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ICHE 2014, Hamburg - Lehfeldt & Kopmann (eds) - © 2014 Bundesanstalt für Wasserbau ISBN 978-3-939230-32-8

Analysis on Historical Changes in River Morphology Influenced by Barrage Construction and Tributary Confluence

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ABSTRACT: The topic in this study is river morphological changes in the last two and a half decades since barrage construction. The major impacts imposed on morpho- and hydrodynamics in this reach are reservoir formation behind the barrage and confluence of a major tributary. They have caused significant regime shifts in morphodynamics and ecosystem such as development of an island in front of the tributary confluence, thalweg migration from the left to right bank around the confluence, vegetation overgrowth on emergent sandbars, erosion of the main channel and sedimentary deposit on the floodplain, loss of spawning habitat for sweetfish, water depth decrease in the area of regatta course and so on. In order to examine the mechanism of the historical changes in river morphology, a numerical analysis on hydrodynamic and sedimentation processes was carried out by using an open source software, the "iRIC". Characteristic geomorphological features mentioned above were well reproduced by the present analysis. Influence of the two major impacts, i.e. barrage impoundment and tributary confluence, on river morphodynamics was discussed by performing a response analysis under two scenarios: no barrage and no tributary confluence.

Keywords: River geomorphology, Sedimentation, 2D flow analysis, Ecological regime shift

1 INTRODUCTION

Restoration, channelization and discharge control for flood management and water use frequently brings irreversible regime shifts in flow, fluvial and ecological systems, which sometimes causes degradation of aquatic nature. Especially, the river management and restoration sometimes bring irreversible changes in hydrodynamics, channel morphology, water quality, fluvial process and ecological structures of fauna and flora. In many cases after construction of some river works, the quality of the river declined in the aspects of flow conveyance capacity, water use, landscape, ecological services, etc.

The topic in this study is annual change of river morphology in a reach that is influenced by both barrage impoundment and confluence of a major tributary in Kako River, Hyogo, Japan. Two and a half decades have passed since the barrage construction (Kakogawa Barrage). In the meantime, the regime has significantly shifted in river morphodynamics and ecosystem. The engineering and ecological issues in this reach are growth of an island in front of the tributary confluence, thalweg migration from the left to right bank near the confluence, vegetation overgrowth on emersed sandbars, erosion of the main channel and sedimentary deposit on the floodplain, loss of spawning habitat for sweetfish or *plecoglossus altivelis*, decreasing depth of water area for regatta course and so on.

So far, extensive studies have been carried out in order to investigate hydrodynamic impacts of river control structures such as weirs, barrages, dams on fluvial and ecological systems in rivers (Bokuniewicz (1994), Ligon, Dietrich and Trush (1995), etc.). In the previous studies, many researchers focused their attention on impacts of morphological and sedimentological processes on fauna and flora in rivers from the viewpoints of engineering, limnology and ecology (Gilvear (1999), Wheaton, Pasternack and Merz (2004), etc.). Since the ecological structure predominantly depends on fluvial process, the key issue is how to properly control streams and sedimentation for creating a sustainable river system (Sear (1994)). In recent years, some preliminary studies have started for restoration of hydrosopheric environment under a concept of comprehensive sediment control (Sumi and Kantoush (2010)). State of the art strategies were proposed for active sediment controls such as sand bypassing at dam, reservoir operation for flushing sediment, sediment replenishment, gravel augmentation. The effect of these technologies on the river ecosystem was investigated in in-situ experiments (Kondolf and Minear (2004), Ock, Sumi and Takemon (2013)). In addition, extensive field and numerical studies were carried out regarding sedimentation around confluence, which is another focal issue in this study (Rice, Roy and Rhoads (2008)).

In order to discuss the mechanism of the historical changes in river morphology as well as to examine engineering countermeasures to minimize river environmental degradation, a numerical analysis on hydrodynamic and fluvial processes was carried out. Flow and sedimentation caused by major flood events which occurred during 1992-2011 were simulated by an open source software "iRIC-Nays2D" (Jang and Shimizu (2005)). The numerical results of river geomorphological changes in the last decades were compared with the field data. After identification of model parameters, the influence of the two predominant impacts, i.e. the barrage backwater and tributary confluence, on river morphology was individually examined by performing a response analysis under some scenarios of individual impact. The numerical model is expected to be a useful engineering tool supporting management and restoration for creating a sustainable river system.

2 FIELD SITE AND ISSUES

The field site is a reach between 12-18km from the river mouth of Kako River. An aerial view of the reach is shown in Figure 1. The Kakogawa Barrage was constructed at the downstream end of the reach for irrigation, city water and flood control in 1987. Kako River is a first-class river stretching through the southern region of Hyogo Prefecture whose total length and catchment area are 96km and 1,730km^2, respectively. The Ministry of Infrastructure, Transportation and Tourism, MLIT, is in charge of river management, which provides us datasets of geomorphology, hydrology and restoration works that are necessary for the present study.

