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River management for hydraulic harmony between flood control and environmental considerations

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ABSTRACT: The author first considers flood flows, which are external forces having shaped the river channel, and the river channel itself, which is the passage of those flood flows, then considers the relationship between the two from a hydraulic perspective, stating that channel properties and floodwater storage by the channel are important indices for comprehensively considering flood control and the river environment. Next, citing data from observations of actual river flooding, the author presents the manner and dynamic behavior of a flood flow as it moves downstream, and discuss the channel properties and the manner of floodwater storage in the channel that serve as criteria for assessment of flood control and environmental considerations. The author further shows that the hydraulic phenomena of flood flows as established through experimentation and observation can be predicted by numerical methods. Lastly, the author defines the issues that must be resolved to implement the proposals herein.

1 INTRODUCTION

A crucial issue in river management is how systematically to achieve an environment appropriate for the river under management. Myriad approaches to river environments have been debated, and such debates have led to a general consensus that flood control, water resources utilization, and environmental factors should be considered comprehensively in river planning, rather than considering the river environment separately. However, since the concept of river environment bears various meaning to various people, comprehensive river plan is not a simple task, and so the current stage is one in which various ideas should be presented and examined.

The objective of this paper is to propose, from a hydraulic perspective, a basic approach for comprehensively considering flood control and environmental factors in rivers. A hydraulic perspective is but one perspective; flood control and environments should also be considered from environmental, ecological, and other perspectives. Nonetheless, this paper views the essence of a river as the transport of floodwaters by means of the river channel and therefore considers, from the hydraulic perspective of dealing with flood flows, how to achieve harmony between flood control and the river environment.

2 REVISION OF THE RIVER LAW AND CLOSE-TO-NATURE RIVER MANAGEMENT

The 1997 revision of the River Law of Japan clearly defines not only flood control and water resources utilization but also improvement and conservation of fluvial environments as the objectives of river management. For river improvement, the revision also mandates management from a comprehensive perspective.

Previously, the approach taken in river management in general was to increase the channel's discharge capacity so as to move floodwaters downstream and into the ocean as quickly as possible. However, with adoption of the maintenance and conservation of fluvial environments as purpose, of the River Law, river improvement advanced to a up-graded level, and today, the river improvement projects must be carried out under plans formulated for the appropriate harmonization of the aforesaid three objectives. In short, river management must not only strive to strengthen a river's flood control and water utilization functions, but also to maintain an environment capable of supporting the habitation and growth of diversified forms of wildlife.

But just what type of river environment is envisioned as ideal? In the decade before revision of the

River Law, close-to-nature river management intended to improve riverine environments was the mainstream of river improvement work, and various new techniques were developed and implemented. Through close-to-nature river management, many rivers that had lost their original functions because of the overemphasis on flood control in previous river management are today regaining the natural qualities befitting a river. In this respect, close-to-nature river management can be considered an effective methodology and technical approach for improving riverine environments.

Nonetheless, it cannot be denied that the current focus in river improvement on both flood control and the environment – including today's close-to-nature river management – primarily concerns local modification, rather than considering the entire river or the channel's upstream and downstream expanses. In this respect, even close-to-nature river management, although promoting environmental improvement, is a far cry from comprehensive river management.

The foremost goal of river planning should be to consider flood control, water resources utility, and the environment comprehensively, from a long-term perspective, and in the context of the entire river basin, i.e., to consider the harmonization of flood control and the environment on a large temporal-spatial scale. Some problems may involve a range of temporal-spatial scales. Close-to-nature river management often focuses on solving current environmental problems on a local level.

3 CRITERIA FOR RIVER MANAGEMENT FOR HYDRAULIC HARMONY BETWEEN FLOOD CONTROL AND ENVIRONMENTAL CONSIDERATIONS

In contrast to assessments of river environments, flood control planning has traditionally looked at the entire river basin from a long-term perspective. Full-fledged investigations of riverine environments being a relatively recent development, no framework exists for considering river environments on a temporal-spatial scale, and plans are often an extension of conventional thinking. For instance, today's close-to-nature river management considers riverine environments on a smaller temporal-spatial scale than is the case in flood control. Thus, current river management cannot be considered to have achieved harmony between flood control and the environment.

To achieve comprehensive river management that does achieve harmony between flood control and environmental considerations, it is necessary to clarify what type of river is desirable in those terms. From a flood control perspective, what is desirable is a channel that is safe with regard to flood flows, i.e., a river in which safety is assured by the substantial effect of human work. In contrast, an environmentally desirable river is one with a high degree of naturalness, including the restoration of degraded environmental elements. Ideally, an environmentally desirable river is one in which the natural forces acting on the channel are not controlled and in which human work has had no impact. However, this sort of environmentally ideal river environment is not practical because of the extensive human activity that occurs along rivers. Here, given the fact that it is flood flows, acting as external forces, that create a river channel, the characteristics of flood flows and of the channel that transports those flood flows should be seen as the basis for considering what the desirable river environment is. Furthermore, the hydraulically determined relationship between flood flows and channel properties can be used not only as the indices for a desirable riverine environment, but also for a river that is desirable with respect to flood control.

