

# Stochastic Modeling to Prediction of River Morphological Changes

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## Abstract

In this paper, a new stochastic method for predicting of river morphological changes in the future is presented in the braided river. The model procedure is as follows: 1-It is to apply regression equation with bed height as a dependent parameter and three independent parameters of maximum daily flow, and its corresponding sediment discharge and bed slope, these equations were derived at certain points along the river cross-sections over a specific time. 2- By applying observed data, sediment rating curve equation as well as a relationship between slope, water and sediment discharge were derived. 3- Simulation of maximum monthly flow by ARIMA stochastic modeling. 4-By substituting values obtained from step 3 into 2 and 1, respectively, river bed height was predicted along the cross-sections. The values of the deepest bed height is selected maximum scour hole depth. Yahagi River in Japan was selected as a case study due to comprehensive and accessible data base. A comparison of observed data and predicted values indicate a reasonable agreement between them.

**Keywords:** ARIMA, Braided River, Non-Linear Regression, Scour Depth, Stochastic Modeling

## 1. Introduction

Prediction of future channel evolution has several practical implications because it may represent a key tool to guide management strategies. Many large rivers in the world have undergone through a great deal of morphological changes, which has led to the development of local scouring, and therefore, it has become an important problem for the river engineering. The change of river morphology from braided rivers to meandering river is along with the depth increase of local scouring<sup>1</sup>. The deepest bed height has a correlation with the mean bed height, standard deviation, skewness factor and flatness factor of the lateral distribution of river bed height. Prediction of bed height changes is a fundamental but problematic task. Braided rivers put an even more complex question, due to their multiple-thread pattern, intrinsic and unsteadiness spatial variability<sup>2</sup>. In the field of river morphology generally up to now the main focus was based on deterministic

concepts, but since the river system is of a dynamic and stochastic nature, therefore these could not predict the exact shape of the river bed, especially e.g. for braided rivers<sup>3</sup>.

River morphology is changing continually through time. Prediction of river's responses toward created changes is a difficult problem, because effective variants in this phenomenon are relative and respond to the changes in river system. Morphological river models are designed to provide physical insight toward the morphological responses and to assist river engineers and managers in the design, operation and maintenance of river systems.

Three modeling techniques have been analyzed with respect to their suitability for predicting plan form changes of braided rivers: a neural network, a cellular model<sup>4</sup> and an object-oriented approach<sup>5</sup>.

A comparison of the modeling approaches for meandering and braided rivers indicates that the modeling of braided river morphodynamics is still in its infancies. Generic process-based models form the basis for future models of braided rivers, however, restrictions

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in computational time, input data availability and process descriptions limit their suitability for such large scale applications today<sup>6</sup>. Based on a comparison of before no one can acquire the private keys of other users, the advantages and disadvantages of the various models, it has been concluded that the branches model is the most promising approach for the short-term development of a model for medium- to long-term predictions.

Most numerical models that are currently used in the field of river morphological changes are based on a deterministic modeling. In these models, morphological response is based on results, which all possible states that could have occurred or may occur in the future, are not considered<sup>7</sup>. Note that the river system is of a dynamic and stochastic nature therefore deterministic modeling is weak for a dynamic and stochastic nature river environment. Specially, these models could not predict the exact shape of the river bed, especially for braided rivers because the bed height variability and variations in cross-sectional<sup>3</sup>.

Prediction requires use of models (e.g. conceptual, physical, analytical or numerical models). Uncertainty associated with any kind of model and complexity of fluvial systems, specifically of braided rivers, are major issues to be taken into account. This means that we should be aware that prediction of channel morphology has inherent limitations since results of any model are affected by a degree of uncertainty and braided rivers are very complex systems that exhibit self-organized critical behavior. Two different modeling approaches were combined: (i) a conceptual model based on a historical analysis of channel changes over the last 200 years and controlling factors and (ii) numerical modeling, using a reduced complexity model (CAESAR). From this conceptual model different future trajectories could be derived, for instance more intense channel widening is predicted if an increase in magnitude and frequency of formative discharges is assumed. The numerical modeling, using constant conditions for flow regime and different conditions for sediment supply (i.e. scenarios), showed that channel widening will continue in the next decades, independently from sediment management strategies<sup>8</sup>. Braiding results from a fundamental instability of wide, shallow channels (the characteristic multi-channel planform only emerges during low flow). The interaction of morphological processes in a wide range of scales can be aggregated into six types of large-scale planform changes: channel migration, channel width change, mid-channel bar growth,

channel formation, channel abandonment and deformation of confluences and bifurcation. These processes are influenced by the often highly variable discharges in braided rivers, variations in vegetation, varying sediment composition, and tectonic and human influences.

