UNSTEADY QUASI-TWO-DIMENSIONAL FLOW ANALYSIS OF FLOOD FLOWS IN A RIVER WITH VEGETATION

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ABSTRACT

The behavior of a flood flow depends on the conditions of rainfall and the channel, and its properties are represented by hydraulic data observed during flooding, particularly temporal change in water surface profile. In river planning and management, it is particular important to quantitatively assess the propagation mechanisms of the water level and discharge of flood flows in the channel. This paper begins with an overview of computational research on flood flows up to the present and emphasizes the indispensability of including unsteadiness in proper river management. Next, the paper stresses the importance of expanding conventionally used quasi-two-dimensional analysis to unsteady quasi-two-dimensional analysis in which temporal change in water surface profile is the solution. Lastly, the paper compares the authors' unsteady quasi-two-dimensional flow analysis method with unsteady planar two-dimensional flow analysis for flooding in the Edo River, and concludes with an emphasis on the appropriateness and engineering significance of unsteady quasi-two-dimensional flow analysis.

Keywords: flood flow, temporal water surface profiles , flood propagation mechanism, unsteady quasi-2D flow analysis, compound channels, vegetation

1. INTRODUCTION

Modern river improvement in Japan has been based on data in flood-management plans, such as levee alignment and position and planned high water level. Large populations living near rivers, as well as extensive investments in social capital located near rivers, makes it difficult to further increase planned high water levels or change levee alignment. Consequently, river improvements are forced to assume no fundamental changes in planned water level or levee alignment.

At the same time, issues affecting discharge capacity and safety have resulted from recent channel changes, particularly bed lowering, conspicuous gut formation, and channel vegetation growth. In response, river improvements and vegetation management to increase discharge capacity are being considered. Vegetation in channels has caused particularly extensive rises in water level (due to increased channel storage) and changes in the flood waveform (i.e., delay in flood propagation)[1]. How a flood flow propagates is highly important in river management and maintenance, and assessing how channel changes affect flood water levels and propagation is an important issue.

2. DEVELOPMENT OF FLOOD FLOW THEORY

2.1 Theory Assuming Quasi-Steadiness in Flood Flows

Today, vast archives of flood data and advanced computational resources have made it possible to elucidate the hydraulic phenomena of floods to a considerable degree. Two widely used practical methods of flood analysis are one-dimensional and quasi-two-dimensional analysis, which focus on peak discharge and treat flood flows as steady flows[1]. In a large watershed, a flood flow often achieves a steady state at or near peak discharge, in which case steady-flow analysis would be appropriate for practical reasons. One-dimensional analysis is particularly effective for simple channels. Quasi-two-dimensional analysis, although technically a type of one-dimensional analysis, takes into account the arrangement of vegetation and lateral mixing due to cross-sectional variation and vegetation and so is effective for the analysis of flood flows in complex channels and channels with vegetation[2),3)]. In quasi-two-dimensional analysis, peak discharge is given, and the flow is solved by determining the roughness coefficient and boundary mixing coefficient so that calculated longitudinal peak water level distribution agrees with the trace of peak water level believed to have been reached at the peak of flooding.

Because of this, non-uniform flow analysis was abandoned as the primary technique for floods in favor of quasi-two-dimensional analysis capable of accounting for cross-sectional changes in complex channels and the presence of channel vegetation[4),5)]. However, it gradually became clear that even quasi-two-dimensional analysis was inadequate for some flood flow problems: Because it does not incorporate the unsteadiness of flood flows, conventional quasi-two-dimensional analysis cannot adequately explain longitudinal decreases in flood discharge and water level due to the storage phenomenon that is characteristic of flood flows. Consequently, differences in storage phenomena from flood to flood are compensated for with roughness and boundary mixing coefficients. As a result, even for a single channel, the values for these coefficients, which explain the trace of peak water level profile, would differ for each flood, presenting problems such as the difficulty of determining fixed values[1)].

2.2 Theory Considering Unsteadiness in Flood Flows

Although flood flows propagate slowly over time, flood phenomena in channels exhibit the important function of channel storage owing to interaction between the temporal changes in hydraulic quantities and spatial variation in channel properties that arise from a flood flow's unsteadiness. These hydraulic phenomenon cannot be explained with conventional steady-flow analysis. Recent changes in channel conditions due to vegetation growth and other factors have resulted in non-negligible storage-related transformations in flood flows[6)], necessitating that these hydraulic phenomena be incorporated into river management. However, unsteady one-dimensional analysis often fails to deliver the mathematical accuracy necessary to handle storage related to complex channels with intricate planforms, channel vegetation, and unsteadiness.