To correlate flood flows and channel properties and arrive at common indices for desirability in terms of flood control and river environments, it is necessary to consider the behavior of floodwater traveling down a river channel. The manner in which floodwater flows down a channel is particular to that channel: various types of flooding can occur in a channel depending on the type and distribution of rainfall in the river basin. Not only is floodwater affected by such channel properties as planform, profile, and cross-sectional form, but flood waveforms also deform at various points along the river. The former is responsible for the unsteadiness of flood flows; the latter indicates the irregularity of river course sections – in particular, there are the effects of meandering shapes in main channels, resistance variation due to vegetation on the flood channel, and changes in downstream boundary conditions. The flood flow is subject to these effects as it moves downstream. As it does, some of the flood discharge is retained in the channel. Therefore, the flood wave-form differs, and an incremental decrease occurs in peak discharge at points farther and farther downstream. This incremental decrease in peak discharge and the variation in flood waveform are unique and important properties of flood flows traveling down a river channel.

The objective of the flood plan control for a river is to assure safety by moving floodwater through the channel quickly by using flood control dams and other river structures to regulate the flood discharge. Consequently, channel planforms have been made linear to give priority to maintaining the channel's cross-sectional shape. To assure passage of the flood flow at design discharge, design high-water level (i.e., longitudinal distribution of peak water level relative to embankment height) has been used as a criterion in river improvement.

Furthermore, as stated in the revised River Law, important issues are how to distribute the basic flood discharge between the channel and the flood control dam, how to construct the channel to achieve the desired discharge distribution, and how to define the roles of channels and dams in the overall river basin. To address these issues it is first necessary to understand the behavior of flood flows in channels and dams. Because channels are formed by flood flows, considering how to distribute flood flow discharge between channels and dams also entails considering the overall riverine environment. Consequently, flood control plan must be drafted from the perspective of improving the riverine environment, and two issues must be addressed in this regard.

The first issue concerns the channel discharge and water level that result from the flood discharge distributed to dams and the channel. To regulate flood discharge, flood control plans employ dams, which (although most effective downstream) lower water levels throughout the river. Thus, flood plans view the channel itself as a means by which floodwaters retained by the dams are moved downstream. In actuality, however, the effectiveness of a dam decreases with distance downstream from the dam, i.e., the dam-induced reduction in water level is less at points farther downstream. The channel, on the other hand, has the capability of reducing discharge by means of flood storage. It is therefore realistic to view discharge and water level regulation by means of a dam as being effective only within a certain distance downstream, beyond which it is appropriate to make efficient use of the floodwater storage function of the channel itself to reduce water level. In other words, a channel's storage effectiveness is analogous to a series of small dams in the channel. Thus, river planning in which flood levels are regulated by effectively using the channel's floodwater storage function, thereby defining the roles of dams and channels more organically, is an approach to flood control that is appropriate for an age of environmental consciousness.

The second issue in flood control plans drafted from the perspective of improving the riverine environment is closely related to the first: Given that flood flows are what have formed a river's present channel and created its very environment, the essential question when considering riverine environments is how to assess and preserve the channel's natural storage and discharge attenuating capabilities. Preserving the channel's storage capabilities allows latitude in the use of flood control dams, thereby permitting the interrelationship among flood flows, channels, and dams to be redefined from the perspective of the entire river. This, in turn, makes possible a new approach to flood control and environmental considerations.

4 THE FRAMEWORK FOR DETAILED INVESTIGATIONS

In conventional flood control plans (with the exception of plans for dams, retarding basins, confluence points, and river mouths), the longitudinal distribution of design flood water levels is determined by non-uniform flow calculations. In such calculations, however, because flood discharge is determined by steady-flow calculations using given peak discharges at reference points, it is difficult to determine accurately the basic hydraulic behavior of flood flows, e.g., the reduction in discharge due to the channel's storage of a flood flow whose discharge and water level change temporally. Storage in an actual channel is such that the flood water level rises during the rising-water phase and falls in the receding-water phase. In this respect, a flood flow determined with non-uniform flow calculations differs from actual flood flows. Plans account for actual flood water levels by adjusting the value of the roughness coefficient so that calculated flood water levels match actual trace water levels. However, because of the lack of trace water levels corresponding to design flood discharge, non-uniform flow calculations cannot indicate how much volume of floodwater is retained at any given section in the channel. Furthermore, because the amount of storage differs depending on the flood discharge scale, determining the peak water level distribution would also entail a different roughness coefficient for each flood. This is the main reason that roughness coefficients vary for each flood. This poses no problem when calculating actual peak flood water level, but the discharge value will differ by the amount of storage volume. In other words, the calculations fail to account for the highly important river function of reducing discharge by retaining floodwater in the channel, i.e., that floodwater is retained by the channel in the rising-water phase and that during the receding phase, the channel releases the previously retained quantities of water as the floodwaters travel down the channel. Consequently, the results of non-uniform flow calculations do not always accurately represent actual floodwater transport. In actuality, the floodwaters' discharge and manner of flowing determine channel properties, which in turn determine how the floodwaters flow, and this interrelationship should be considered an important basic determinant of riverine environments.

In river improvement plans, fully utilizing and technically assessing the natural flood control, water use, and environmental functions of a river will culminate in the overall desirable form for the river. As for a river's flood control and environmental functions, the author has already stated that flood flow and channel properties should be used as criteria in such assessment. A channel's floodwater storage functions, environmental functions, and ecological functions can be enhanced through such steps as creating highly variegated planforms, cross-sectional forms, and profiles. This, in turn, requires understanding the relationship between floodwaters and channels as close to reality as possible and introducing it in actual plans. What is needed at present is to perform hydraulic model experiments and field observations of floods to correctly identify the important criteria for assessing the mechanism and quantities of floodwater storage in actual channels, and to work on collecting and interpreting elucidative data. Also required is to determine how much can be learned through analysis based on two-dimensional unsteady flow calculations using such basic data. The preceding proposals can be considered in light of the results of large-scale model experiments and large-scale field observations of flood flows.