It is very important to identify and recognize factors which affect the behavior and morphology of the rivers such as the form of river, waterway geometry, and the shape of the river bed, discharge and the profile of the river<sup>9</sup>. In this article, a new stochastic method is presented for predicting scour hole depth in the future. Since Process of the changes in river cross section are usually caused by change in water and sediment discharges or by river works. Moreover, river slope plays a key role in channel morphological changes therefore In this research, local scouring relationship with river morphological changes are investigated by stochastic modeling in braided rivers based upon for parameters such as maximum flow, sediment discharges, river bed slope river and bed height. The maximum annually flow, sediment discharge and river bed slope were taken as the input to the model.

The governing equations are regression equation of bed height (with three independent parameters of maximum annually flow, and sediment discharge and bed slope), sediment rating curve equation, slope equation (with two independent parameters of maximum monthly flow and sediment discharge), and simulation of maximum monthly flow by ARIMA stochastic modeling. While prediction of maximum monthly flow and bed height the next years are output of the model. The model was then tested by data obtained from Yonezu station of Yahagi River in Japan. A comparison of observed data and predicted values indicate a reasonable agreement between them.

## 2. Model Structure

### 2.1 General Processes

The following is model procedure:

- 1) Presentation of it is to apply multivariate regression equation based on bed height as a dependent parameter and three independent parameters of maximum daily flow, and its corresponding sediment discharge and bed slope.
- 2) Presentation of sediment rating curve equation and slope equation.

- 3) Prediction of simulation of daily maximum stream flow using Auto Regressive Integrated Moving Average stochastic modeling (ARIMA).
- 4) Prediction of cross-sections and scour hole depth.

## 2.2 Processes of Model Analysis

The first step is choosing some points with equal distances ( $\Delta y$ ) on the cross section that divide it to equal sections (the distance between  $j$  and  $j+1$  should be meters). Then in a specific time (Some years) choose one start and one end point for all the cross sections. In the last part of the first step, for each point related to the specific time a regression model with a dependent parameter bed height ( $Z_j$ ) and some independent parameters including the maximum daily flow ( $Q$ ), sediment ( $Q_s$ ) discharged bed ( $S$ ) slope as follow can be applied:

$$Z_j \propto (Q, Q_s, S) \quad (1)$$

For detecting the best model of river cross section prediction, in each point many linear and nonlinear regressions are applied. In prediction models coefficient value for  $p$  (p-value), coefficient of determination and squares sum of error is applied to evaluate models accuracy. In the second step, in order to estimate sediment transition in rivers, sediment rating curve equation is used.

$$Q_s = a Q^b \quad (2)$$

We use the equation to estimate the situation of sediment transition and its changes through section during the time in future. As a result sediment transition equation is calculated based on analyzing of maximum stream flow and maximum sediment discharge in a month. In the third step, the maximum stream flow can be predicted in a future year ( $t$ ) using ARIMA (Auto Regressive Integrated Moving Average). The results will be replaced in rating curve sediment and slope equations that are the results of second step. Finally we can calculate the independent parameters including river sediment discharge and river bed slope in year ( $t$ ). In the last step, maximum stream flow, maximum sediment and bed slope can be replaced in the chosen regression model related to each point ( $j$ ) from the first step. Calculating the bed height in each point ( $j$ ) leads to river

cross section prediction in year  $t$ . Finally in a predictable cross section, the minimum bed height can be introduced as a scour hole depth. Stochastic modeling flowchart is shown in Figure 1.

## 3. Application

### 3.1 Study Area

The modeling approach presented above was applied in the braided of the Yahagi river in Japan (Figure 2). The length of the river is 117 km, and the catchment area of the river is about 1.830 km<sup>2</sup>. The main sections of the river are following Yonezu, Kido, Miyai bashi, Iwazu and Takahashi that locate at 10, 13.5, 18, 29, 40 km upstream from the river mouth. The study area at this search is data of Yonezu section. Yonezu cross sections are shown in Figure 3.