Then why did analysis skip directly to unsteady planar two-dimensional analysis, rather than first proceeding to unsteady quasi-two-dimensional analysis, which is an expansion of the quasi-two-dimensional analysis that was the mainstream technique for flood flow analysis? The interaction between flood flow unsteadiness and a channel's cross-section and profile plays an important role in storage. More specifically, storage cannot be calculated unless not only unsteadiness but also variation in channel shape are properly incorporated. This is why analysis evolved not to unsteady one-dimensional techniques but instead to unsteady planar two-dimensional techniques, which incorporates the temporal changes in water surface profile that correctly reflect river storage[6)]. Rate of storage is defined as the difference between the discharge that enters a river section from upstream and the discharge that exits that section, and is a phenomenon in which the water surface height of a flood flow increases and then decreases in a time-series manner. This is the essence of a flood flow and could never happen in a steady flow. This indicates that a flood flow cannot be appropriately analyzed unless temporal changes in water surface profile are sufficiently incorporated. The hydraulic phenomena that occur in a flood flow are immediately reflected in the water surface profile. The temporal changes in water surface profile that occur as a result of these phenomena are the essence of a flood flow, and it soon became clear that the ability to explain this was indispensable to the elucidation of flood phenomena. Water level of flood flows are observed with greater accuracy than discharge, velocity, and other hydraulic quantities: Temporal changes in water surface profile can be determined with a series of longitudinally deployed water gauges. Once temporal and spatial data on water level are collected, it becomes easy to incorporate temporal changes in water surface profile into unsteady-flow analysis.

The authors have used unsteady planar two-dimensional equations in which temporal change in observed water surface profile is the solution (assuming these observations to be correct) to calculate discharge hydrographs, storage hydrographs, velocity distribution, and other hydraulic quantities and, through comparison with observed data, have shown this technique to be valid[6),7)]. Because it explains temporal change in water level profile over a spatially large area, this technique yields the temporally spatially and optimum solution when the flood flow is viewed broadly longitudinally and laterally. This permitted the easy analysis of many flood-flow phenomena that are reflected in temporal change in water level profile—e.g., diverging flows[8)], confluence[9)], the relationship between channel changes and the flood-flow propagation mechanism[10)], inflow into retarding basins[11)], outflow discharge hydrographs for inundations caused by levee failure[12)], flood flow in the tidal reach with large tidal variation[13)], and bed evolution in flood period[14)]—and as a result the technique came to be used in river planning, design, and management.

Non-uniform flow analysis and quasi-two-dimensional analysis cannot incorporate the unsteadiness-related storage mechanism and so cannot sufficiently incorporate section variation properties. In addition, the error in observed discharge and flood trace water level used in the analysis is compensated for with the roughness and boundary-mixing coefficients. Consequently, these two coefficients differ for each flood, which impacts the method's reliability. In contrast, unsteady planar two-dimensional analysis incorporates the unsteadiness and section variation of flood flows and, by using water level instead of discharge as the boundary condition, and by using temporal changes in water surface profile instead of flood trace water level, enables highly accurate calculations free of physical ambiguity. In the case of channels with vegetation, this method employs a true roughness coefficient based on the channel's cross-sectional shape and profile and on friction with the channel's bed and which excludes the resistance of vegetation (which is assessed with a vegetation permeability coefficient) and so provides a solution that guarantees a constant roughness coefficient value for a given channel[15)].

The major reason that unsteady planar two-dimensional analysis can properly explain observed flood flows is that it incorporates the temporal changes in observed water surface profile. Although the unsteadiness of a flood flow is much smaller than that of ocean waves, it is still not possible to express the fundamental properties of flood flows without unsteadiness. In this sense, if conventional quasi-two-dimensional analysis were modified to incorporate unsteadiness and temporal changes in observed water surface profile, then the resultant unsteady-flow quasi-two-dimensional analysis should provide the similar accuracy to unsteady-flow planar two-dimensional analysis.