5 ASSESSMENT OF CHANNEL STORAGE OF FLOODWATER AND PEAK DISCHARGE ATTENUATION – OBSERVATION PLANS, ITEMS, AND PREPAREDNESS WITH CLEAR OBJECTIVES

This section first discusses a flood flow observation plan and framework for assessing the storage of flood flows by actual rivers and the resultant attenuation in peak flood discharge. Next, basic data needed to ascertain flood flow conditions – particularly storage – in actual rivers having various channel properties are identified from the observations of actual river flooding. Finally, the author considers, in this context, the significance of new channel designs that strive for balance between flood control and environmental considerations as discussed in the preceding sections.

The author (Fukuoka 2000) and others (Watanabe & Fukuoka 2001) have performed a series of experiments in which flood flows of different hydrographs were released into large compound meandering channels to clarify the manner in which floodwaters flow down channels with a complex planform and the mechanism of floodwater storage and peak discharge attenuation. Using the results obtained, the degree to which a channel's planform, cross-sectional shape, and roughness resulting from flood channel vegetation clusters affect floodwater storage and peak discharge was estimated, and the inadequacy of conventional flood control plans based on non-uniform flow calculations was shown.

Furthermore, Watanabe, Fukuoka, and Mutasingwa (2002), attempting to explain storage and discharge attenuation numerically, analyzed the results of these large-scale compound meandering channel experiments and the results of observations of flooding in Maruyama River, whose planform and cross-sectional shape are shown in Figures 1 and 2, demonstrating that the results of the aforementioned large-scale meandering watercourse experimentation agree with flood-related hydraulic phenomena in an actual river. These calculations employed an unsteady two-dimensional shallow water flow equations described with a general curvilinear coordinate system. This numerical flood model was shown to appropriately describe peak discharge attenuation and temporal-spatial changes in observed longitudinal water surface profile and hydrograph in the unsteady Maruyama River (Figures 3 and 4). Figure 5 shows a time change of storage volume rate between Sections A and C in the Maruyama River. Thus it became possible to use the unsteady two-dimensional numerical analysis of flood flows to assess flood hydrographs and flood flow deformation in actual rivers, particularly flood flow storage and attenuation in peak discharge in the channel.

Researches conducted by the author and others have shown that floodwater storage in the channel is large in types of sections such as the following: (1) sections with a compound cross-sectional shape and an extensively meandering main channel; (2) sections in which

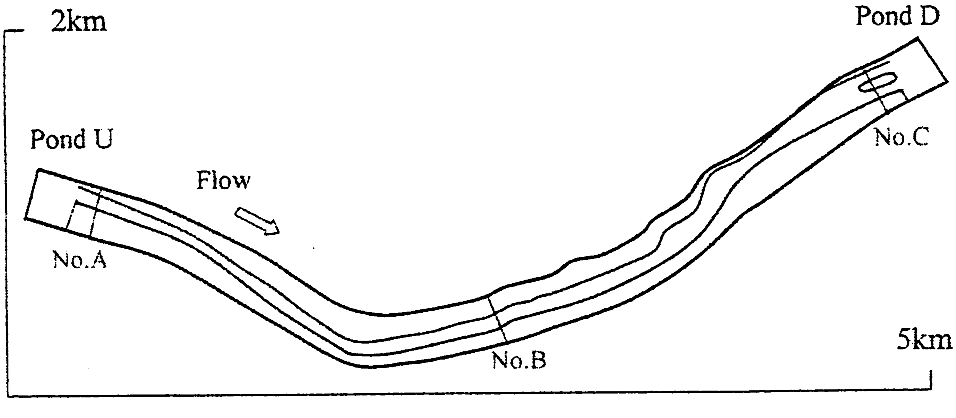

Figure 1. Plan shape of the Maruyama River (calculated area).

the channel planform exhibits irregular longitudinal variation; (3) sections with extensive roughness in the floodchannel, particularly sections with dense vegetation in the floodchannel and along the main channel; (4) sections (i.e., a river mouth or confluence of two rivers) where water level changes at the points defining the flow's boundary conditions have effects upstream; and (5) sections upstream from locations where river structures are across a river.

In Japan, a concerted effort is being made to observe flooding in the above-mentioned five types of channel sections and generate data to use in river planning that reflects the relationship between channel properties and floodwater storage, thereby achieving river management that balances flood control and environmental considerations. The section below discusses the planning and framework for flood observation carried out thus far in actual rivers, as well as some of the results achieved.

With the aforementioned objective, the "Food Flow Nonlinear Properties Research Team" was formed to create a suitable observation plan and observation framework, laying the foundation for actual flood flow observation. The research team was headed by the author (Professor Shoji Fukuoka, Hiroshima University) and comprised of representatives of the River Planning Section of the Ministry of Construction's Kanto Regional Construction Bureau (now the Kanto Regional Improvement Bureau of the Ministry of Land, Infrastructure, and Transport) – the rivers' administrator – and engineers of the construction offices responsible for administrating the seven rivers chosen for observation. Presented here are the results of observation of the Edo River, the upper reaches of the Tone River, and the middle reaches of the Ara River.

