eco-friendly reservoir sediment flushing operation.

Keywords: Sediment flushing; suspended sediment concentration; fish; impact assessment; Yellow River.

1 INTRODUCTION

Sediment concentration of the river usually increases rapidly within a short period during natural flood and reservoir sediment flushing. This leads to a sharp drop in the amount dissolved oxygen in the river, and causes acute hypoxia stress effect on the fishes. And under severe cases, it may result in the death of fishes. During flood season, the sediment concentration of rivers that are running through arid regions in North China will change dramatically. In the Yellow River, over 85% of sediment originates from the flood season, and it is usually just caused by several storm floods. Moreover, to mitigate the reservoir sedimentation, extend the reservoir service life, and recover the consecutive movement of sediment along rivers, most reservoirs conduct sediment flushing. During sediment flushing, downstream river channel of the reservoir is subjected to continuous high sediment concentration. During sediment flushing period for Sanmenxia Reservoir and Xiaolangdi Reservoir in the Yellow River, the sediment concentration usually goes as high as hundreds of kilograms per cubic meter. As the sediment flushing continues, lots of fishes are seen floating on the water. They are either dead or have fallen into coma, and this scene is commonly seen along the Yellow River. This phenomenon is known as "the drifting fish". Thus, the research on the acute impact of high sediment concentration on fishes and its corresponding mitigation measures are currently a key focus in the sediment-laden river management and project operation.

Since 1990s, scholars have conducted researches on the impact of high sediment concentration on fishes. Through field investigation, scholars found that the sediment concentration during reservoir sediment flushing and natural floods can reach tens or even hundreds of kilograms per cubic meter. This has led to death of fishes and drop in the biomass of the river. In terms of impact mechanism, Staub (2000) considered that in high sediment-concentration flow, fishes have to increase their amount of movement, respiratory rate and oxygen demand, and may be prone to gill blockage; when the dissolved oxygen content is lower than 2mg/l or the sediment concentration is over 30kg/m^3, hypoxia will become a vital factor threatening the survival of fishes. Newcombe et al. (1996) pointed out that the sediment with grain size less than 75μm can pass through gill membranes into interlamellar spaces of gill tissue. While those with grain size larger than 75μm can cause mechanical damage to the fish gill. To assess the extent of impact of sediment concentration on the living status of fishes, Newcombe et al. (1991;1996) had proposed to apply Stress index (SI) method to this assessment, based on the data and samples of previous research. They also put forward the suspended sediment concentration-exposure duration model (SEV model). When sediment flushings were being conducted by reservoirs in Europe and Japan, Baiyinbaoligao et al. (2008) and Crosa et al. (2010) used the SEV model to assess the impact on downstream fishes.

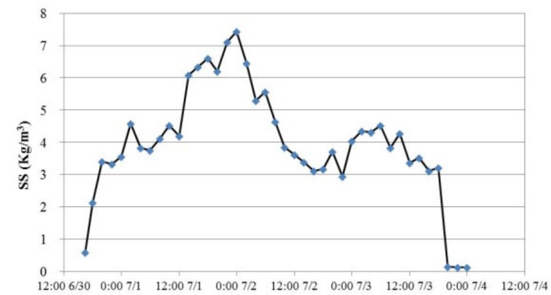
However, scholars found that impact of sediment on fishes varies in places and species of fishes, thus showing obvious diversity (Rowe et al., 2009; Bilotta et al., 2012). In different regions, the control limit of sediment concentration (or turbidity) varies according to the different object species (Crosa et al., 2010; Meyer et al., 1999; Schneider et al., 2006). In the past days, most of the researches in Europe and Japan had been done on trout and other migratory fishes that are under relatively low sediment concentration (generally below 40kg/m^3). Only a few had been done on other species of fishes that are under relatively high sediment concentration. Thus, the existing achievements and principles require further verification. Considering the diverse river habitats and the sediment tolerance capacity of different fish species, the research in this field should be further expanded towards the range of sediment concentration and affected fishes, and combined with conditions of the sediment-laden rivers in China.