The major hydraulic impacts in this reach are the barrage backwater and confluence of the left-bank tributary, Mino River with catchment area of 304km^2, that perpendicularly joins the main stream at the 15.8km point.

In Figure 1 pictured before the barrage construction, a dynamic fluvial process is recognized with alternate sandbars and riffles and pools covered by sand and gravel. They are typical geomorphological features developed in Segment 2.1. On the other hand,

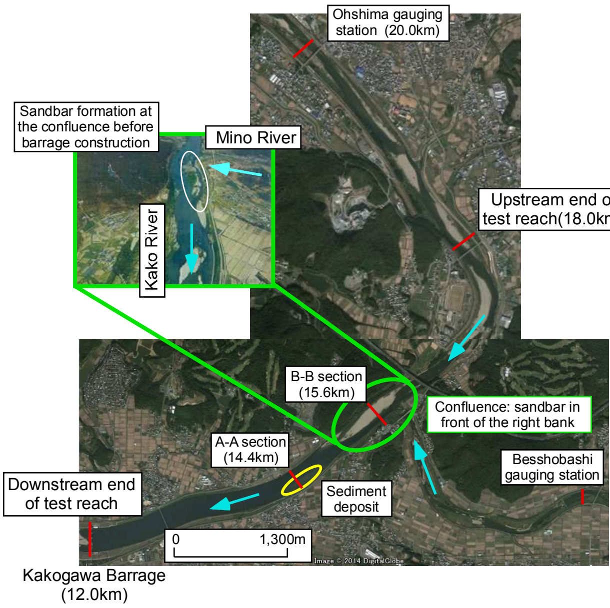
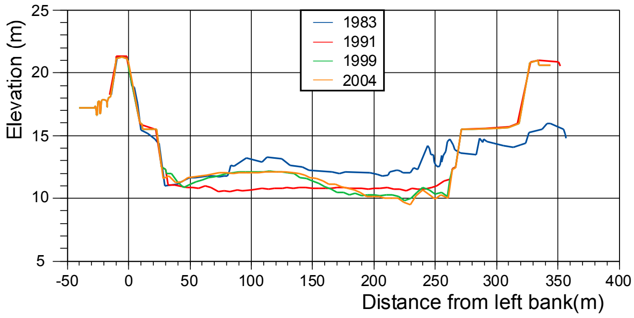
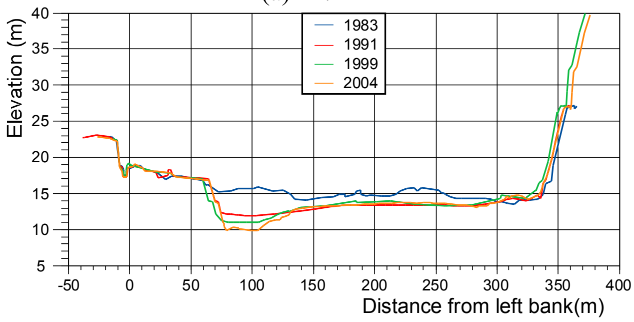


Figure 1. Study area.



(a) 14.4km



(b) 15.6km

Figure 2. Historical changes of cross section profiles.

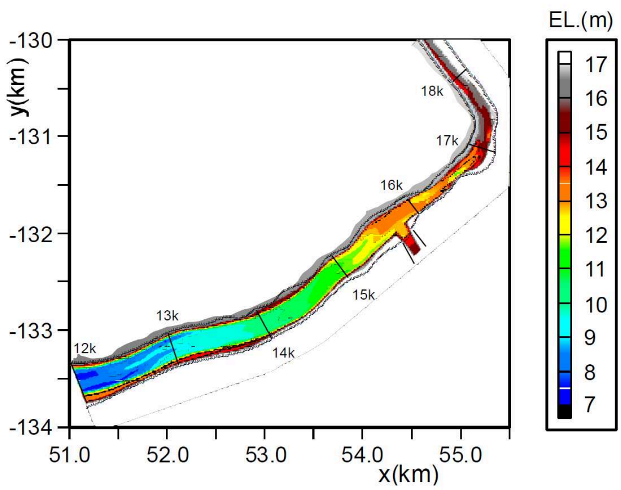


Figure 3. Initial bed profile (1991).

the river morphology underwent significant changes in the last two and a half decades since the barrage construction in 1981, as follows.

- A large island grew and developed in front of the confluence at 15.6km. As a result the thalweg that used to run close to the right-bank was shifted to the left bank shore.
- The structure of riffles and pool or meandering thalweg profile significantly changed; high amount of sediments were deposited near the left-bank at 14.4km, while the main channel was eroded in front of the right-bank.

