Fundamental studies for river-training works

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Abstract

The main purpose of river-training works is flood control. Recently, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan, has decided to incorporate environmental conservation to river training policies, which involves water quality, landscape, and diversity of wildlife habitats. To take those aspects into account, geological deformations by fluvial processes in river channels need to be simulated appropriately. However, it is still difficult to conduct river training works based on reliable predictions. This paper will introduce one of the examples of river-training works and associated fluvial processes, which were unpredictable and brought about unwelcome consequences. Also, the paper described an aDcp-based field survey and a resultant flow field. Finally, the authors will discuss the limitation of aDcp-based measurements and the conventional data processing method, and propose an alternative method to elevate simulation accuracy.

Introduction

In Japan, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) establishes fundamental-river-management policies and river-improvement plans for

109 river systems, which are class A river systems managed by MLIT. Based on those policies and plans, river-training works have been implemented throughout the country.

Urban characteristics, however, such as buildings and other land use being located very closely to rivers, force MLIT to make anguished decisions on which types of river training works should be taken for river improvement. Levee raising increases a potential risk for floods, while channel straightening and widening requires expensive compensation for relocation. Consequently, MLIT often selects river-bed excavation as the most feasible measure for river improvement in urban areas.

On the other hand, there are studies pointing out that river-bed excavation brings about unpredictable, and sometimes, unwelcome consequences, such as the change of river courses, deforestation of floodplains, and channel shortening. Fujita et al. (1995) reported, based on field observations, that 1) a channel narrowed around an edge between the main channel and floodplain after an artificial channel widening; 2) that was mainly caused by the transportation and deposition of wash load; 3) vegetation on the floodplain influenced wash-load trapping; and therefore 4) the trapped sediments caused the channel narrowing.

As a matter of fact, more than quasi-2D numerical simulation with bed variation, which is one of the major simulation tools for MLIT, does not have enough accuracy to predict complicated phenomenon during floods. Though the general familiarity with numerical simulation is adequate enough, lack of understanding, in other words, lack of measurement techniques does not elevate accuracy of numerical simulation. Therefore, better observation during floods for sediment transport, discharge, and flow around the river bed needs to be implemented.

Recently, the use of acoustic Doppler current profilers (aDcp) has been highlighted as one of the observation tools for measuring river flow, and measurements in rivers have been carried out in different studies (e.g. Gordon, 1989 and Muller 2002). Other studies found that aDcps were capable of measuring flow field, suspended sediment (e.g., Dinehart and Burau, 2005), and also bed-load velocity (e.g., Rennie and etc). On the other hand, Kinoshita (1998) pointed out the difficulty and insecurity of floating aDcps on the water surface during floods, especially in rivers where streams are steep, litter or drift woods float, and water surfaces vibrate, as many rivers in Japan represent those characteristics. Additionally, Muto (2004) mentioned the limitations of aDcps in terms of observational principles. Despite the difficulties, the authors still find it worthy of efforts to find a better aDcp-based observation system for understanding fluvial processes during floods, including a method of data processing and the boat design specifically for mounting aDcps.

In this paper, the authors will introduce 1) an example of consequences after a river-bed excavation and floods, 2) an example of field observation via acoustic Doppler instruments, and 3) an upgraded method for data processing using aDcp-based data.

Example of consequences after a riverbed excavation and floods

In October 1997, a catastrophic flood occurred in a river in Kyusyu area. Since the flood caused extensive damages including embankment breaches, inundation, and sedimentation and scours in the river channel, MLIT decided to make intensive efforts to implement river training for increasing the river's flow capacity. The training works, including bed excavations and deforestation of floodplains, were implemented in the entire river section from 3.8 up to 15.5 km upstream.

The following discussions are based on one-dimensional-varied-flow simulation. Though a computational technique allows us to use simulation with more than one dimension, the authors used quasi-2D varied-flow simulation is not always sufficient but still reliable and accurate, since 1) most class A rivers in Japan have continuous levees, 2) checking flood-stage marks is obligated to river administrators after floods, 3) the interval between flood-stage marks is much shorter than that between water-level-gauge stations, and 4) flood-stage marks draw an envelope curve.