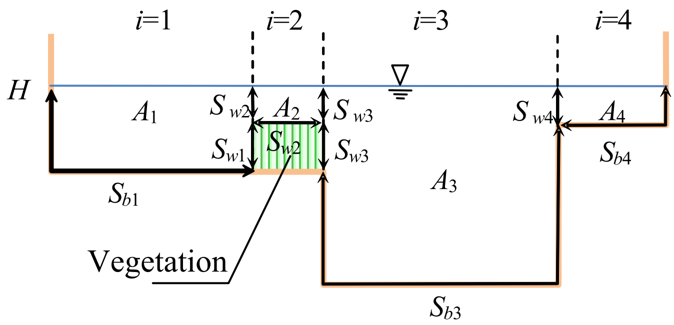


Fig.1 General cross-sectional from with vegetations and section division method of quasi-two dimensional analysis

3. UNSTEADY QUASI-TOW-DIMENSIONAL ANALYSIS OF FLOOD FLOWS IN COMPOUND MEANDERING CHANNELS WITH VEGETATION

The authors' technique was constructed by expanding conventional quasi-two-dimensional analysis[2),3)] into unsteady-flow analysis. Consequently, and cross-sectional forms shown in Figure 1 are the same as previously[2),3)]. The section-integrated continuity equation and equation of motion are shown as equations (1) and (2), respectively.

$$\frac{\partial A}{\partial t} + \frac{\partial VA}{\partial x} = 0 \tag{1}$$

$$\frac{\partial VA}{\partial t} + \frac{\partial \beta V^2 A}{\partial x} + gA\frac{\partial H}{\partial x} = -\int_{S_b} \frac{\tau_b}{\rho} dS - \int_{S_w} \frac{\tau}{\rho} dS \tag{2}$$

where V = section-averaged velocity, A = cross-sectional area, H = water level, ρ = water density, τ_b = bed shear stress, S_b = wetted perimeter where τ_b acts, τ = shear stress acting at the vegetation boundary, S_w = wetted perimeter where τ acts. Dividing the cross-sectional form as shown in Figure 1, the quantities in equations(1) and(2) can be calculated as follows.

$$A = \sum_i A_i,\ Q = VA = \sum_i u_i A_i,\ \beta V^2 A = \sum_i \beta_i u_i^2 A_i \tag{3}$$

$$\int_{S_b} \tau_b dS = \sum_i \tau_{bi} S_{bi}, \quad \int_{S_w} \tau dS = \sum_i \tau_i S_{wi} \tag{4}$$

where A_i = cross-sectional area at i, u_i = section-averaged velocity at i, b_i = work correction coefficient at i (in this paper, β_i= 1), τ_{bi} = bed shear stress at i, S_{bi} = wetted perimeter where τ_{bi} acts, τ_i = shear stress at the vegetation boundary at i, S_{wi} = wetted perimeter where τ_i acts. The equation of motion for each section is expressed with equation (5)[5),6)].

$$A_i I_e = \tau_{bi} S_{bi} + \tau_i S_{wi} - \left(\tau'_{i+1} S'_{wi+1} - \tau'_i S'_{wi}\right) \tag{5}$$

where τ_{bi} = downstream shear stress acting on ι-1 at the boundary between i and ι-1, S'_{wi} = wetted perimeter where τ_i acts, I_e = energy gradient. When the flow at each section is uniform, I_e will equal the water level gradient or the bed gradient. The authors, by introducing energy gradient I_e, made it possible to extend the quasi-two-dimensional method shown in equation (5) into the unsteady-flow technique represented by equations (1) and (2). Bed shear stress τ_{bi} is defined as shown below using Manning's roughness coefficient n_i, shear stress acting at the vegetation and inter-section boundaries τ_i, τ'_i and boundary mixing coefficient f [5),6)].

$$\tau_{bi} = \rho \frac{n_i^2 u_i |u_i|}{R_i^{1/3}}, \quad R_i = A_i / S_{bi} \tag{6}$$

$$\tau_i = \rho f u_i |u_i| \tag{7}$$

$$\tau'_i = \rho f \delta u_i |\delta u_i|, \quad \delta u_i = u_i - u_{i-1} \tag{8}$$

The flow of calculations is as follows. The resistance term on the right side of the equation of motion (2) is calculated with section velocity u_i, which is determined with equation (5). Through recursive calculation, the energy gradient I_e in equation (5) is calculated so that calculated discharge agrees with continuity equation (1). The calculation process is shown in Figure 2. As in previous research[2),3)] the cross-section is divided into flood channel, main channel, and vegetation area as shown in Figure 1. The inside of a vegetation cluster is treated as a dead-water zone, and its resistance is assessed with the shear stress τ that acts on the vegetation boundary. As with the authors' unsteady-flow two-dimensional analysis for flood flows[6)], the boundary conditions are defined as the temporal change in water level at the upstream and downstream ends, and roughness coefficient n_i and boundary mixing coefficient f are determined so as to minimize the difference between calculated and observed results for temporal change in water surface profile and the observed discharge hydrograph for the channel section in question.