### 3.2 Data Collection

The following is the data used in the study:

#### 3.2.1 Available Data

- A huge amount of data has been collected for the Yonezu section in the study area, amongst which:
- 1) cross-sectional profiles ( data available from 1965 to 2000)
  - 2) Rating curves (data available from 1965 to 1999)
  - 3) bed long profiles (data available from 1965 to 1999)
  - 4) grain size curves relate to years 1965,1983 and 2000
  - 5) Rating curves (data available from 1965 to 1999)

#### 3.2.2 Calculated Data

##### 3.2.2.1 Bed Load

Evaluation of sediment transport rate in fluvial systems is a fundamental but problematic task. Braided rivers put an even more complex question, due to their intrinsic unsteadiness and spatial variability<sup>2</sup>. Moreover, direct measurement of bed-load in a braided river is almost impossible because of the number and frequency of samples needed to represent the lateral and temporal variation Spatial and temporal patterns of sediment transport in braided streams are influenced by their hydraulics. Relatively small changes in flow hydraulics can initiate much larger changes in channel form and sediment transport. These pulses can be related to changes in channel morphology on a case-by-case basis, but it is more difficult to isolate general rules governing

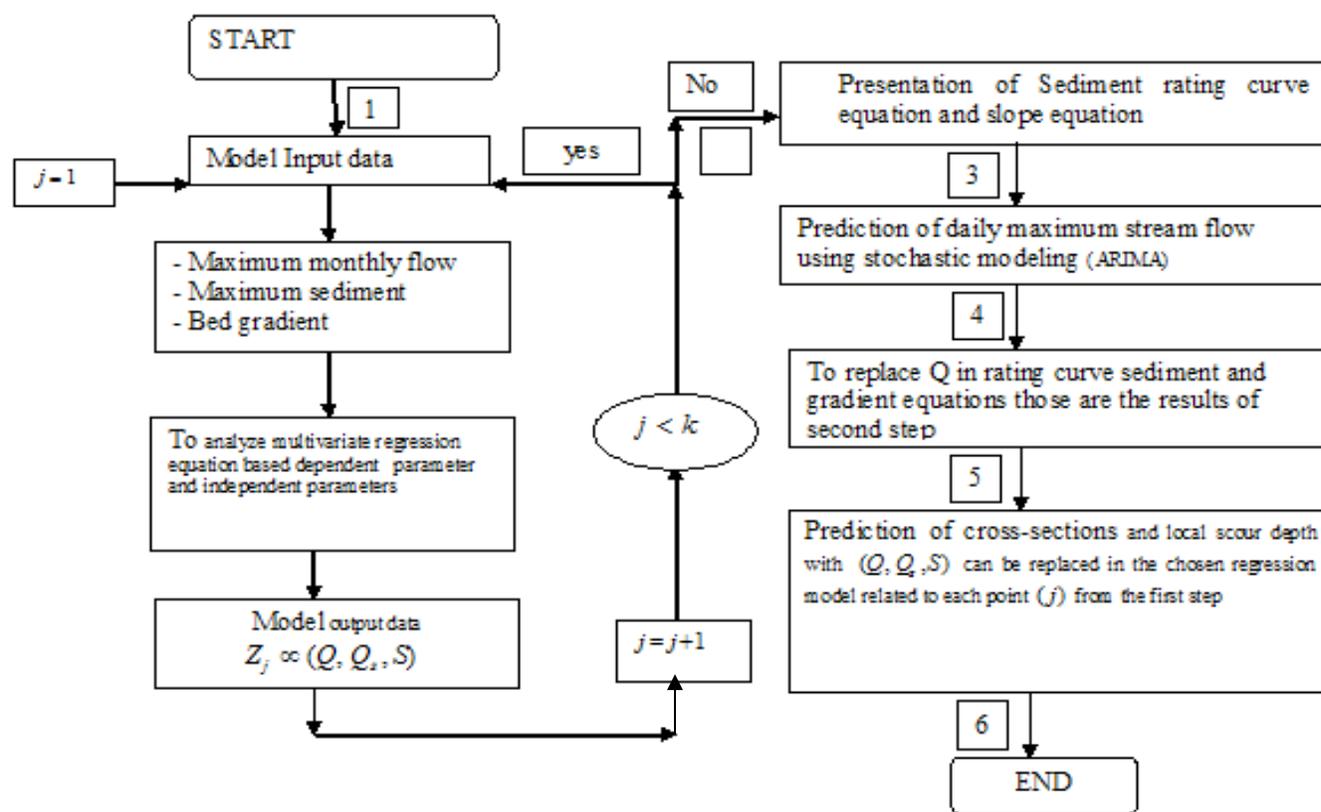


Figure 1. Stochastic modeling flowchart of bed level local scouring prediction.