Figures 1 show two quasi-2D simulation results for discussing how channel improvements affect fluvial-hydraulic properties, such as water-surface and bathymetry elevation, cross-sectional area of flow, shear velocity, and non-dimensional shear stress. Simulation conditions are set as follows, 1) two geometries are based on field surveys before and after intensive channel improvements, 2) discharge is selected as the mean-annual-maximum value, which is recommended by Yamamoto (1994), and 3) the roughness of the river is estimated based on flood-stage marks. In those figures, curves in black and red represent the variations before and after channel improvements, respectively. Also, blue dots represent the points and elevations of the flood-stage marks. Based on the simulated water surface, two aspects are indicated that 1) the water levels successfully decreased in the section between 4.0 and 16.0 km, and 2) the points, where the water-surface slope had the maximum value, moved from 9.2 km to 11.5 km. Consequently, the shear velocity and non-dimensional shear stress in the 9.5-10.5 km section decreased dramatically; for example, τ_* decreased from 0.27 to 0.08. Conversely, in the 11.5-12.0 km sectionthose properties increased; in other words, τ_* increased from 0.05 to 0.14. Since this τ_* property is a dependable variable for channel stability, those sections need to be carefully analyzed as being discussed in the following paragraph with aerial photos. Though the authors do not show the observational results in detail, there are only few fluvial processes observed in the river except at the sections mentioned above; thus, that justifies reliability of quasi-2D numerical simulation.

Figures 2a and b show a comparison of two aerial photos taken in 2003 and 2006. Detail explanation needs to be referred the report (Hattori et al. 2004). Floods, which exceeded the mean-annual-maximum value, occurred three times in between those two years. The aerial photos in this figure represent geometries around 11.0 km from the river mouth. At this location, deforestation was conducted outside the curved channel for the purpose of increasing the river's flow capacity and conserving riverine forests inside. In addition, around the upstream and downstream areas of the location, river-bed excavation was implemented on their floodplains. As these figures show, 1) the left-bank floodplain at 11.5 km was scoured, which exposed the bank to danger, 2) the stream shortcut across the inside of the curved channel, which also exposed the right bank to danger, and 3) the riverine forests which were supposed to remain on the floodplain and to be conserved were washed out. Those consequences were unpredictable before channel improvements, and considered to be unwelcome.

The above discussion indicates that river-training works need to be implemented with reliable simulation and with adequate understanding associated with sediment/flow discharge, flow distribution around river bed. Measurement techniques for obtaining those flow properties, therefore, are fundamental for conducting reliable river planning.