In this paper, based on the field investigation to Xiaolangdi Reservoir in the Yellow River during its sediment flushing periods in 2009 and 2010, as well as the data of laboratory experiment for the impact of sediment concentration on carps, the impact of sediment concentration on fishes has been assessed by the use of SEV model which was proposed by Newcombe and Jensen (1996). The author also attempts to revise the model to be applicable for assessing the impact of sediment on typical species of fishes in the Yellow River.

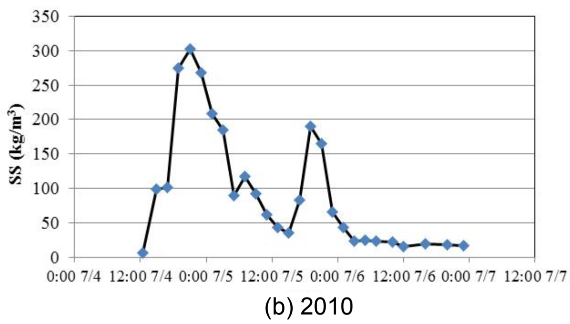
2 MATERIALS AND METHODS

2.1 Data from field investigation

During the sediment flushing period in 2009 and 2010, field surveys (Baoligao et al., 2016) had been done for river sediment concentration, water quality and fish living status at 3km downstream from the Xiaolangdi Dam. It had been found that during the sediment flushing conducted in 2009, the sediment concentration was comparatively low, with its peak at 7.44kg/m^3, and there was no occurrence of water flow of high sediment concentration (Figure 1). In 2010, water flow of high sediment concentration had been detected during sediment flushing, with two peaks: 302kg/m^3 and 190kg/m^3. The sediment collected in the sediment flushing period in 2009 and 2010 was of fine grain size. The percentages of sediment with grain size below 0.062mm in the above two periods accounted for 99% and 93% respectively.



(a) 2009



(b) 2010

Figure 1. Variation of sediment concentration in downstream river reaches of Xiaolangdi dam during sediment flushings in 2009 and 2010.

During the sediment flushing period of Xiaolangdi Reservoir in 2009, the maximum sediment concentration was merely 7.44kg/m^3, and it turned out to be the lowest peak value among annual the joint sediment flushings in the Yellow River since 2002. No deceased fishes had been found during the field investigation. In 2010, water flow of high sediment concentration had been detected and the deceased fishes covered 5 orders, 5 families, and 11 species. Big fishes like bighead carp, chub and carp, and small fishes like whitebait had been affected by this sediment flushing.

  / ISSN 1562-6865 (Online) - ISSN 1063-7710 (Print)

2.2 Data from laboratory experiments

Laboratory experiments had been conducted for quantitative research on the impact of various sediment concentrations on fishes and their living status. As carp is one of key species in the ecosystem of Yellow River — a famous sediment-laden river in China, also the most well-known economic fish species in Yellow River, it was selected as the typical species. In the laboratory experiments, stress effect on carps under various sediment concentrations had been studied.

Facilities and processes of the experiments had been introduced in the paper (Baoligao et al., 2016). Suspended sediment from Yellow River had been adopted, with maximum grain size of 0.116mm, and medium grain size of 0.075mm. It is difficult to collect enough wild carp (at least 70 carp) to meet the requirements of Laboratory experiments, so carp (0.5~1kg) was collected from fish ponds near the Yellow River. Carp were acclimated for one week before being placed in the tank where the SSC had been set to a test level. Lethal effects of suspended sediments were studied by Rowe et al. (2009) with 7~10 New Zealand fishes in each experiment, and by Muraoka et al. (2011) with 10 Japanese Ayu in each experiment. Thus, we put 10 carp in each experiment. The sediment concentrations in the 7 experiments were 16, 38, 60, 89, 118, 151 and 182kg/m^3 respectively. The researchers wanted to observe the living status of fishes under different sediment concentrations.