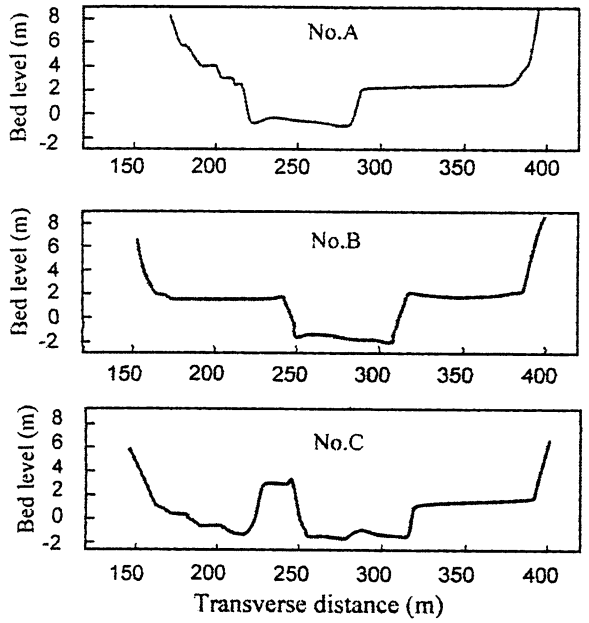

Figure 2. Cross-sectional shape of Section A–C at the Maruyama River.

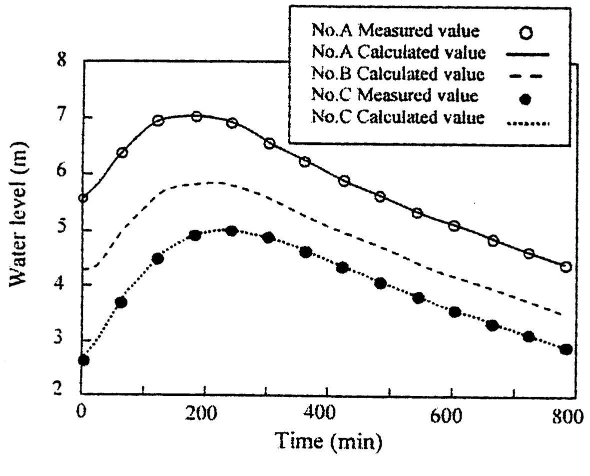

Figure 3. Water level hydrograph at the Maruyama River.

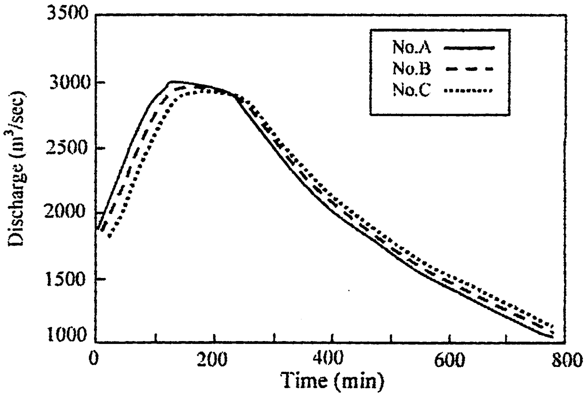

Figure 4. Discharge hydrograph at the Maruyama River (Calculated value).

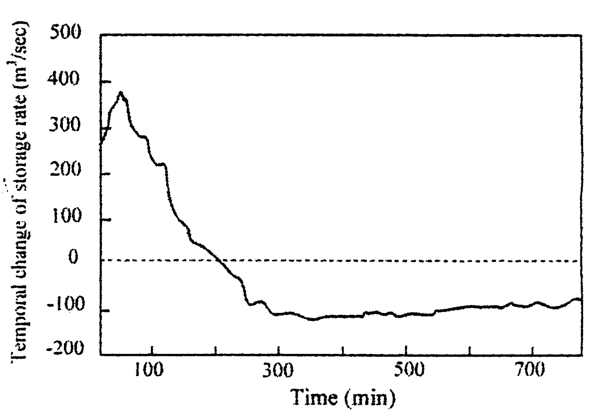

Figure 5. Temporal change of storage volume rate between Section A–C in the Maruyama River.

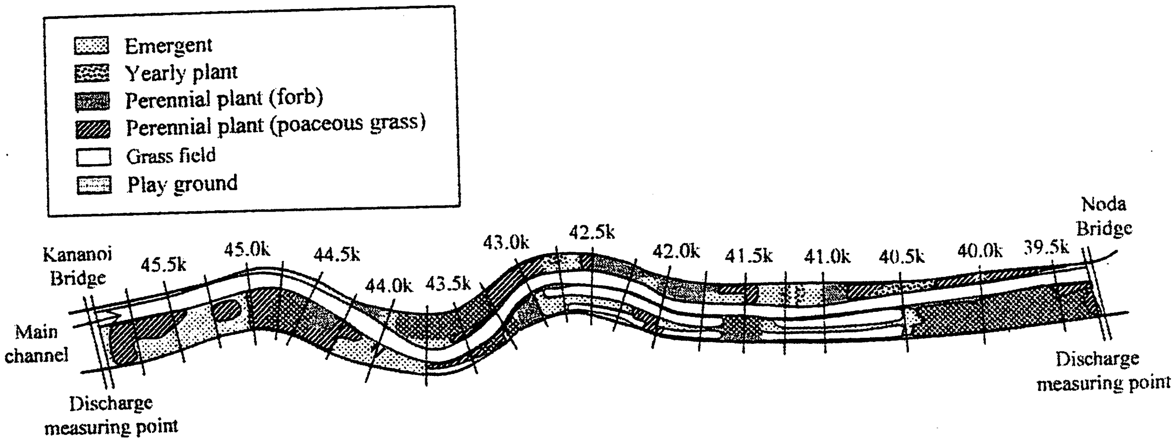

Figure 6. Plan shape and vegetation distribution at the Edo River (35.9–45.8 km).