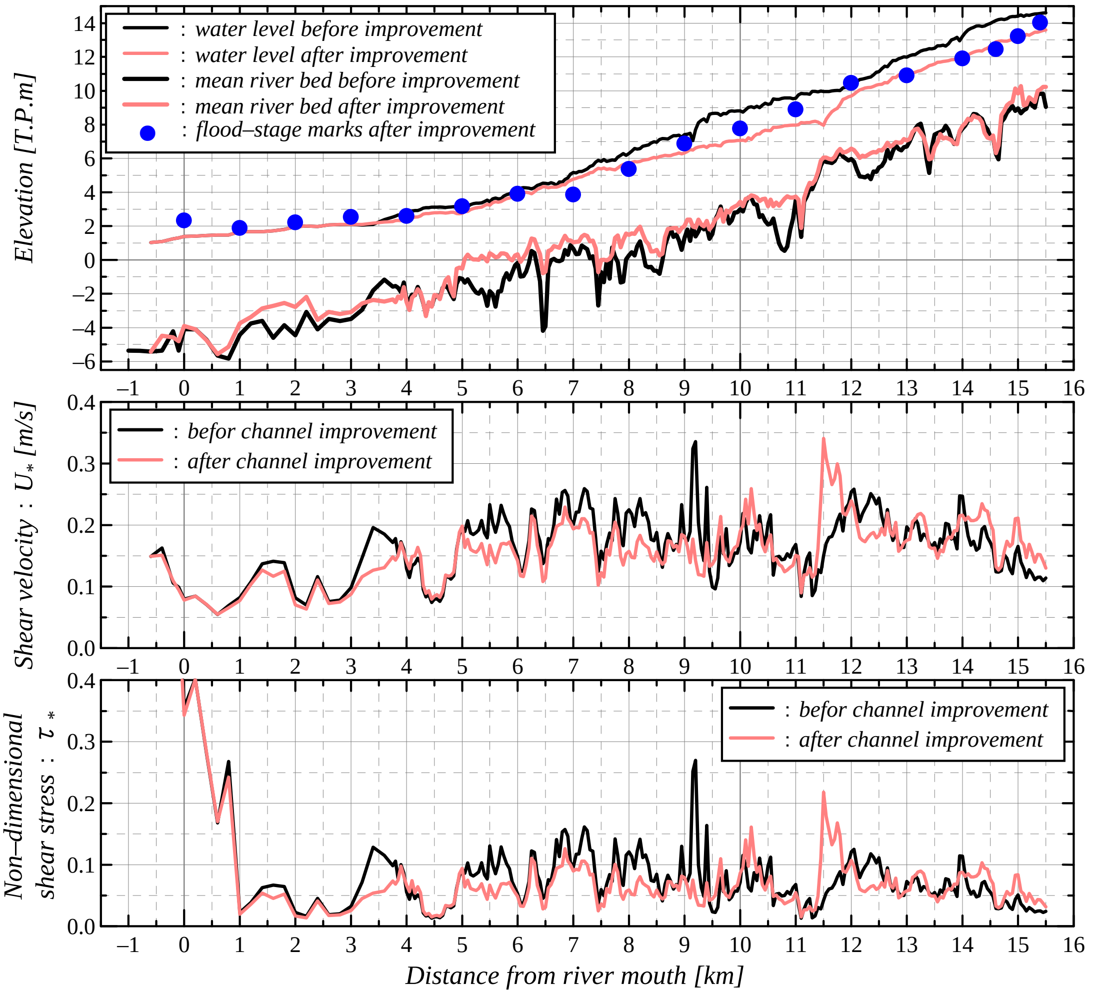

Figure 1 Calculation results of the flow properties

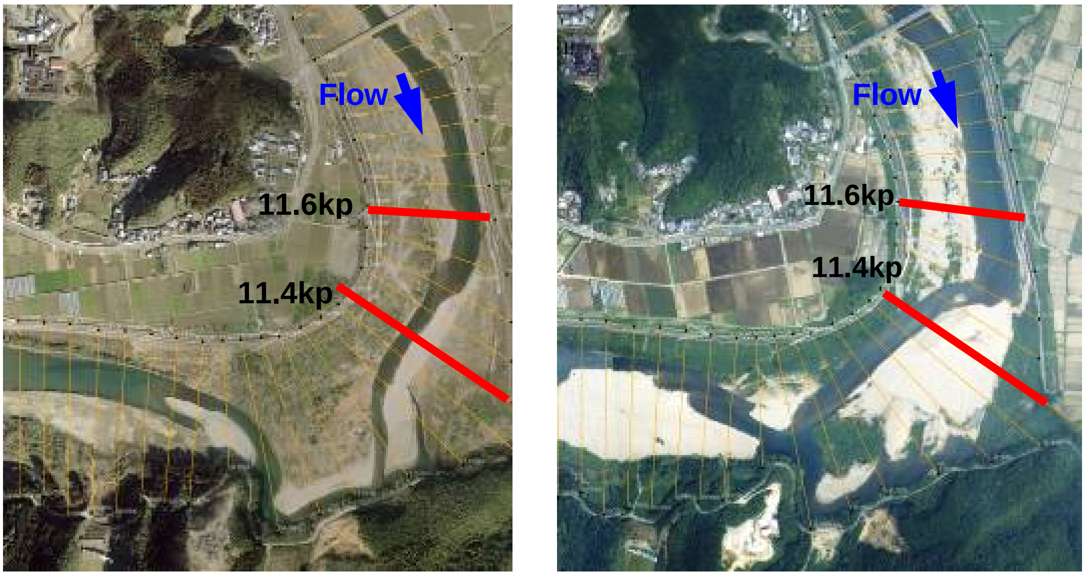

Figure 2-a (left, 2003) and 2-b (right, 2006) Aerial photos around 11.0 km

Example of field observation via acoustic Doppler instruments

This section of the paper explains one of the examples of field observation with an aDcp mounted on an unmanned boat, which was designed by Kinoshita (1998). The boat mounts an aDcp Rio Grande, a Teledyne RD Instruments product, and a real time kinematic GPS (RTK-GPS) for location positioning. The point of interest, enclosed in a red circle in Figure 3, shows a characteristic of scour around the spur dyke. Though the observation took about 30 minutes to complete measurements, the authors confirmed that the flow was steady. As a matter of fact, water surface elevation at a point kept constant during this observation.

A next series of figures show data obtained by the boat-mounted aDcp. These figures respectively show the top views of the river area in terms of bathymetry (Figure 4), a velocity field and absolute velocities on a geodetic coordinate plane (Figure 5), and a velocity field on a geodetic coordinate plane and downward velocities (Figure 6). Black, cross-sectional curves in each figure represent the boat course for data collection performed at 1.5 second intervals with an average of 5 pings. The locations of the black arrows in Figure 5 and 6 represent the centers of each interval of data collection. Spaces without the cross-sectional curves were interpolated with a kriging method.

The bathymetry, as shown in Figure 4, shows the specific characteristics of 1) curved channels, and 2) scours around dykes, whose deepest scour located just downstream of the dyke. The deepest point in this observation area was approximately T.P.-4 m, and its entrance approximately T.P.2 m; therefore, the maximum depth caused by the local scour was roughly 6 m.

The velocity field in Figure 5 observed at 0.75 m from water surface shows that 1) the flow with a velocity of 200 cm/s entered in the observation area; 2) the flow with a velocity of more than 170 cm/s (yellow color in this figure) started to shrink as it got closer to the spur dyke, became the thinnest where the maximum scour depth located, and expands again downstream; and 3) the flow behind the dyke shows the characteristics of unsteady eddies rotating around a vertical axis.