3 NUMERICAL ANALYSIS OF FLOW AND SEDIMENTATION

3.1 *Outline of the model*

A hydrodynamic and fluvial analysis was carried out by using an open source software, the "iRIC (international River Interface Cooperative) Software", developed under a bilateral cooperation between the USGS and the Foundation of Hokkaido River Disaster Prevention Research Center, Japan. The solver used in this study is the "Nays2D" that is capable of analyzing unsteady two-dimensional river flows and various scales of sedimentation processes. The analytical domain is a 6km long reach stretching from the Kakogawa Barrage at 12.0km, through the confluence of Mino River at 15.8km and a major meandering part around 17km to the straight reach at 18.0km.

Figure 3 shows the river bed profile that was surveyed in 1991. Since this is the first dataset after the barrage construction, it was used as an initial condition in the present analysis. The computation duration is between 1991 and 2012.

The downstream boundary is the cross section at the Kakogawa Barrage and the upstream boundary of 18.0km is placed at a cross section just upstream of the meandering reach. Discharges were given at the upstream boundary of main stream and at the confluence of Mino River. The water level at the barrage was given as a downstream boundary condition. Water levels and discharges were recorded at the two stream gauging stations, Ohshima (20.0km) and Kunikane (14.2km), shown in Figure 1, which provides individual discharges in Kako and Mino Rivers, respectively.

3.2 *Determination of model parameters and computational conditions*

A preliminary analysis was conducted in order to determine numerical parameters such as Manning's roughness coefficient, grain size distribution of bed materials, length of the virtual approaching stretch, start-up computation duration, etc.

Manning's roughness coefficient was given as n=0.028 for the main channel and n=0.055 for the floodplain, respectively, which were identified by MLIT as the best fitting values to the historical flood records. The threshold elevation separating the main channel and floodplain was determined from a numerical solution of water level for the average discharge of annual flood. This is approximately equivalent to a bank-full flow discharge in the main channel. The whole analytical domain was categorized into main channel and floodplain by using the threshold elevation. Then, Manning's coefficient was assigned to each computational mesh according to the two categories.

In order to give a well-developed velocity and sedimentation flux at the upstream boundary, a virtual approaching stretch was connected to the upstream boundary.

Little difference was recognized in the numerical solution of sediment transport between the cases of mixed grain size distribution and uniform grain size of 60% equivalent diameter. In other words, it was confirmed that the uniform-size bed materials provide good approximation in describing fluvial process in this reach. Therefore, uniform bed materials with diameter d_{60}=0.0442m was assumed in the analysis. For saving computational time, only flood events whose discharges exceeded a threshold discharge Q_C that gave the critical bed shear stress were analyzed. Considering d_{60} of bed materials and the maximum water depth of h=3.1m at the stream gauging station "Ohshima", the threshold discharge for critical bed shear stress was determined to be Q_C=868(m^3/s)Thirty flood events with peak discharges ranging between Q_{max}=868~5,250m^3/s were selected in this manner and the hydrographs for Kako and Mino Rivers were generated as the upstream boundary conditions.

Duration of the initial start-up computation was determined to be two hours after performing preliminary computations with varying start-up duration.

The sediment flux was given at the upstream boundary by computing a bed load transport under the dynamic equilibrium state in the 0.6km long virtual approaching stretch. Wash load was not considered, since the sediment yield was scarce in this catchment. A general coordinate system and computational grids were automatically generated by using a module equipped in the iRIC. The computational grid is shown in Figure 4. The analysis started in 1991 when the cross-section survey was surveyed for the first time after the barrage construction and completed in 2013.

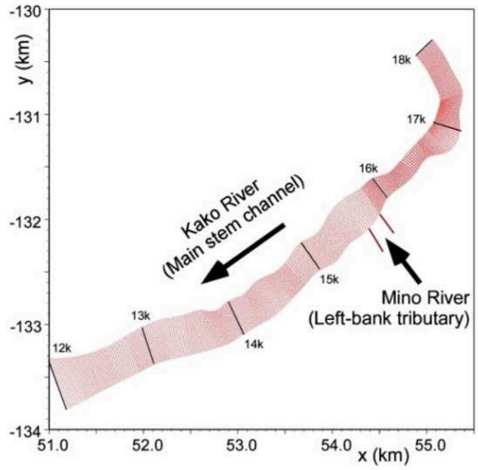


Figure 4. Computational grid.

4 REPRODUCTION OF RIVER GEOMORPHOLOGY

River geomorphology in the test reach was surveyed in 1991, 1999 and 1994 by MLIT. As mentioned above, the dataset collected in 1991 (see Figure 3) was used as the initial condition of bed profile. The numerical solutions were compared with the field data in 1999 and 2004. In this study, two types of analyses, i.e. the "middle-duration" analysis and a "long-duration" analysis, were carried out as follows.