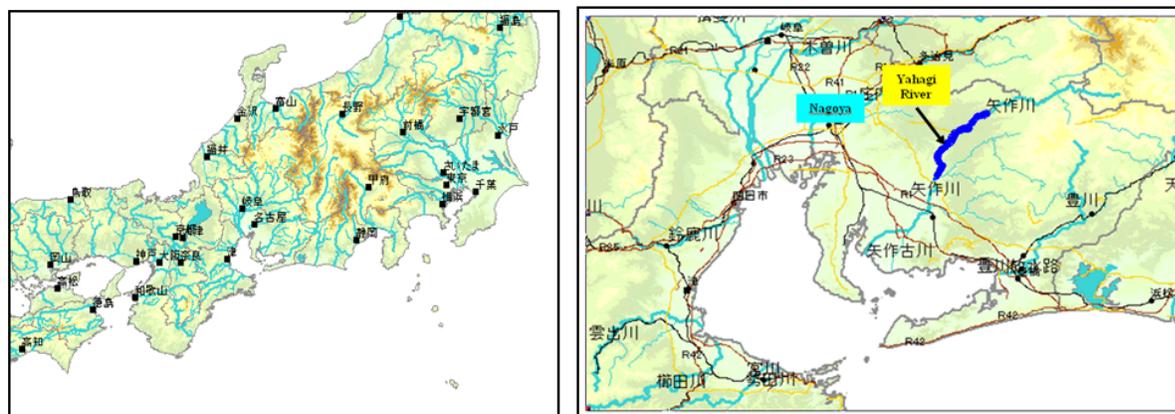


Figure 2. Showing the Yahagi River in Japan.

this behavior. For this reason, approaches which consider sediment transport as a stochastic phenomenon, rather than as a deterministic one, have proved successful in studies of braided streams. In braided rivers the bed load is dominant; therefore, parameter of sediment discharge, on the basis of the assumptions and the size of the sediments and flow conditions, three sediment transport equation were used to calculate the bed load such as Bagnold, Meyer-peter and Einstien Brown.

### 3.2.2.2 River Bed Slop

River bed slope is an important ingredient in morphological changes. In this research by taking hold of bed long profile, river bed slope is determined by dividing the bed height to the river length in both sides of the station ( $S = \Delta z / L$ ). In the equation,  $\Delta z$  is the height difference between the first and last part of the selected area (the area that contains Yonezu station)

and  $L$  is the length of that. For slope calculation, the length of river is chosen between (9 km-11 km) that means 1 km upper and 1 km lower than Yonezu station.

### 3.2.2.3 Rating Curve Discharge

When the rating curve discharge is known, the hydraulic geometry of a cross section analysis is easy if in each given discharge mean flow height from rating curve discharge and width, hydraulic radius section area of related profiles in cross section be calculated. This process can be repeated in discharges with different heights to find hydraulic geometry relations. If the rating curve discharge be known, hydraulic geometry of the cross section is easy because in each discharge, the mean flow depth can be calculated using rating curve discharge and width, hydraulic radius and area of cross section related to cross section profiles. This process can be repeated in different discharges and different bed heights to different hydraulic geometry equations.