5.1 *Observations of flooding in the Edo River (a tributary of the Tone River) and assessment of channel storage of floodwaters*

The Edo River, which has a drainage basin surface area of 158 km^2, flows through Tokyo after branching off from the Tone River (which has a drainage basin surface area of 16,840 km^2, Japan's largest) at a point 122 km from the river mouth. Geographic conditions surrounding the Edo River's call for an especially high level of safety with regards to flood control. Flooding caused by Typhoon 15 in September 2001 was observed in a 7-km section between 39 km and 46 km from the river mouth.

Figure 6 shows the channel ground cover in the observed section, along with the embankment alignment and main channel alignment. In this section, the floodchannel is wide, the main channel meanders considerably, and tall, dense vegetation grows on the inner bank side of the floodchannel in the channel curve, assuring a considerable floodwater storage capacity. Discharge observation was conducted by means of floats released once each hour at the upstream and downstream ends of the section. Observation was conducted every hour during the rising water phase and every 2 hours in the receding water phase from 11:00 p.m. on the 10th to 12:00 midnight on the 14th at the Kanenoi Observation Station (the upstream end of the observation section, i.e., the 46 km point) and from 12:00 midnight on the 11th to 4:00 p.m. on the 14th at the Noda Observation Station (the downstream end of the observation section, i.e., the 39 km point). Water level was observed (as with discharge observation) every hour in the rising water phase and every 2 hours in the receding water phase at 23 points along the left and right banks (see Figure 6). The results of discharge and water level observation are shown in Figures 7 and 8, respectively. Using continuity conditions, storage (S) in this 7-km section can be determined from floodwater inflow and outflow quantities (Q_{in}, Q_{out}) as given by the results of hydrograph observation. Storage (S) as calculated with the following equation is shown in Figure 8.

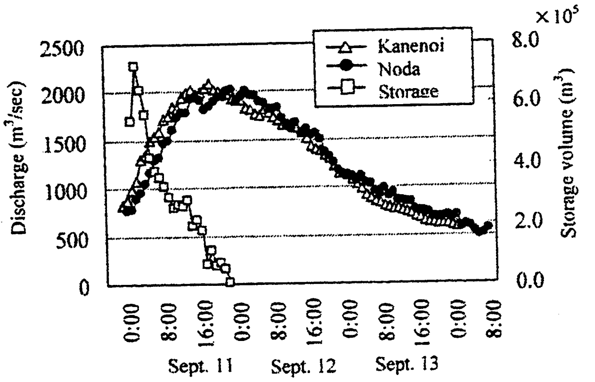

Figure 7. Discharge hydrograph and storage volume at the Edo River (Typhoon 15th 2001).

$$Q_{in} - Q_{out} = dS/dt \tag{1}$$

These results are compared with the results of two-dimensional shallow water flow analysis.

5.2 *Flood observation near the confluence of the Tone and Watarase Rivers*

Near its 132 km point, the Tone River meets a tributary, the Watarase River. The portion of the Tone River drainage basin up to the Kurihashi Observation Point (situated at the confluence point) is 8,588 km^2, whereas the drainage basin of the entire Watarase River is 2,621 km^2. The vicinity of this confluence point sees a wide variety of flooding owing to rainfall conditions throughout the basin, the typhoons that pass through, and weather fronts. Since the high water level is kept at the confluence point for a long period,