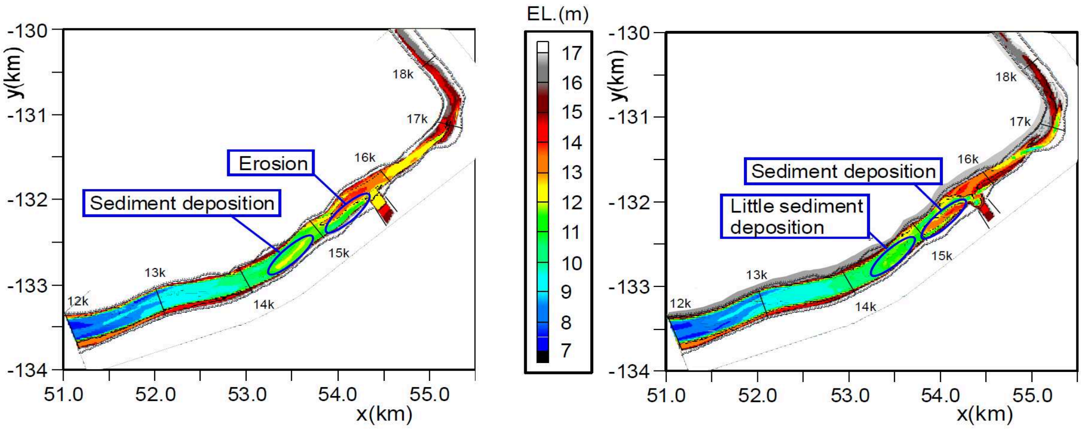
(i) Middle-duration analysis: The computation duration was divided into three terms; 1991~1999 (Term-I), 1999~2004 (Term-II) and 2004 ~2012 (Term-III). The field data in 1991, 1999 and 2004 were individually given as the initial condition for each analysis.

(ii) Long-duration analysis: The analysis was performed throughout entire duration of 1991-2012. Only the data obtained in 1991 was given as the initial condition.

In both of the analyses, the solutions were compared with the measurements in 1999 and 2004.

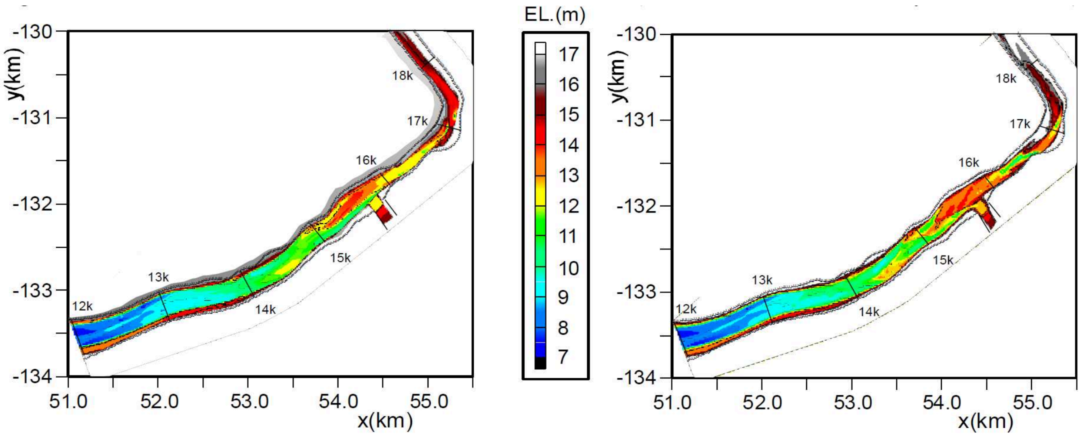
4.1 *Middle-duration analysis*

Since no field data is available for 2012, only the solutions for 1991~1999 (Term-I) and 1999~2004 (Term-II) are compared with the data. Figures 5 and 6 compared the simulated contour lines of river bed



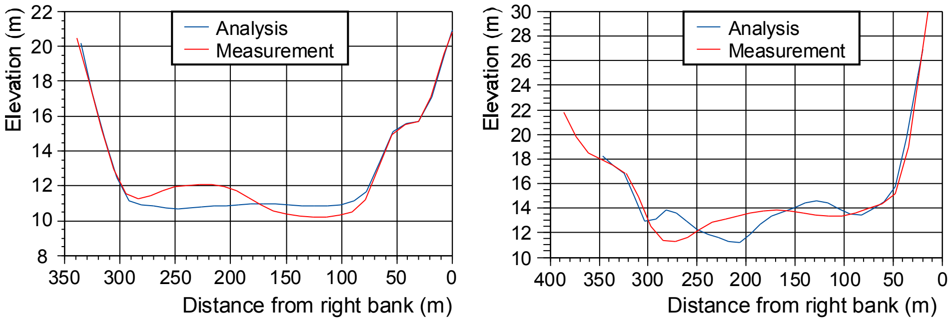
(a) Measurement (1999) (b) Analysis (1999)

Figure 5. Contours of river bed elevation in 1999 (middle-duration analysis: Term-I).