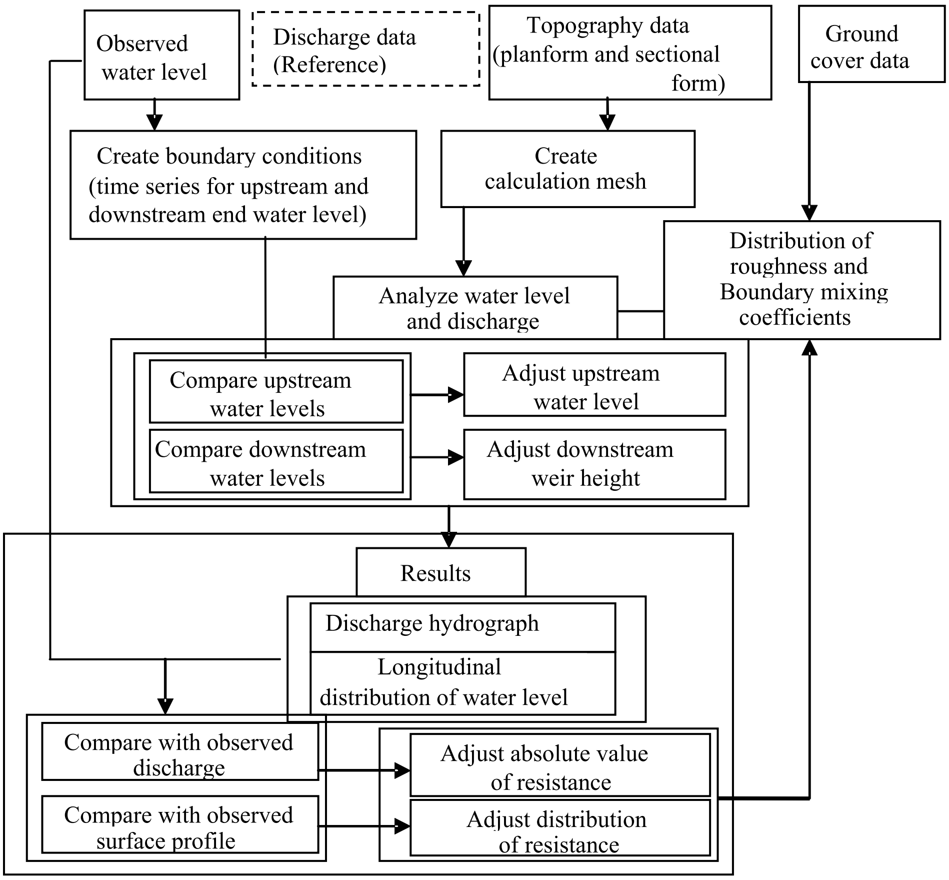


Fig 2 Flowchart of overall analysis

The water surface profile and the temporal changes therein contain all the information relating to the flood flow, including channel cross-sectional shape and vegetation resistance[7)].

Therefore, the authors' method, which seeks to re-create temporal change in observed water surface profile according to unsteady equations of motion that account for the channel's cross-sectional shape, vegetation, and other factors, is a practical method capable of appropriately assessing changes in the hydraulic quantities of flood flows.

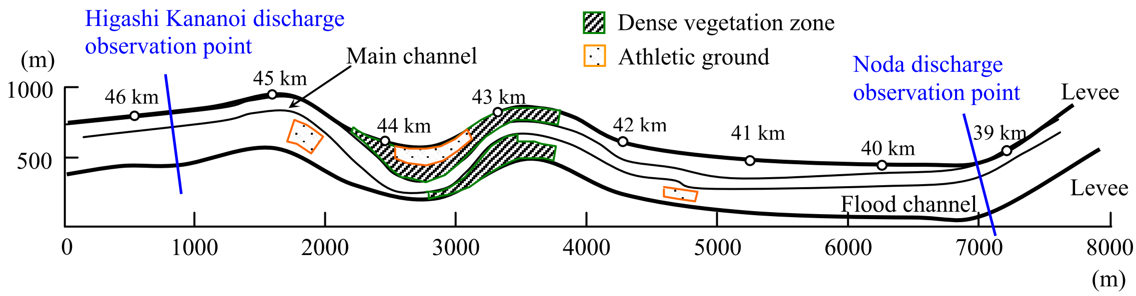


Fig.3 Planform of the Edo River section observed (46.0km – 39.0km)

4. INVESTIGATING THE VALIDITY OF UNSTEADY QUASI-TWO DIMENSIONAL ANALYSIS

Using temporal change in the water surface profile of an observed flood flow in the Edo River—a compound meandering channel with vegetation—Fukuoka et al. performed unsteady planar two-dimensional flow analysis and demonstrated that the technique can produce highly accurate discharge hydrographs[10]. This section investigates the applicability of the authors' unsteady quasi-two-dimensional analysis technique by comparing results obtained with the technique with results obtained with the unsteady-flow planar two-dimensional technique of Fukuoka et al.