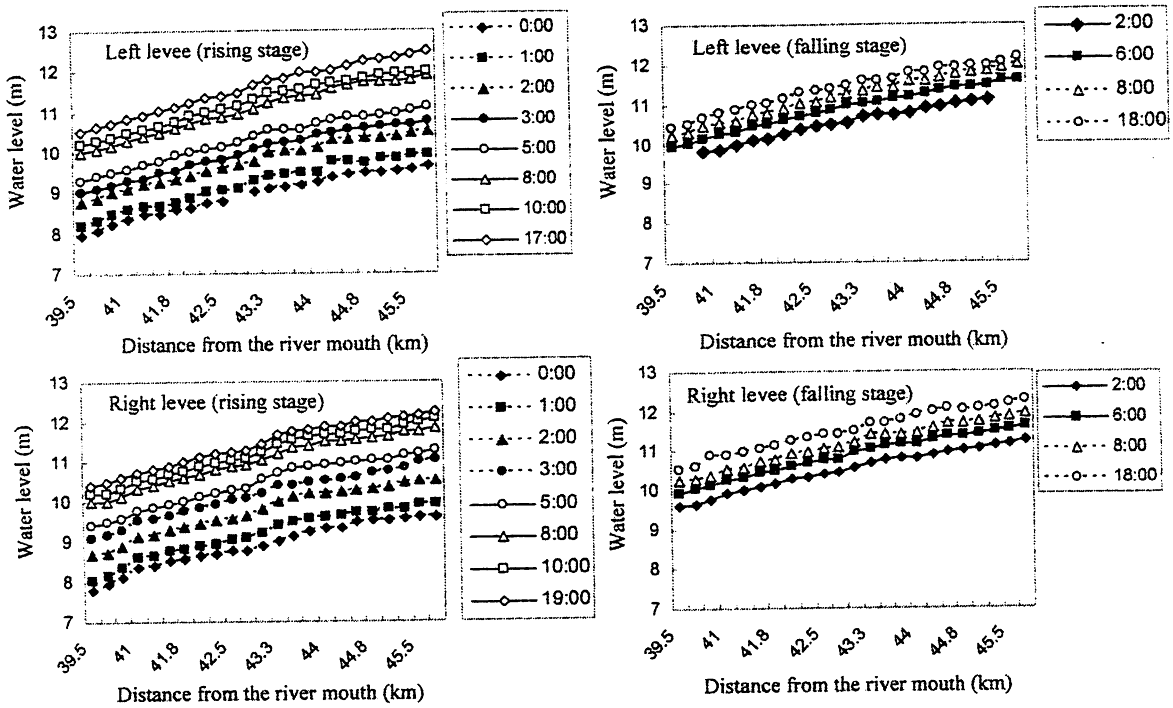

Figure 8. Temporal change of water surface profiles at the Edo River (Typhoon 15th, 2001).

a part of flood discharge of the Tone River flows back to the Watarase River and is stored within it.

Flood observation was carried out to determine channel storage of the two rivers near the confluence point and to derive a calculation method for the flood flows there, which flow in a complex manner.

The flood observed was one caused by Typhoon 15 in September 2001. Flow conditions at the confluence point are shown in Figure 9, and the locations of the flood observation stations are shown in Figure 10. Discharge was observed for the Tone River at the Kawamata, Sakitama Bridge, and Kurihashi Observation Stations and for the Watarase River at the Furukawa Observation Station. Observations were made every 2 hours in the rising water phase and every 3 hours in the receding water phase by means of floats. Normal water level observation was conducted in the Tone River with a total of 11 simple water level gauges positioned on the right bank at 1 km intervals between the 130.00 km and 138.5 km points; and in the Watarase River at a total of 5 points between the Koga Observation Station (the 3.5 km point) and the confluence point (the 0.0 km point).

As clearly shown in Figure 11 (the longitudinal distribution of water level between the 130.0 km and 138.5 km points of the Tone River), flood flows in this river are characterized by a sharp water surface slope in the rising water level phase and a gentler surface water slope in the falling water level phase. In contrast, the water level in the Watarase River, its tributary, rises with longitudinal water surface profile that is roughly flat (see Figure 12). This clearly shows a condition in which there is the reverse flow of discharge from the Tone into the Watarase River owing to the high water level at the confluence point. Then, as the water level at the confluence point begins to drop, the flow becomes a forward one, and water previously stored in the Watarase River is released. Because of problems with the accuracy of discharge during reverse flow (Q_{in} at the Koga Observation Point) as determined by

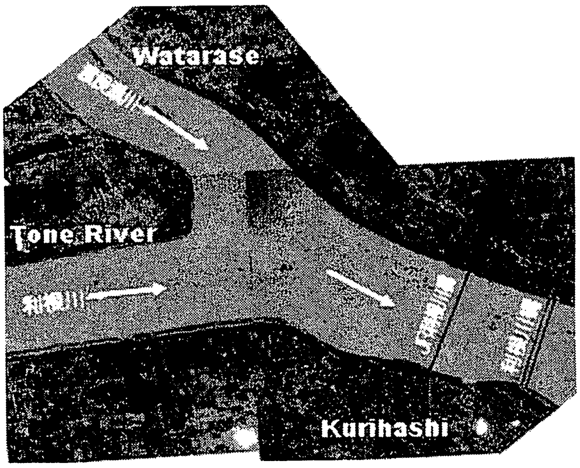

Figure 9. Flood Flow around confluence of theTone River and the Watarase River(Typhoon 15th, 2001).

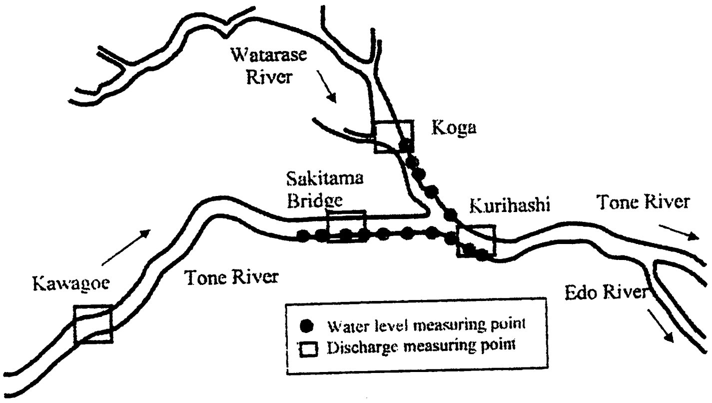

Figure 10. Observation plan of flood flow at the Tone River.