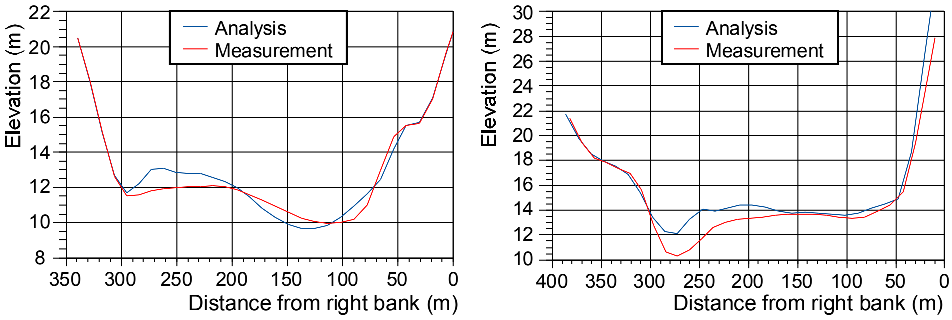
(a) Measurement (2004) (b) Analysis (2004)

Figure 6. Contours of river bed elevation in 2004 (middle-duration analysis: Term-II).



(a) 14.4km (1999) (b) 15.6km (1999)

Figure 7. Spanwise profile of river bed at the cross sections in 1999 (middle-duration analysis: Term-I).



(a) 14.4km (2004) (b) 15.6km (2004)

Figure 8. Spanwise profile of river bed at the cross sections in 2004 (middle-duration analysis: Term-II).

profiles with the field data. Details are shown in spanwise profiles of the cross sections at 14.4km and 15.6km in Figures 7 and 8, respectively. Figures 5 and 7 show that the numerical solution in 1999 does not correlate with the measurement, while the river bed profile in 2004 is well reproduced by the analysis as shown in Figures 6 and 8. Note that sediment deposition near the left-bank and erosion in the main channel at 14.4km observed in 1999 are not accurately described by the model. Around the confluence of Mino River (15.6km), there is a certain discrepancy of thalweg structure between the analysis and measurement. On the other hand, the numerical solutions during Term-II (1999~2004) are shown in Figures 6 and 8 that provide a satisfactory agreement with the field data. The results suggest that the model performance in reproducing fluvial and geomorphological processes strongly depends on analytical accuracy during the first term right after barrage construction. It is supposed that artificial perturbation must be added to the initial bed profile, since it plays as a trigger to generate geomorphological changes.

4.2 *Initial perturbation*

In general, sedimentation phenomena are governed by both deterministic dynamics and stochastic disturbances. The former is strictly described by the governing equations of kinematics and dynamics. They are, of course, involved in the present model. On the other hand, the latter is not generally taken into consideration in an ordinary hydrodynamic model, although there must be various natural disturbances in hydrological, hydrodynamic, geomorphological and fluvial processes.

Characteristic geomorphological changes observed in this reach are sediment deposition near the left-bank shore at 14.4km distance and development of an island and thalweg migration from the left- to right-bank around the confluence at 15.6km. The reach at 14,4km was used for a regatta course where the water recently became shallower than the regatta draft. Focusing on the geomorphological features and referring to the bed profile in 1999, a small perturbation is artificially added to the initial river bed profile in order to improve the model's performance. As shown below, a small faction, ϕ, of perturbation is added to the original bed elevation z_0 at the cross section of 14.4km.

$$z' = z_0 + (z_1 - z_0)\phi \tag{1}$$

where z': the modified bed elevation in 1991 with the additional perturbation, z_0: the origical bed elevation surveyed in 1991, z_1: the bed elevation observed in 1999, $\phi = 0 \sim 1.0$: fraction of the initial perturbation. The perturbation is given one-mesh long $\Delta x \fallingdotseq 20$m in the streamwise direction.

A response analysis was performed to examine sensitivity of the solution on ϕ. Simulated bed profile at the cross section of 14.4km are compared for three different values of ϕ in Figure 9. Figure 10 shows contours of river bed elevation for ϕ=0.05 and 0.1, where the solution for the default value ϕ=0 is already shown in Figure 5(b). Figure 5(a) is the field data that should be compared with Figure 10. Figure 9 indicates that the solution for ϕ=0.3 apparently overestimates sedimentary deposit at the left-bank side of 14.4km. Summarizing Figures 9 and 10, it is concluded that ϕ=0.05 would provide reasonable reproduction.

After all, the long-duration analysis for 1991~2012 was carried out with the addintional perturbation of ϕ=0.05 to the river bed elevation at 14.4km and15.6km.

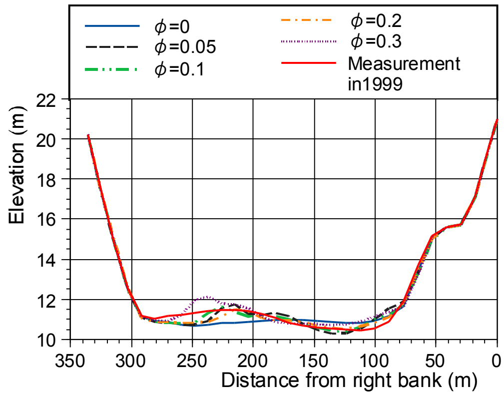


Figure 9. Response of bed profile at 14.0km in 1999 to the initial perturbation ϕ.