### 3.2.2.4 Prediction of Simulation of Daily Maximum Stream Flow Using (ARIMA)

The morphological response statistics are the most sensitive to river discharge variation. River discharge is not constant and a function of time. The variation in the river discharge leads to a continuous adaptation of the river bed; therefore, the variability will always induce changes in the bed height. The height of the accretion peaks and the erosion peaks are discharge-dependent. Therefore, in order to a stochastic prediction the bed height variability (in space and time) is necessary, on the basis of the historical discharge data, the discharge time series in the future is predicted with the help of stochastic methods. Different discharge time series, which are equally likely to occur, yields a different morphological response. In order to analyze time series for monthly maximum data from linear stochastic models known as either Box-Jenkins or ARIMA (Autoregressive Integrated Moving Average) is used in stochastic modeling<sup>10</sup>. For fitting seasonal ARIMA model to the time series of monthly maximum stream flow data, three-stage procedure of model identification, estimation of model parameters and diagnostic checking of estimated parameters has been adopted. The steps of time series modeling from linear models can be summarized to first analysis, recognition and estimation of parameters, exam and choosing the best model.

In this research, 50 years statistics of maximum monthly flow in the Yonezu section are used for estimating model parameters and 7 years statistics are used for checking the accuracy.

## 3.3 Prediction of Cross-Sections and Scour Hole Depth

After the maximum stream flow discharge prediction by in year  $t$ , it can be replaced in rating curve sediment and slope equations resulted from step 2. As a result, sediment discharge and river bed slope independent parameters can be calculated in year  $t$ . using predictable parameters such as the maximum stream flow, the maximum sediment discharge and the bed slope and replacing them in a chosen regression model related to each point resulted from the first step, the bed height in each point and the river cross section in year  $t$  can be estimated. Then in the predicted cross section in year  $t$ , the minimum bed height is chosen as erosion pit depth that is predicted by a stochastically modeling in year  $t$ .

## 4. Results

### 4.1 The Result of Multi transitive Linear Regression Models

$$(Z_j \propto (Q, Q_s, S))$$

The result of multi transitive linear regression models related to braided rivers because of having multiple branches has a complex cross section. So, in each point we can't have one or a few regression models. In each in cross section more than 50 equations examined and between them the equation was chosen that had the minimum coefficient value of  $p$ , the maximum coefficient of determination and the minimum sum square of errors. Table1 shows the best regression models for bed height determination that have the maximum numbers and best evaluation factors for bed load estimation. The best regression models are related to  $j$  points that have minimum different in bed height. Because of complex cross section in braided rivers, the regression model has a special order in all ascendant, decreasing and almost normal cross sections.

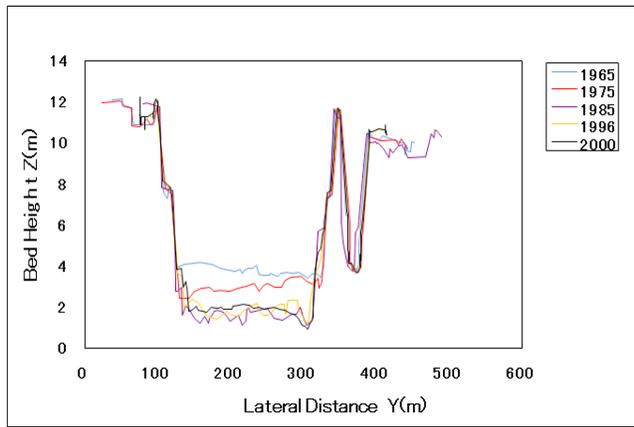


Figure 3. Showing the cross sections at Yonezu section.

mean shear stress, surface water slope, stream power and water flow area unit power, sediment discharge always is a dependent variable under stream unit power control. This relation is not only true in straight rivers, but also is correct in the rivers that change their plan patterns from direct to meander and braided modes. As a result, the Bagnold equation because of using unit stream power, presents the best regression models. Based on the fact that the median sediment diameter in the study area in different years is between (1.6 – 2.1) mm, so based on sorting criteria for sediment size proposed by<sup>11-13</sup> it is in the category of large and very large sands. For bed load determination, using (Mere-peter) equation that is based on experimental results and is calculated with medium size segments