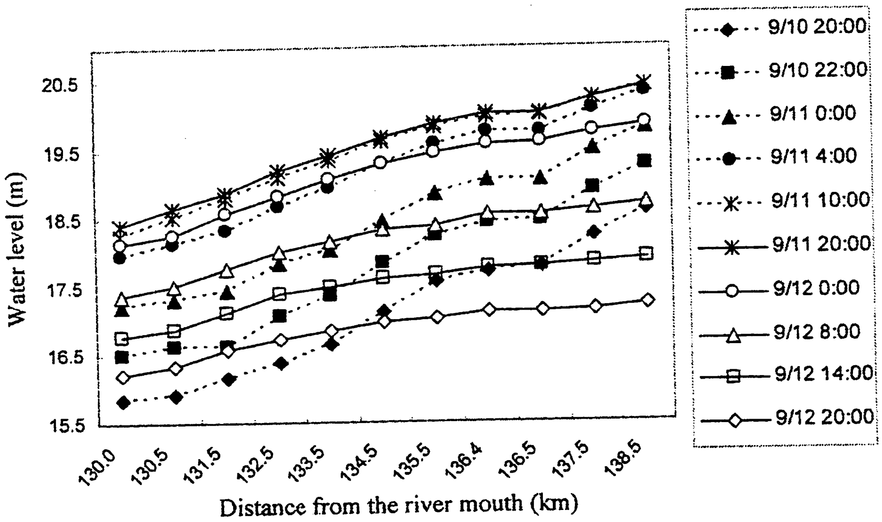

Figure 11. Temporal change of water surface profiles at the Tone River (Typhoon 15th, 2001).

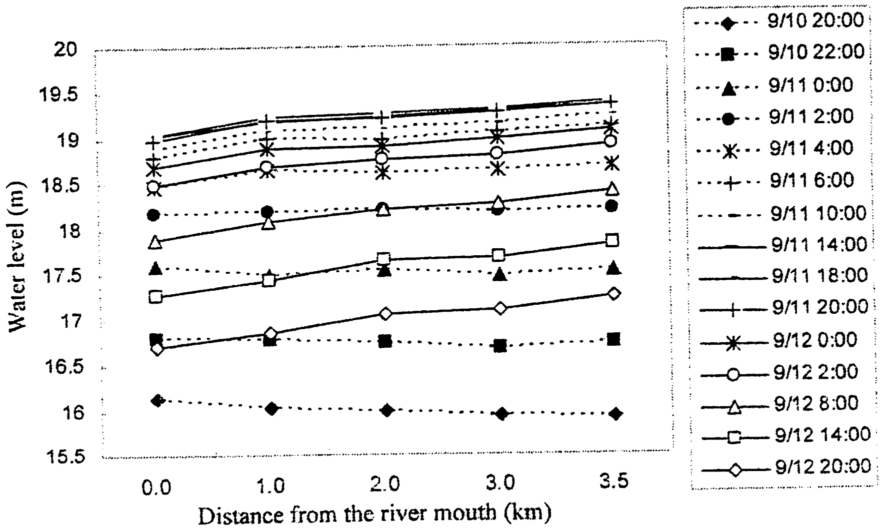

Figure 12. Temporal change of water surface profiles at the Watarase River (Typhoon 15th, 2001).

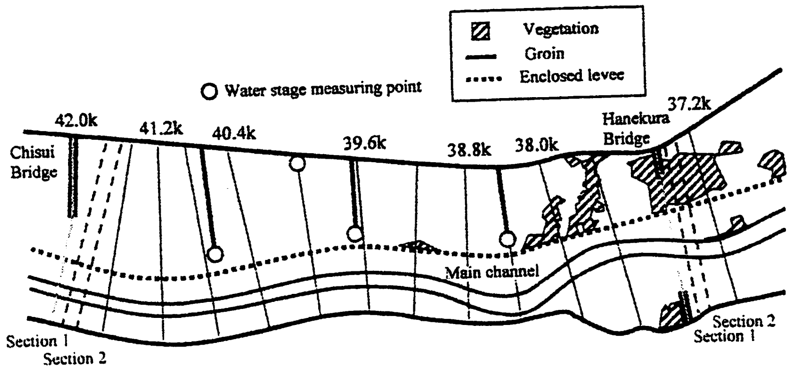

Figure 13. Observation plan of flood flow at the Ara River.

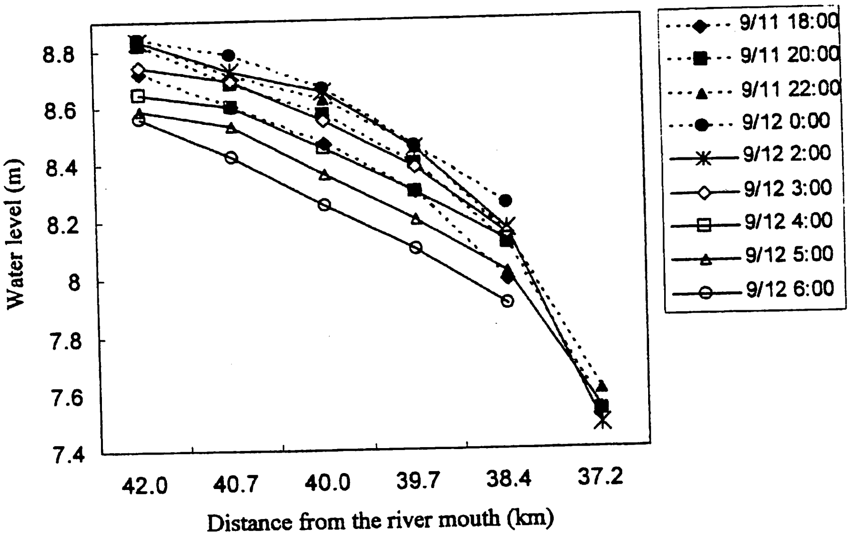

Figure 14. Temporal change of water surface profiles at the Ara River.

floats, it would not be appropriate to calculate storage with equation (1). Instead, storage is calculated with a continuity equation and equation of motion based on an unsteady two-dimensional shallow water flow analysis method developed by Watanabe and Fukuoka (2002).