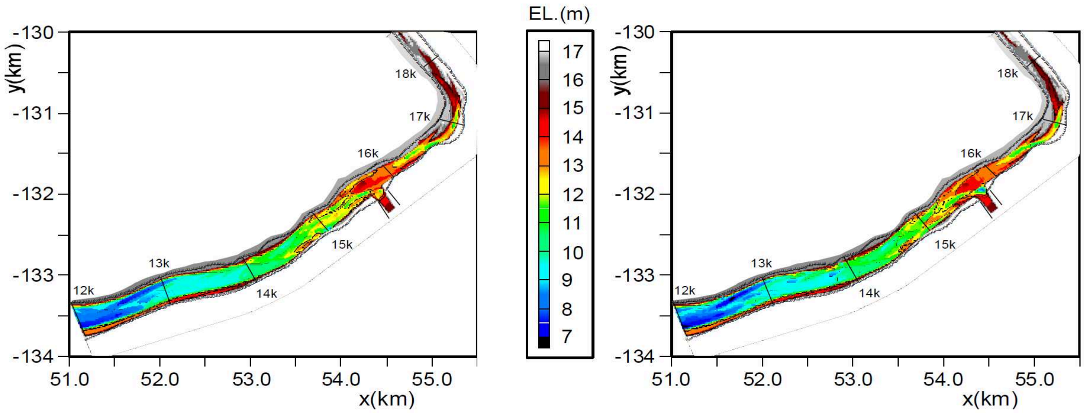
4.3 *Long-duration analysis*

Solutions of river geomorphology obtained by the long-duration analysis are shown in Figures 11 and 12. They are contours of river bed elevation and cross section profile in 1999 and 2004, respectively. The field data that should be compared with Figure 11 are shown in Figures 5(a) and 6(a).

Comparing between Figures 5 and 11(a) and between Figures 7 and 12(a), (b), the long-duration analysis shows better performance in reproducing geomorphology in 1999 than the middle-duration analysis. By adding small perturbation only in a very short stretch, the model's performance is significantly improved. Regarding the result in 2004, the middle-duration analysis provides a slightly better agreement with the field data than the long-duration analysis, since the measured bed profile in 1999 is given as an initial condition in the middle-duration analysis. Nevertheless, characteristic features of geomorphology such as sediment deposition at 14.4km, sandbar profiles and meandering structure of thalweg are well reproduced by the long-duration analysis. It is concluded that the present analysis is capable of describing decades-long variation of river morphology, if an adequate perturbation is given.

5 IMPACTS OF BARRAGE BACKWATER AND CONFLUENCE ON GEOMORPHOLOGY

Focusing on the two major impacts, i.e. barrage construction and tributary confluence, how the two impacts individually affect river morphodynamics was investigated. A response analysis was conducted with two scenarios, which were no barrage and no tributary confluence, respectively. The present situation serves as a reference case in the response analysis. In the case of no barrage impoundment, the downstream boundary condition of water surface elevation was determined by assuming the hydraulic gradient line to be parallel to the bed slope. The effect of the confluence was simulated by equating the tributary discharge to zero. For both of the scenarios, the long-duration analysis was carried out during 1991~2012. Figure 13(a) shows river bed elevation in 2012 in the case when the barrage is absent. Geomorphological features such as alternate sandbars and meandering thalweg that were observed before the barrage con-



(a) ϕ=0.05 (b) ϕ=0.1

Figure 10. Response of river bed profile in 1999 to the initial perturbation ϕ. The solution in the case of ϕ=0.0 is equivalent to the default solution in Figure 5(b).