Tap water was used in the experiment after exposed in atmosphere for more than 12h. Then, water temperature was 24°C, and DO was 8mg/l. They are close to the temperature (24~28°C) and DO (7.5~8.5mg/l) in natural river water. During the experiment, the water temperature, dissolved oxygen, mortality rate of fishes under different sediment concentrations were measured and recorded. With the increase in SSC, carp mortality rates increased gradually, and the DO decreased (Figure 2 and Figure 3).

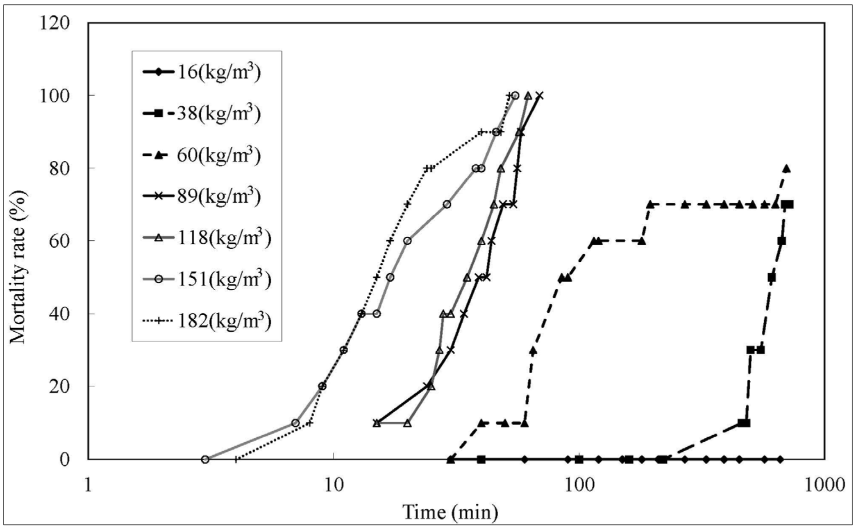


Figure 2. Lethal effects of different SSCs on carps in laboratory experiments.

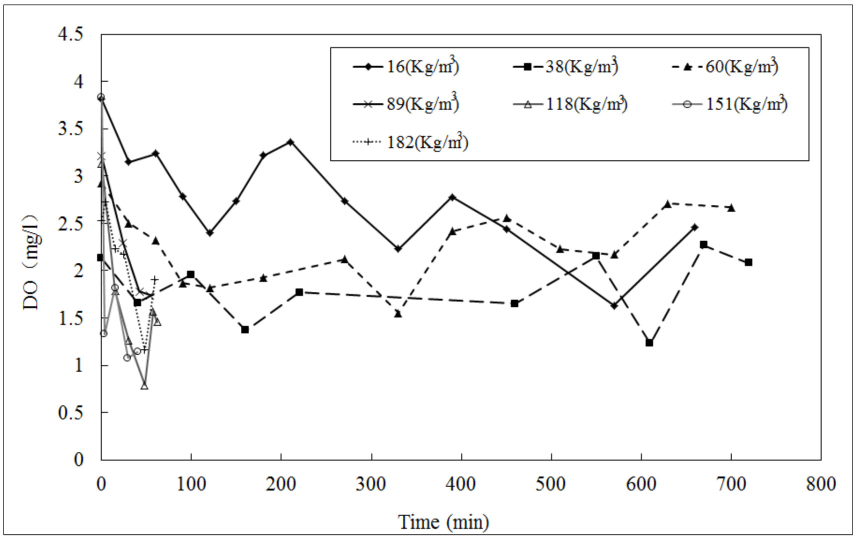


Figure 3. Variation of DO in laboratory experiments.