Figure 3 shows the planform and ground cover surface conditions of the section of the Edo River investigated. The floodchannel in this section consists primarily of grassy plains, with sparse vegetation spread out over a large area. In the 42.5–44.0 km section, however, the vegetation is dense. The flood in question occurred in September 2001. Intense measurements were made over a 45-hour period from 12:00 a.m. September 11 to 9:00 p.m. September 12, with water level measured hourly on the left and right banks at 250-meter intervals in the 46–41 km section and at 500-meter intervals in the 41–39 km section. Water level was measured with an automatic water level gauge at the 46-km point (Higashi Kananoi) and the 39-km point (Noda). Discharge was measured hourly at these same two points. Analysis focused on a 120-hour period from 12:00 a.m. September 10 (24 hours before flooding) to 12:00 a.m. September 15 (hour 96). Here, conditions at the start of observations, at 12:00 a.m. September 11, are used as the baseline for the calculations. The upstream and downstream boundary conditions used were observed water level at the 44.5-km point and the 39.0-km point (Noda).

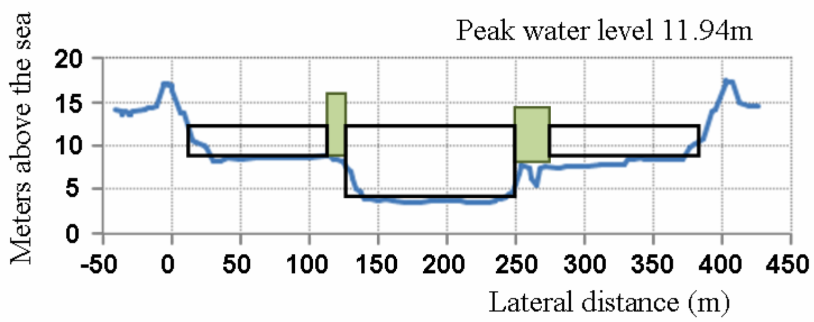


Fig.4 Cross-section division at 44km

The calculation cross-sections were chosen at 500-meter intervals longitudinally, and each cross-section was divided as shown in Figure 4 using post-flooding measured cross-sections as well as aerial photographs and ground cover diagrams to determine the locations and state of vegetation. Referring to previous research,[7),8),10)] the authors used fixed values for the main channel and floodchannel roughness coefficient and boundary mixing coefficient for the entire flooding period so that the computationally obtained temporal change in water surface profile would agree overall with the observed values.
This is shown in Tables 1 and 2.

Table 1 Boundary mixing coefficient f P[4),5)P]

Mixing phenomenon	Boundary mixing coefficient
Mixing between main channel flow and flood channel flow	0.17
Mixing between flow within vegetation adjacent to banks and main channel flow	0.03
Mixing between flow within vegetation and main flows	0.10

Table 2 Manning roughness coefficient

Place	Main channel	Flood channel Left bank ground	Flood channel Right bank ground
Roughness coefficient	0.03	0.04	0.04

In this analysis, the flow field is solved so that the calculated water surface profile agrees with observed temporal changes in water surface profile. This is the same for both unsteady quasi-two-dimensional flow analysis and unsteady planar two-dimensional flow analysis. As the latter has already been shown to adequately explain observed hydraulic quantities for flood flows, this section will compare the results obtained with this technique with those obtained with the authors' unsteady quasi-two-dimensional flow technique in order to demonstrate its appropriateness.

Figure 5 shows the observed water level profile and temporal changes in water level profile obtained with unsteady quasi-two-dimensional flow analysis and unsteady planar two-dimensional flow analysis. Despite some differences in temporal change in the water level profile calculated with unsteady quasi-two-dimensional flow analysis for the sharply meandering 42–45 km section, the observed water level profile is accurately re-created, with almost no difference with the results obtained with unsteady planar two-dimensional flow analysis, which appropriately accounts for waterway meandering and other planform changes. Cross-sectional velocity distribution at peak water level is shown in Figure 6. In unsteady quasi-two-dimensional flow analysis, vegetation clusters are treated as dead-water zones and so have zero velocity in the non-submerged vegetation areas. The figure shows that that the cross-sectional velocity distribution at peak water level as determined with unsteady-flow quasi-two-dimensional analysis and with unsteady planar two-dimensional flow analysis are in general agreement, indicating that the unsteady quasi-two-dimensional flow analysis technique rather accurately predicts cross-sectioned velocity distribution. Figure 7 compares observed and calculated discharge hydrographs and shows that the discharge hydrograph calculated with unsteady quasi-two-dimensional flow analysis accurately reflects observed discharge. The only slight difference with the results obtained with unsteady planar two-dimensional analysis indicates that the authors' technique can produce highly accurate discharge hydrographs.