5.3 *Analysis of the floodwater storage effect of a broad floodchannel and groins in the Ara River*

In the middle reaches of the Ara River, the broad floodchannel and groins built along the left and right banks suggests considerable flood storage and retarding water capacity. It was therefore decided to measure discharge in the section containing large floodchannel and the groins (i.e., from Chisui Bridge [37.2 km point] to Hanekura Bridge [42.0 km point]) to determine the groins' storage effect.

Figure 13 shows the river plan form, groin placement, and discharge and water level observation points in the Chisui Bridge-Hanekura Bridge section. The flood observed was caused by Typhoon 15 in September 2001. Discharge inflow (Q_{in}) was measured at Hanekura Bridge; outflow (Q_{out}), at Chisui Bridge. Figure 14 shows the longitudinal distribution of water level in the rising and receding water phases. Because depth was low – i.e., only a maximum of 1.0 m, the average floodchannel height – accuracy of the discharge as determined with floats was low, and so reliable storage quantity could not be determined from the flood observation data obtained.

5.4 *Observation results and discussions*

The preceding has shown that although the primary objective of flood flow observation was the same for all three rivers – namely, to estimate channel storage – each river required a different method of storage assessment because of differences in river properties and in the primary determinants of storage. Flood observation and two-dimensional shallow water flow analysis with the objectives described herein are indispensable to the assessment of channel storage in rivers of differing channel properties.

Flood flows, because they transport river sediment and change river topography, are inextricably linked to river ecosystems and sometimes even affect the very survival of plant and animal life there. Flood flows in turn are greatly affected by channel topography and undergo a process of storage and peak discharge attenuation as they flow through the channel. These flows result in scouring and in the resultant deposition and transport of sediment. Because flood flows and sediment transport have an impact on riverine environments, river development that balances flood control and environmental considerations ultimately require a way of thinking that encompasses sediment transport caused by flood flows. In addition, further cases must be examined and the results used to arrive at highly reliable river plans.

6 CONCLUSIONS AND REMAINING ISSUES

This paper has discussed an approach to river management that strives for hydraulic harmony between flood control and environmental considerations. The issues involving flood control and riverine environments are broad, encompassing not just hydraulics but also socioeconomics, engineering, ecology, and aesthetics. River development that achieves harmony between flood control and environmental considerations can also be discussed from such perspectives, and the author hopes for active debates and discussions on such matters.

Implementing the suggestions in this paper in actual river planning requires that numerous issues be resolved. The most important issue is how quantitatively to ascertain, assess, and incorporate into a plan the many determinants of a channel's floodwater storage capacity, such as flood hydrograph shape, channel plan form, cross-sectional shape, and boundary conditions. One effective method is to observe temporal changes in the discharge hydrograph and water surface profile of floodwaters in each section of the river, to use hydraulic data obtained for numerical analysis and to enhance the reliability of such numerical analysis. The storage capacity of each river section is calculated from flood hydrographs and various river data and compared with observed data to estimate the storage of the entire river reach. For a planning-scale river, overall storage volume can be determined similarly by examining hydrographs for floods of various scales to arrive at a highly reliable plan.

Planning that uses the river channel to retain a portion of the basic flood discharge is highly significant with regard to achieving harmony between flood control and environmental considerations in river management, for this approach would permit greater flexibility in the use of dams, increasing the possibility of improving the riverine environment. In this regard, another issue is to determine what size and waveform of the design flood hydrographs should be used in river planning.

The time is near for river management in which channel storage is incorporated into plans with the objective of improving riverine environments. When that happens, steps will be taken to increase channel storage, such as designing appropriate river plan forms, cross-sectional shapes, and meandering shapes for main channels, and appropriate placement of vegetation in the floodplain.

Currently, restoration of meanders, conservation of vegetation, and other steps are being taken in some rivers for environmental reasons. Such efforts will, as stated in this paper, lead to increases in channel storage and, ultimately, will overlap with flood control-related needs. At the same time, because increased storage volume translates into longer flood durations, river sections with considerable storage potential also require considerations to assure embankment safety.

The most important issue in achieving the goal stated in the title of this paper – hydraulic harmony between flood control and environmental considerations in river management – is the collection of precise flood data for a given river. Because of the time-consuming and labor-intensive nature of such work, it is important to create a framework for addressing this issue persistently over time.

REFERENCES

Fukuoka, S. 2000. Flow and topographic changes in compound meandering rivers: International Conference on Hydro-Science and Engineering, Keynote Lectures, (CD-ROM), 2000.

Watanabe, A. & Fukuoka, S. 2001. Hydraulic characteristics of unsteady flows in meandering compound channels: Vol. I, Proceedings of Theme D, XXIX IAHR Congress, 83–89.

Watanabe, A., Fukuoka, S. & Mutasingwa, A.G. 2002. Analysis on the flood flow storage in compound meandering channels by using unsteady two dimensional numerical model: River Flow 2002.