2.3 Model used to assess the acute impact of sediment concentration on fishes

The impact of sediment on fishes is related to the combined action of following factors: sediment concentration, dissolved oxygen, duration, pollutants attached to the sediment, sediment grain size, fish species (Bilotta and Brazier, 2008). These factors are correlated with each other and of complicated mechanism of action. Many scholars found that the dissolved oxygen content falls when the sediment concentration rises up. This relationship is closely correlated. Based on specific river and typical fish species, Newcombe and Jensen (1996) pointed out that sediment concentration and exposure duration are key impact factors, and set up the suspended sediment concentration-exposure duration model (hereinafter referred to as "SEV model", see Formula [1]).

$$SEV = a + b\ ln(ED) + c\ ln(SS) \qquad [1]$$

In the Formula: SEV (Severity Effect Value) serves as an index showing the degree of impact of the sediment on fishes. It ranges from 0 to 14, which represents the status varying from "no impact" to "a mortality rate that is close to 100%". The higher the SEV, the more severe the status is. If SEV is over 10, it means that it has lethal impact in fishes. SEV=10, 11, 12, 13, 14, respectively corresponding to mortality rate of fishes=0–20%, 20–40%, 40–60%, 60–80% and 80–100%. ED refers to the duration (h) of fishes exposing to sediment-laden water body. SS refers to the sediment concentration (mg/l); a, b, c refer to regression coefficients.

The SEV was regressed on the ED and the SSC by Newcombe and Jensen (1996) for adult freshwater nonsalmonids. The equation coefficients are provided as: a=4.0815; b=0.7126; c=0.2829 (Formula [2]).

$$SEV = 4.0815 + 0.7126\ ln(ED) + 0.2829\ ln(SS) \qquad [2]$$

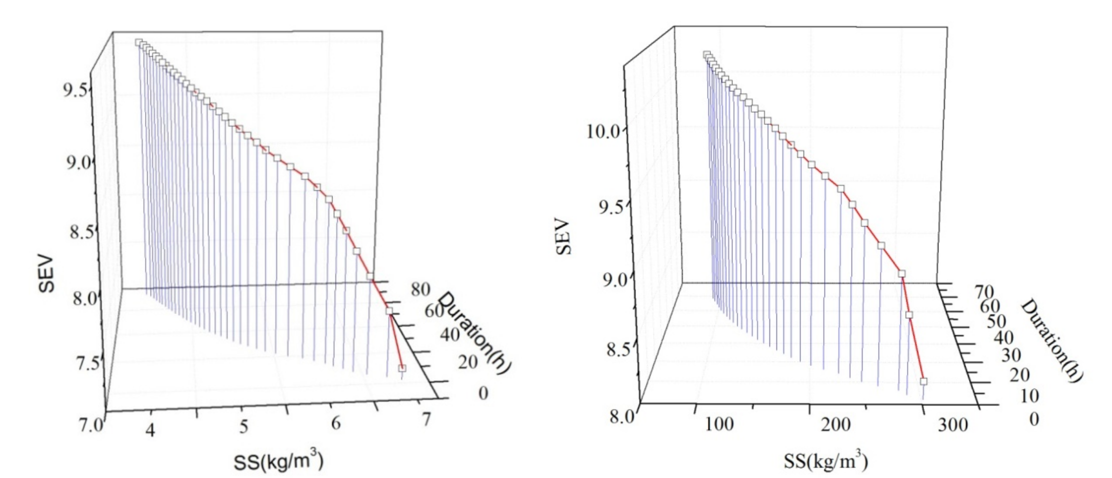
In this paper, the impact of different sediment concentrations on fishes was assessed by using the above formula and data from field investigation during the sediment flushings in 2009 and 2010, and laboratory experiments. The assessment had been verified with mortality rate of fishes in laboratory experiment. Furthermore, by using the data from laboratory experiment, the author attempts to revise the model to be suitable for assessing the impact of sediment of Yellow River on typical species of fishes.

3 RESULTS AND DISCUSSIONS

3.1 Assessment on impact of reservoir sediment flushing on fishes

The impact of sediment flushings on fishes in the Yellow River in 2009 and 2010 had been assessed by the application of SEV model (Formula [2]). It was estimated that in 2009, SEV was 7.1-9.5 (see Figure 4), which would not stress the fishes to death based on the connotations of variables in SEV model. That was consistent with the result of the investigation in 2009. During the sediment flushing conducted in 2009, it was detected that sediment concentration was relatively low with 4.4kg/m^3 in average, and with a peak value of 7.44kg/m^3. The dissolved oxygen content in the river remained over 3mg/l, no deceased fishes had been observed. During the sediment flushing in 2010, SEV was 8.2-10.2, corresponding to a mortality rate of fishes below 20%. But through field investigation, the peak value of sediment concentration reached 302kg/m^3, the dissolved oxygen content in the river channel was below 2mg/l, and plenty of dead fishes were seen in the river.