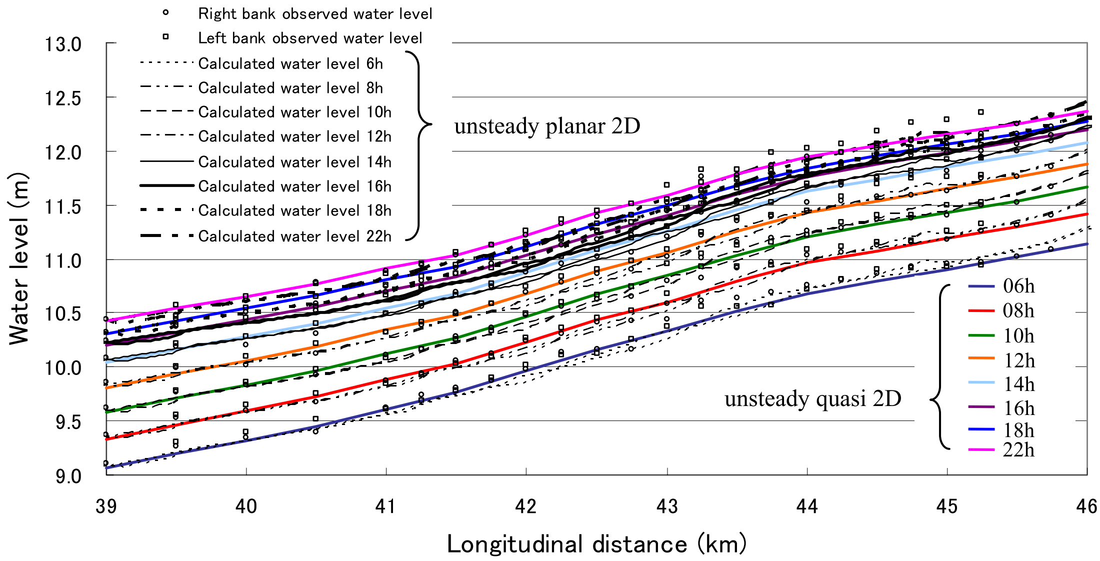


Fig. 5(a) Longitudinal distribution of observed and calculated water level (rising-water phase)

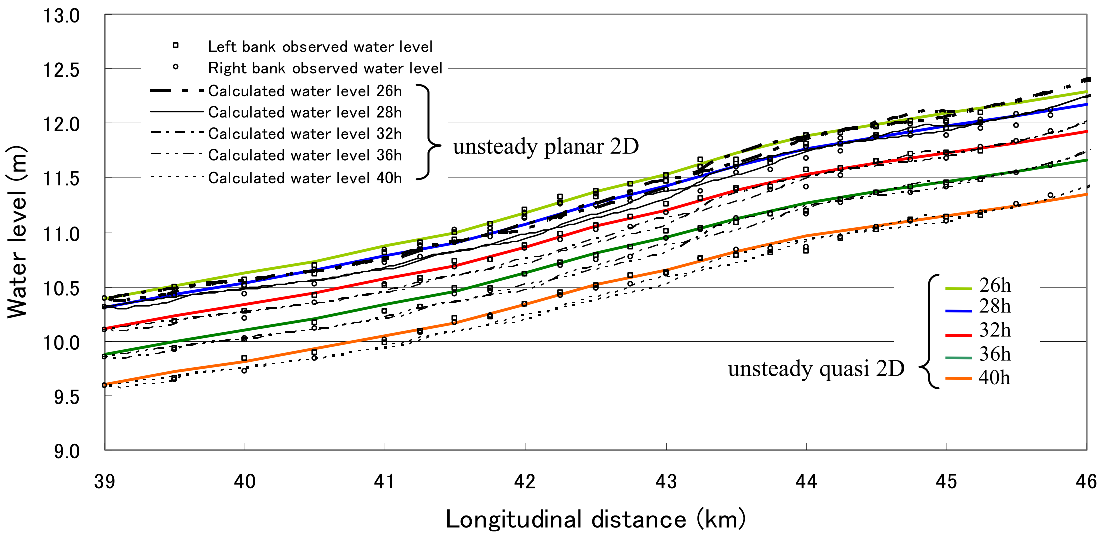
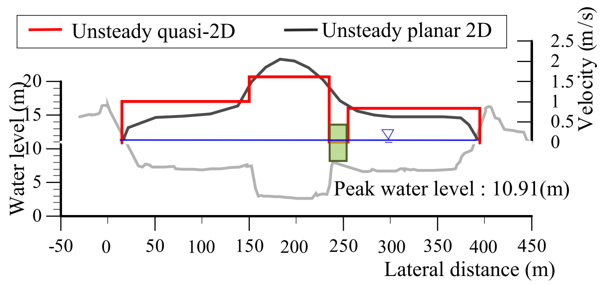
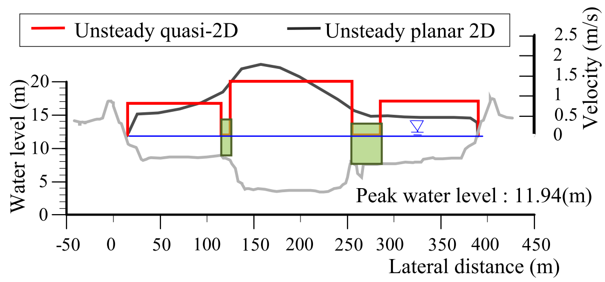