The downward velocities in Figure 6 observed at 2.25 m from the water surface show that 1) the downward flow started from the nose of the dyke, and it spread around the area where the maximum scour depth located, and 2) the flow in this depth showed a velocity of about 30 cm/s. Though the authors do not show other figures for flows in different layers, it may be worthy of note that a downward flow velocity of about 50 cm/s was recorded.

Based on the above discussion, the authors conclude that the spur dyke is working effectively for the bank-protection purpose, since the dyke helps move the maximum scour depth and the center line of the stream towards the center of the river channel.

The discussion of Figure 4-6 shows how an aDcp-based measurement system can help conduct more visible field observation. They are effective to understand flow properties associated with very short-term fluvial processes. For examples, a series of field observations at different flood stages contribute to the understanding of very short-term, local fluvial processes, such as 1) bathymetries at a time, 2) hydraulic forces associated with not only shear stresses but also downward flows at the same time, and 3) bathymetries as a consequence of the hydraulic forces at the next time step. As previously stated, it is not always possible to obtain high-density point data in wide rivers, since field observation constantly involves some degree of difficulty and insecurity. However, a cross-sectional measurement or even a point measurement, which is mostly conductible in terms of difficulty and insecurity, helps understand fluvial processes during floods.

As was stated before, it is fundamental to collect flow data at the vicinity of river beds for understanding sediment transport. However, observational principles make aDcp instruments less suitable for measuring around river beds as long as down-looking aDcps are used. To overcome this matter, the authors will introduce a new data-processing method in the following section.