The result estimated by SEV model reflected the different impacts of sediment flushing on fishes in 2009 and 2010. As the mortality rate of fishes were not quantified through field investigation, it is unfeasible to verify the assessment by the model. Further verification should be based on relevant data of fish mortality rates from laboratory experiments, in which the impact of different sediment concentrations on fishes were tested. In the current study, the Chemical composition of suspended sediments is considered to be relatively stable with little influence on fishes.



(a) 2009 (b) 2010

Figure 4. Assessed impact extent of sediment flushings on fishes in 2009 and 2010 with the application of the SEV model.

3.2 Assessment and verification with data of laboratory experiments of impact of sediment on fishes

By putting the data from the experiments that showed the impact of different sediment concentrations on fishes (see Figure 2) into SEV model, the researcher got a SEV ranging from 5.9 to 8.5 (see Figure 5). This meant that no fishes would die in such case. However, plenty of fishes died under such high sediment concentrations in the experiments. It was evidently enough to prove that the SEV model tends to underestimate the acute impact of high sediment concentration on carps in a short time. Crosa et al. (2010) had also discovered that the estimated value was relatively low when applying SEV model to assess the impact of sediment flushing of an Alps Reservoir.

A possible cause of the above phenomenon is that data samples for fitting the model (Formula [2]). Checking the database of the SEV model for adult freshwater nonsalmonids (Newcombe and Jensen, 1996), the data for carp (common) were 25000mg/l (exposure concentration) and 336h (exposure duration). Therefore, this makes the model more suitable for assessing the impact of low sediment concentration on fishes in a long term. This may be the reason why the SEV model tends to underestimate acute carp mortality rates in a short duration (< 12h). It can see from the estimated result shown in Figure 3, in terms of sediment concentration and exposure duration (independent variables), fishes are more prone to die when exposing to low sediment concentration for a long term than exposing to high sediment concentration. This means that the relatively long exposure duration is more sensitive than sediment concentration in the SEV model to kill the fish.

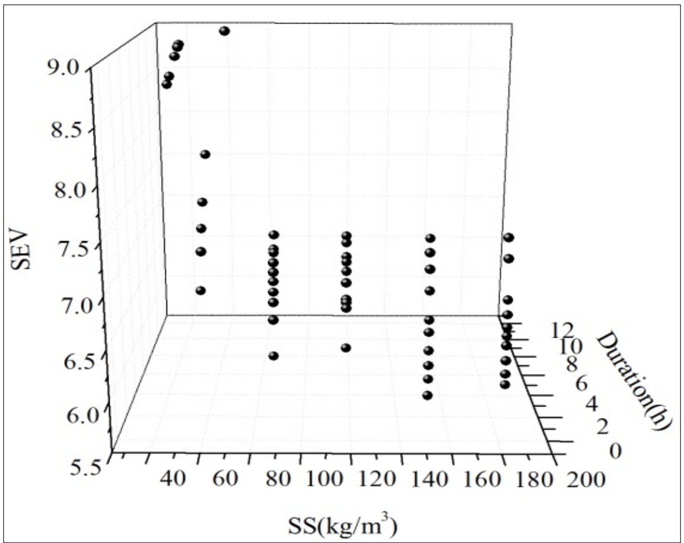


Figure 5. Assessed impact extent of different sediment concentrations on fishes in laboratory experiments by applying the SEV model

3.3 Revised model for assessment of the impact of suspended sediment on carps in the Yellow River

To improve the fitting parameters of SEV model and make it more suitable for assessing the acute impact of high sediment concentration on cyprinid fish, we included sediment concentration, exposure duration and mortality rate to refit the SEV model. So, we put forward the modified Formula [3]. The fitting result is well related since the multiple correlation coefficient for regression was 0.77, and it passed F-test and t-test (P value is far lower than the significance level 0.05).