Fig. 5(b) Longitudinal distribution of observed and calculated water level (receding-water phase)



(a) 41km(Straight reach)



(b) 44km(Meandering reach)

Fig. 6 Comparison of cross-sectional velocity distribution (peak water level)

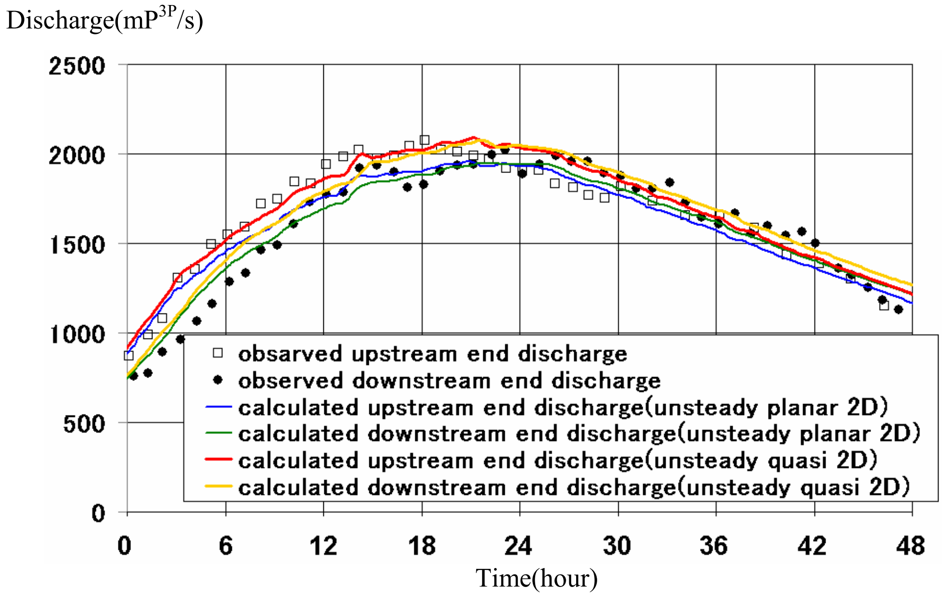


Fig.7 Comparison between the observed and calculated discharge

As stated in section 2.2, conventional quasi-two-dimensional flow analysis retained some ambiguity in how the roughness and boundary mixing coefficients are determined, unavoidably necessitating different combinations of values for each different flood. In contrast, unsteady quasi-two-dimensional flow analysis incorporates the unsteadiness and temporal changes in water surface profile of flood flows, and so by properly assessing vegetation areas true values based on channel cross-sectional shape and other factors can be used for the roughness coefficient. As for the boundary mixing coefficient, in the case of the Edo River, water surface profile, discharge hydrographs, and other hydraulic quantities were calculated by using existing standard values. For floods in other rivers, further investigation is necessary to determine whether these coefficients can be determined in the same manner. Because it can reference data used in conventional quasi-two-dimensional flow analysis for vegetation area quantities and coefficients of roughness and boundary mixing, unsteady quasi-two-dimensional flow analysis is a highly practical technique whose advantages include requiring less time and labor, particularly in comparison with unsteady planar two-dimensional flow analysis. As with this latter technique, unsteady quasi-two-dimensional flow analysis can also be used to study flood flow behavior in the context of vegetation management and river improvements, e.g., main channel widening and floodchannel lowering, making this an advantageous technique for many aspects of river management.