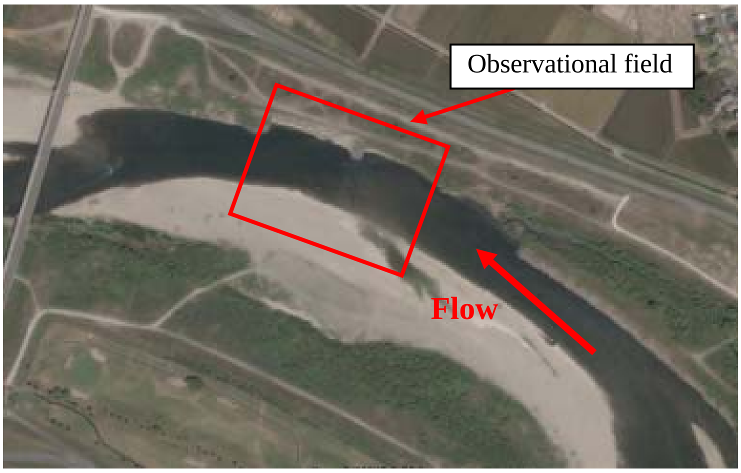

Figure 3 Observational field

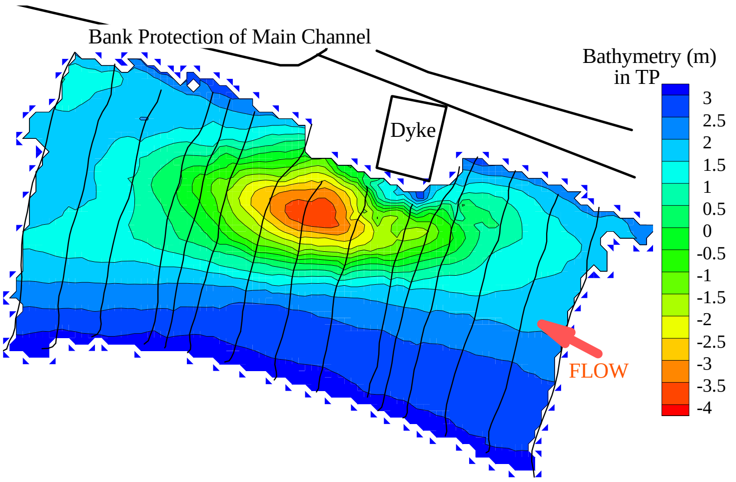

Figure 4 Bathymetry around the spur dyke

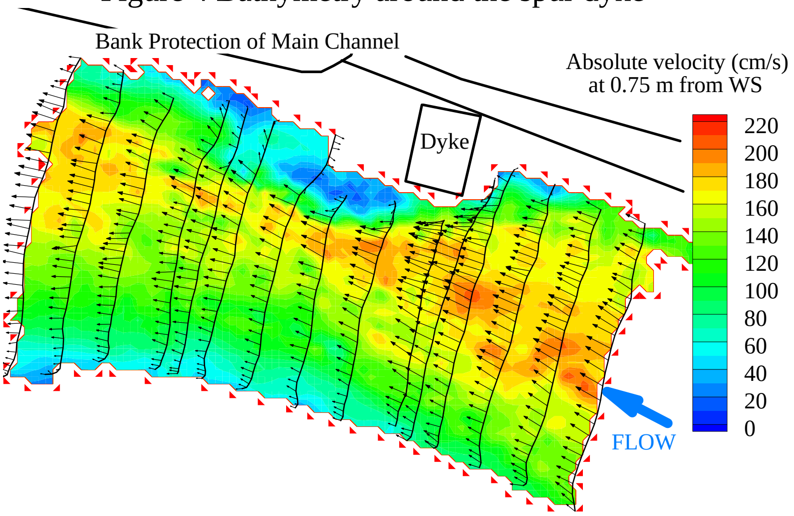

Figure 5 Absolute velocity taken by the aDcp at 0.75 m from water surface

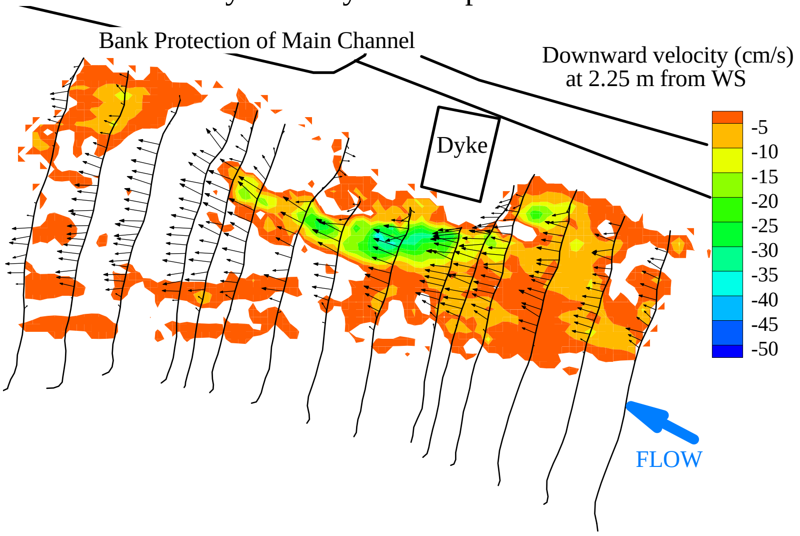

Figure 6 upward velocity taken by the aDcp at 2.25 m from water surface

Principles of the use of aDcps and the introduction of a new data processing method

In this section, the authors will explain briefly the principles of the aDcp use and a new data processing method. Other documents (e.g., Simpson 2001) should be referred to for detailed explanation. Generally, aDcp instruments for river measurements are equipped with three or four transducers. Here, for the sake of a brief explanation of the conventional method, assume that a down-looking aDcp with four transducers is used, and that one pair of the transducers are located parallel to a cross section of the river channel. In the conventional method, the flow at H_1 in Figure 7 is calculated as follows; 1) velocities in beam directions, such as Vf_{12} and Vf_{22}, are measured by the Doppler effects at each point; 2) the flow distribution at the measurement location (X_1) inside the observational width, whose length scale is $2H_1 \times \tan\theta$, is assumed to be homogeneous; then 3) the velocity at H_1 is calculated. Obviously, a length scale becomes longer as a measurement location is deeper. Therefore, aDcps with the conventional method can not guarantee the identical instrumental precision.