$$SEV = -29.3818 + 1.6303\, ln(ED) + 3.6217\, ln(SS) \qquad [3]$$

The SEV values (results of Modified SEV model as shown in Figure 6) had been calculated by the use of modified Formula [3]. They are compared with the SEV values (results of SEV model as shown in Figure 6) calculated by the use of original Formula [2], and the data from observation data through the experiments. The comparison shows that the SEV calculated by modified Formula [3] is closer to the data collected from actual observation. The revised model of Formula [3] is more suitable for assessing the impact of high sediment concentration on cyprinid fish in the Yellow River. The parameters (1.6303 and 3.6217) in the revised model are higher than parameters (0.7126 and 0.2829) in the original model. This implies that the revised model could increase the under estimated fish mortality rate under acute lethal impacts of high suspended sediments. This revised model still needs further verification with data of suspended sediment on cyprinid fishes. As data from field surveys and experiments accumulates, the model should be improved in the future.

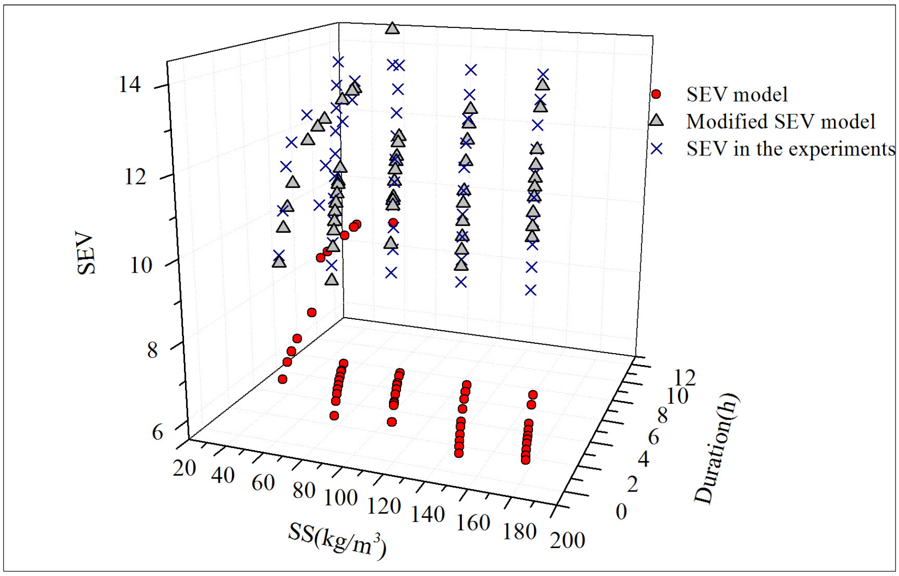


Figure 6. Comparison of assessed impacts of sediment concentration by applying SEV model and revised SEV model.

4 CONCLUSIONS

The impact of sediment flushings of Xiaolangdi Reservoir on downstream fishes in the Yellow River in 2009 and 2010 were assessed using the suspended sediment concentration-exposure duration model ("SEV model" for short) proposed by Newcombe and Jensen (1996), based on data from field investigation. The assessed results showed that the sediment flushing in 2009 would not cause the death of fishes, but the sediment flushing in 2010 would result in lethal effects. This reflects the different impact extents of sediment flushings in 2009 and 2010 on fishes. The assessment and estimation results were further verified with experimental data.

Based on the data from laboratory experiments concerning the impact of different sediment concentrations on carps, SEV model was applied and verified in the assessment of impact of sediment on carps. It turns out that the assessed values are evidently lower than the observed mortality rates of fishes from the experiments. The model tends to underestimate the acute impact of high sediment concentration (especially over 25kg/m^3) on fishes.

The SEV model had been refit by using the experimental data. A revised model suitable for assessing the impact of high sediment concentration (in Yellow River) on typical fish species had been proposed. The assessed SEV values of the revised model were closer to the observed values than that of the original model.