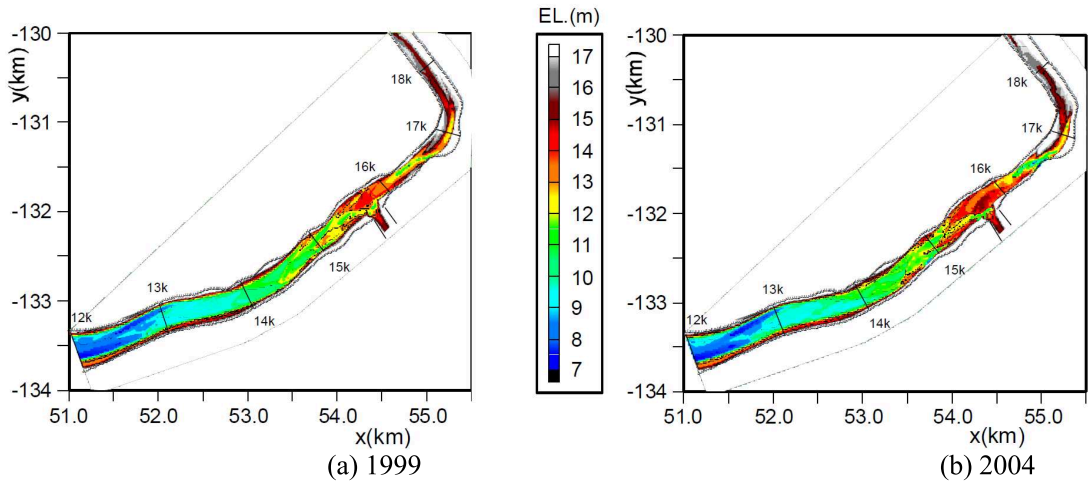


Figure 11. Contours of river bed elevation reproduced by the long-duration analysis. The results should be compared to the field data shown in Figures 5(a) and 6(a), respectively.

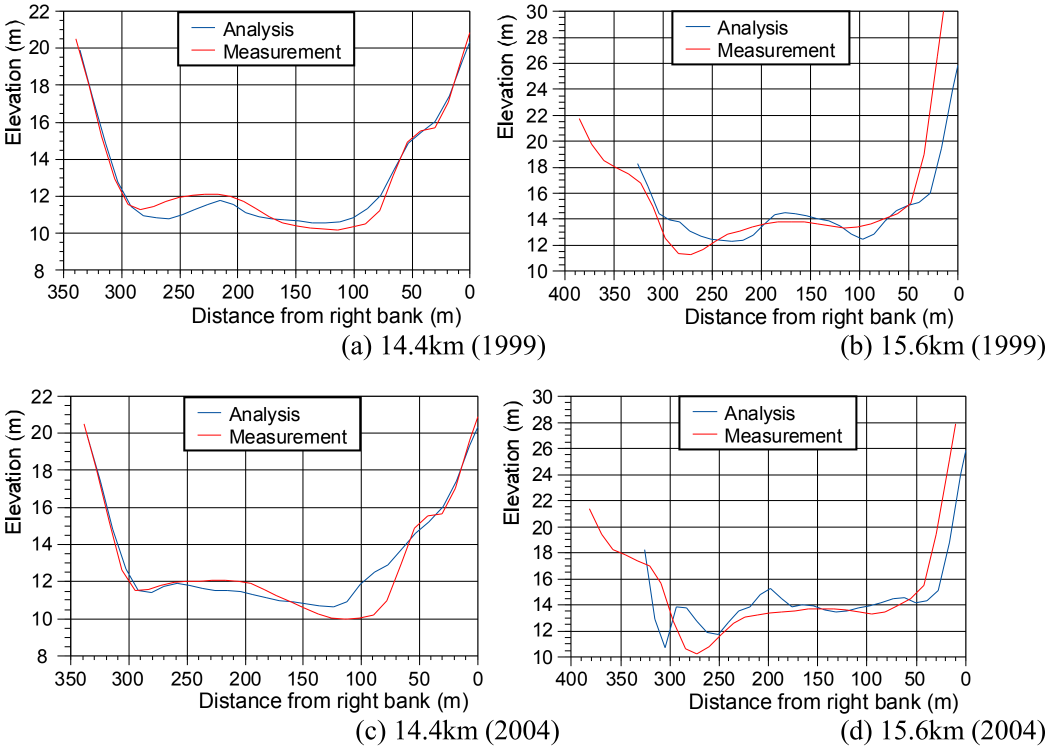


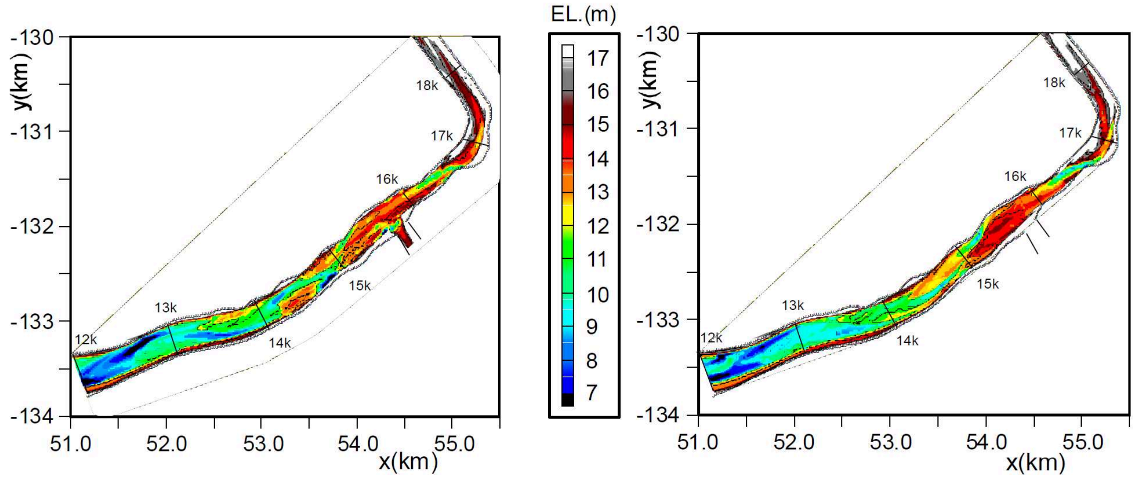
Figure 12. Comparison of the river bed profile between the field measurement and the long-duration analysis.

struction still remains in 2012. However, the shallow region produced in the left-bank shore at 14.4km develops even when the barrage is absent. It is supposed that this sediment deposition area is a part of the natural alternate sandbar and is generated independently of the barrage construction. Another shallow water appears at the right-bank shore at 13.6km in Figure 13(a), which corresponds to the sequence of the alternate sand bar.