Now, as one of the trial, 1) set two more aDcps (1) and (3) on either side of the aDcp (2), as shown in Figure 7, 2) name the velocities in the beam direction as Vf_{ij}, whose i and j represent transducers and aDcps, respectively, and 3) for calculating the velocity at X_2, select Vf_{12} and Vf_{21}; similarly, Vf_{22} and Vf_{13} for X_3. By selecting different aDcps, this method makes the length scale shorter compared with that of the conventional method. Though it is not feasible to use several aDcps, it is still possible to apply this new data processing method with a few binding conditions, such as 1) appropriate boat operation and 2) steady flow.

The following paragraphs are going to describe the validation of the new data processing method using artificial data sets, which represent the flow patterns of secondary currents. Nezu (1992) explains that flow patterns during floods have secondary currents, which have upward and downward velocities in the cross direction, and the size of the eddy scale is same as the flow depth. To discuss the secondary currents, the 2D Rayleigh-Benard convection was selected and simulated, as shown in Figure 8.

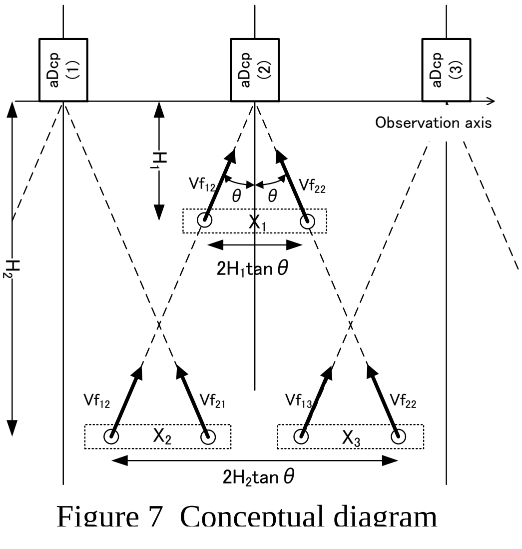

Figure 7 Conceptual diagram

Figures 8, 9 and 10 show contour diagrams of non-dimensional vertical velocity, and arrows representing vertical and lateral velocities. Figure 8 shows part of the original Rayleigh-Benard convection, and maximum upward velocities appear cyclically with an interval of the water depth. Figure 9 shows a Rayleigh-Benard convection converted by the conventional data processing. A comparison of Figures 8 and 9 revealed that the conventional method 1) moved the eddy center deeper from z/H = 0.5 to

0.2; 2) underestimated the vertical velocity by about 36% less, and 3) simulated river-bed flows differently, while lateral flows near the water surface similarly.