The achievement of the research may further the understanding of quantitative principles of the stress effect of sediment-laden water on fishes, and provide scientific basis for river sediment management and eco-friendly reservoir sediment flushing operation.

ACKNOWLEDGEMENTS

This study is supported by National Natural Science Foundation of China (Grant No. 50879092) and Key Laboratory of Watershed Sciences and Health of Zhejiang Province (No. KFKT2016005). The authors thank Professor Sun Dongpo from the North China University of Water Resources and Electric Power, Mr. Li Xiangyang from the Yellow River Conservancy Commission, and residents from Huayuankou Community for their help.

REFERENCES

Baoligao, B. & Sumi T. (2008). Study on the Impact of Reservoir Sediment Flushing on Downstream Fishes. *Journal of Tianjin University* (in Chinese), 41(9), 56-60.

Baoligao, B, Xu, F, Chen, X, Wang, X. & Chen, W. (2016). Acute Impacts of Reservoir Sediment Flushing on Fishes in the Yellow River. *Journal of Hydro-Environment Research*, 13, 26-35.

Bilotta, G.S., Burnside, N.G., Cheek, L., Dunbar, M., Grove, M.K., Harrison, C., Joyce, C., Peacock, C. & Davy-Bowker, J. (2012). Developing Environment-Specific Water Quality Guidelines for Suspended Particulate Matter. *Water. Res.,* 46(7), 2324-2332.

Bilotta, G.S. & Brazier, R.E. (2008). Understanding the Influence of Suspended Solids on Water Quality and Aquatic Biota. *Water. Res.,* 42(12), 2849-2861.

Crosa, G., Castelli, E., Gentili, G. & Espa, P. (2010). Effects of Suspended Sediment from Reservoir Flushing on Fish and Macroinvertebrates in an Alpine Stream. *Aquat. Sci.,* 72(1), 85-95.

Meyer, J., Sutherland, A., Barnes, K., Walters, D. & Freeman, B. (1999). A Scientific Basis for Erosion and Sedimentation Standards in the Blue Ridge Physiographic Province, *Proceedings of the 1999 Georgia Water Resources Conference*, University of Georgia, 321-324.

Newcombe, C.P. & Macdonald, D.D. (1991). Effects of Suspended Sediments on Aquatic Ecosystems. *North. Am. J. Fish. Manage.,* 11(1), 72-82.

Newcombe, C.P. & Jensen, J.O. (1996). Channel Suspended Sediment and Fisheries: A Synthesis for Quantitative Assessment of Risk and Impact. *North. Am. J. Fish. Manage.,* 16(4), 693-727.

Rowe, D.K., Hicks, M., Smith, J.P. & Williams, E. (2009). Lethal Concentrations of Suspended Solids for Common Native Fish Species that are Rare in New Zealand Rivers with High Suspended Solids Loads. *New Zealand J. Mar. Freshwater Res*., 43(5),1029-1038.

Schneider, J., Badura, H., Knoblauch, H., Frei, R. & Eberstaller, J. (2006). Flushing of the Run-Of River Plant Bodendorf in Styrria/Austria in Respect of Technical and Ecological Impacts, In *The 7th International Conference on Hydroscience and Engineering* (ICHE-2006), Philadelphia, USA, 10-13.

Staub, E. (2000). Effects of Sediment Flushing on Fish and Invertebrates in Swiss Alpine Rivers. *International Workshop and Symposium on Reservoir Sediment Management*, Toyama City, Japan, 185-193.

Sun, L, Baoligao, B., Niu, C. & Li, C. (2012). Acute Stress Caused by Sand Discharging on Yellow River Carp (Cyprinus carpio) in Xiaolangdi Reservoir. *Acta Ecologica Sinica* (in Chinese), 32(7), 2204-2211.

Swinkels, L.H., Van de Ven, M.W.P.M., Stassen, M.J.M., Van der Velde, G., Lenders, H.J.R. & Smolders, A.J.P. (2012). Suspended Sediment Causes Annual Acute Fish Mortality in the Pilcomayo River (Bolivia). *Hydrol. Process*., 28(1), 8-15.