Figure 13(b) represents river bed profile in 2012 when the tributary discharge is assumed to be zero. The thalweg tends to migrate to the right-bank when the tributary is absent, while it is actually running along the left-bank shore. The sandbar island stretches longer in this case compared to the prototype.

6 CONCLUDING REMARKS

A historical change of river morphology was analyzed by using a two-dimensional fluvial hydrodynamic model. The test area is the middle-reach in Kako River stretching between 12.0-18.0km from the river mouth, where thalweg and sandbar structures were significantly modified after barrage construction. The major impacts on morphodynamics are the barrage backwater and confluence of the major left-bank tribu-



(a) No barrage backwater (b) No confluence of Mino River

Figure 13. River bed elevation in 2012.

tary. Focus was placed on sediment deposition near the left-bank at 14.4km and development of sandbar island and thalweg migration in front of the tributary confluence. As the first step, a preliminary analysis of the middle-duration was conducted to examine the model's performance, where the total term 1991-2012 was divided into three terms, i.e. 1991-1999 and 1999-2004, to compare the numerical solution of river bed profile with the field data. The solution during the first term, 1991-1999, provided poor results of geomorphological change. On the other hand, the solution during the second term, 1999-2004, agreed well with the results. Considering that some stochastic disturbance may play a predominant role in fluvial process right after barrage construction, a small perturbation was added to the initial bed profile in order to improve model performance. A better solution was obtained in this manner and the historical change of geomorphology which occurred during 1991 to 2012 was successfully reproduced by the long-duration analysis. A response analysis was also carried out to examine the individual impact of the barrage backwater and the tributary confluence on river morphology. The model could be a promising engineering tool to simulate morphodynamics and ecology in rivers. Performance of river restoration can be numerically examined in this manner and a proper strategy for river management can be proposed for recreating a sustainable river system.

ACKNOWLEDGEMENT

The study was supported by the Himeji River and Road Management Office, the Ministry of Land, Infrastructure, Transport and Tourism. The present study was financially supported by the Grant-in-Aid for Scientific Research (B) (Project No. 23360212, 26289164, Leader: Kohji Michioku).

REFERENCES

Bokuniewicz, H. (1994). Sedimentation Associated with an East River Tidal Barrage, Annals of the New York Academy of Sciences, 17, pp.51–56, DOI: 10.1111/j.1749-6632.1994.tb21844.x.

Gilvear, D. J. (1999). Fluvial geomorphology and river engineering: future roles utilizing a fluvial hydrosystems framework, Geomorphology, 31(1–4), pp.229–245.

Jang, C. and Shimizu, Y. (2005). Numerical simulation of relatively wide, shallow channels with erodible banks, Journal of Hydraulic Engineering, ASCE, Vol. 131, No. 7, pp. 565-575.

Kondolf, G.M., Minear, J.T. (2004). Coarse sediment augmentation on the Trinity River below Lewiston Dam: Geomorphic perspectives and review of past projects, Report to Trinity River Restoration Program, Weaverville, CA.

Ligon, F.K., Dietrich, W.E., Trush, W.J. (1995). Downstream ecological effects of dams, BioScience, 45, pp.183–192, doi: 10.2307/1312557.

Ock, G., Sumi, T., Takemon, Y. (2013). Sediment replenishment to downstream reaches below dams: implementation perspectives, Hydrological Research Letters, 7(3), pp.54–59.

Rice, S., Roy, A., Rhoads, B. (2008). River Confluences, Tributaries and the Fluvial Network, John Wiley and Sons Ltd, 474 pages.

Sear, D.A. (1994). River Restoration and Geomorphology, Aquatic Conservation-Marine and Freshwater Ecosystems, 4(2), pp.169–177.

Sumi, T., Kantoush, S.A. (2010). Integrated management of reservoir sediment routing by flushing, replenishing, and bypassing sediments in Japanese River Basins, Proc. 8th International Symposium on Ecohydraulics, pp.831–838.

Wheaton, J.M., Pasternack, G.B., Merz, J.E. (2004). Spawning habitat rehabilitation-I. Conceptual approach and methods, Int. J. of River Basin Management, 2, pp.3–20. doi:10.1080/15715124.2004.9635218.