Figure 10 shows a Rayleigh-Benard convection coverted by the new data processing method. As shown in this figure, the new data processing method also underestimated the vertical velocity by about 8% less, while the eddies were expressed similarly to the original convection. This fact shows that data conversion by the new data processing method is successfully completed; therefore, it justifies the new data processing.

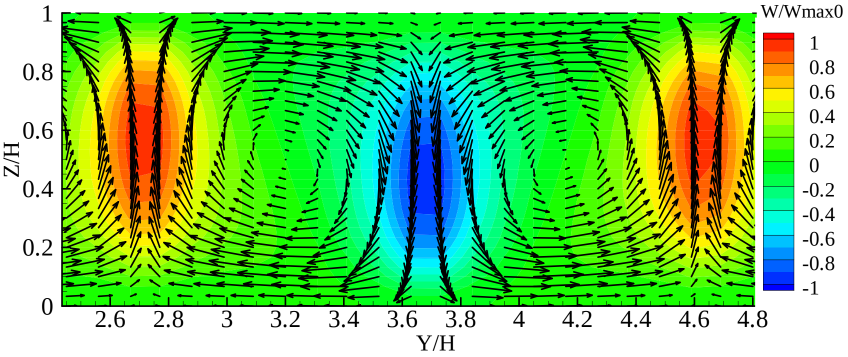

Figure 8 Flow field representing 2D Rayleigh-Benard convection

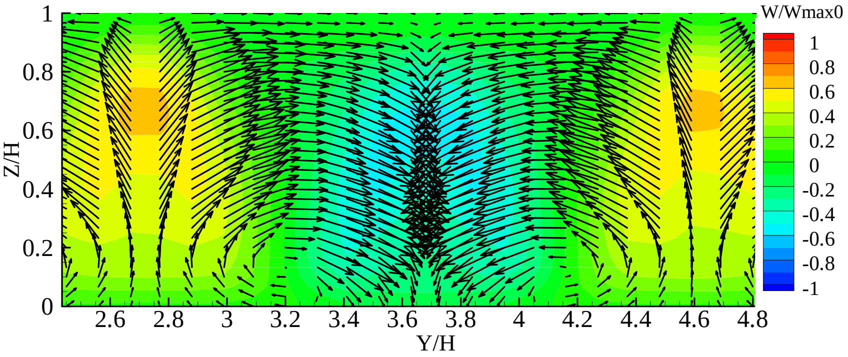

Figure 9 Flow field converted by the conventional data processing

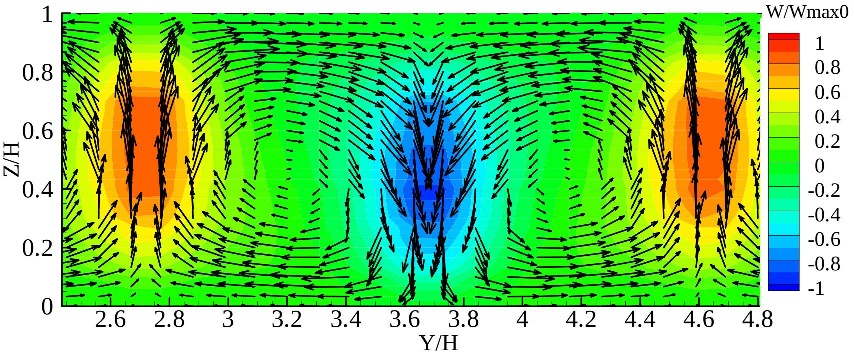

Figure 10 Flow field converted by the new data processing

Conclusion and recommendation

This paper has particularly explained the improvement of flow-observation techniques and observational accuracy, which comprise the very foundation of river training. Strategic, efficient river management requires not only the improvement of these fundamental factors but also the elevation of accuracy in simulation techniques for possible changes of river courses using obtained data. It is also necessary to have an integrated viewpoint of flood control and environmental conservation by strengthening the relationship between actual conditions and future predictions, so that it is possible to implement comprehensive river improvement based on reliable future predictions.

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