5. CONCLUSION

The primary conclusions of this paper are presented below.

1. The authors have extended quasi-two-dimensional flow analysis into the unsteady-flow regime to create an unsteady quasi-two-dimensional flow analysis technique that takes into account the temporal changes in water surface profile during flooding. Because it appropriately assesses temporal change in water surface profile and vegetation growth areas, this technique can use a channel's actual roughness coefficient—which can be determined from such factors as channel cross-sectional shape and bed materials—as well as the constant

boundary-mixing coefficient that is standardized in quasi-two-dimensional flow analysis.
2. Upon using the authors' unsteady quasi-two-dimensional flow technique on the Edo River, essentially no difference was observed between the results and those obtained with unsteady planar two-dimensional flow analysis, indicating that this method is capable of assessing various hydraulic quantities with sufficient accuracy for actual applications.

REFERENCES

1) Fukuoka,S.(2005), Flood hydraulics and river channel design, Morikita publishing company
2) Fukuoka,S., Fujita,K.and Niida, H. (1992), Prediction in flood water level of river courses with vegetation, *Journal of Hydraulic, Coastal and Environmental Engineering,* No.447/Ⅱ-19, pp.17-24, JSCE.
3) Japan Institute of Construction Engineering(2002), Manuals for river course planning, Sankaido publishing company.
4) Fukuoka,S. and Fujita,K (1989), Prediction of flow resistance in compound channels and its application to design of river courses, *Journal of Hydraulic, Coastal and Environmental Engineering,* No.411/Ⅱ-12, pp.63-72, JSCE.
5) Fukuoka,S. and Fujita,K.(1990), Hydraulic effects of luxuriant vegetation on flood flows, *Public Works Research Institute Report*, No.180.
6) Fukuoka,S., Watanabe,A., Hara,T. and Akiyama,M.(2004), Highly accurate estimation of hydrograph of flood discharge and water storage in rivers by using an unsteady two-dimensional flow analysis based on temporal change in observed water surface profiles, *Journal of Hydraulic, Coastal and Environmental Engineering*, No.761/Ⅱ-67, pp45-56, JSCE.
7) Fukuoka,S.(2006), River's maintenance and management based on observed water surface profiles of flood flow, *Advances in River Engineerin*g, vol.12, pp.1-6.
8) Fukuoka, S., Watanabe, A., Tabata, K., Kazama, S. and Gocho, H.(2006), Evaluation of hydrograph of flood discharge and roughness coefficient at the branched section in the Tone River and the Edo River, *Annual Journal of Hydraulic Engineering*, vol.50, pp.1165-1170, JSCE.
9) Fukuoka, S., Nagai, S. and Sato,H.(2005), Evaluation of hydrograph of flood discharge and flood water storage in the main river and tributary –In the case of Tone River-, *Annual Journal of Hydraulic Engineering*, vol.49, pp.625-630.
10) Sato, H., Fukuoka, S. and Deguchi, K. (2007) Analysis of changes in channel situation on the propagation mechanism of flood flow, *Advances in River Engineering*, vol.13, pp327-332.
11) Fukuoka,S., Kon,T. and Okamura,S. (2007), Assesment of flood control effects of the Tsurumigawa multi-purpose retarding basin, *Journal of Hydraulic, Coastal and Environmental Engineering*, vol.63 No.3, pp238-248.
12) Fukuoka, S., Yamazaki, K., Kuroda, Y., Iuchi, T. and Watanabe, A. (2006), On river bed variation mechanism in a steep channel and method to calculate inundation discharge by dyke breach, *Advances in River Engineering*, vol.12, pp55-60.
13) Suzuki,S. and Nakamura,S., Kawaguchi,K. and Fukuoka,S.(2008), Flood flow and bed variation in rivers subjected to large tidal variation, *35th Annual Meeting of Civil Engineering*, Kanto Branch, JSCE.
14) Osada,K. and Fukuoka,S.(2008), Development of 1-D river bed variation analysis method based on sediment transport mechanism in stony bed rivers, *Annual Journal of Hydraulic Engineering,* vol.52, pp.625-630
15) Fukuoka, S., Sato, H., Fujisawa, H. and Ohnuma, F.(2007), Assesment of permeability coefficient of vegetation and roughness coefficient under various flood and channel conditions, *Annual Journal of Hydraulic Engineering*, vol.51, pp.607-612.