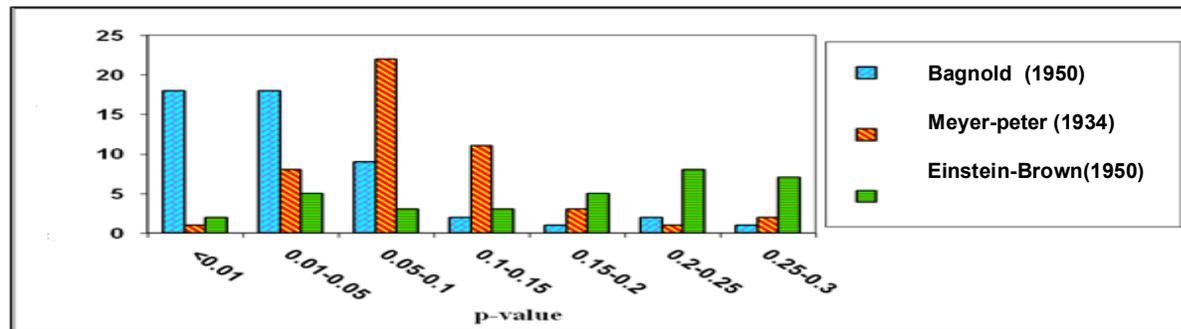


Figure 4. Showing the relation between the numbers of acceptable regression P-value based on the sensitivity of sediment transport equation in the study area section.

Table 1. Bed height regression models based on maximum flow, sediment discharge and slope Parameters using Sensitivity analysis

Bagnold (1950)	Meyer-peter (1934)	Einstein-Brown (1950)	sediment equation
$z = a + b(\frac{Q}{Q_0}) + cS$	$z = 10^a Q^b Q_0^c S^d$	$z = a + b(Q, Q_0, S)$	$z = 10^a (Q, Q_0, S)^b$
a Positive b Positive c negative	a negative b Positive c negative	a Positive b Positive	a Positive b Positiv
	a Positive b negative c negative		
			<b>Positive and negative Coefficient regression model</b>

In Figure 4, the influence of analyzing sediment estimation equation sensitivity on bed height determination regression models shows that the best regression models are in orders based on using Bagnold equation Meyer-peter equation and Einstein-Brown Equation. The reason is that in the relation between sediment discharge, water flow discharge, mean velocity,

(3 – 6.28) mm, comparing with Bagnold equation less equations with lower statistical characters and less accuracy. In the following, the number of chosen regression models that have used Einstein-Brown equation for bed load sediment transport is low in other hand they have high p-values that shows these models are acceptable with low probability. The other hand, the model has low values

for coefficient correlation and high values for square sum of errors that shows there isn't a meaningful relation between dependent and independent variables. It is because of not using this equation for bed load estimation in bed rivers with sandy materials and also not using surface sediments with medium diameters instead of sub pavement with normal diameters that both are recognized in this research.

### 4.2 Rating Curves

Table 2 demonstrate the results related to Bagnold, Meyer-peter and Einstein-Brown equations. There isn't a meaningful relation between steam flow discharge and sediment discharge because of using maximum values and choosing the values from different years. The following non-parametric test (Mann-Kendall) can be applied

**Table 2.** Equations for bed load estimation

$R^2$	Regression equation	Sediment equation
0.6329	$y = 0.025 x^{1.1071}$	Bagnold
0.5867	$y = 0.0085 x^{1.3067}$	Meyer-peter
0.621	$y = 8E - 06 x^{2.871}$	Einstein-Brown

In Table 3, based on the equation used for bed load estimation, the best slope models are explained. The p-value shows that with 95% certainty, all the three models are acceptable.  $R^2$  and SSE values represent high correlation between stream flow and sediment discharge. to decide whether trend exists in the monthly maximum data.

**Table 3.** Showing river bed slope regime in Yonezu staion

SSE	$R^2$	p-value	slope equation	Sediment equation
0.0001422	0.873	0.045	$S = 0.213 \left( \frac{Q}{Q_s} \right)^{-0.388}$	Bagnold
0.0009663	0.816	0.014	$S = 0.157 \left( \frac{Q}{Q_s} \right)^{-0.32}$	Meyer-peter
0.00085	0.984	0.002	$S = 0.312 (Q)^{-0.515} (Q_s)^{0.249}$	Einstein-Brown

### 4.3 Prediction of Monthly Maximum Stream Flow

The first step includes normalization and stability of time series Box and Cox conversion and choosing  $\lambda = -0.16$  that leads variance calculation.

The test statistic showed that within the 5% significance interval, the hypothesis cannot be rejected. So, seasonal differentials are not necessary in the model. Because the modeling is in monthly scale, the alternative mode in statistical equations such as mean and variance is obvious. For suitable omit of the unstable operative, seasonal subtraction can be used. The result is time series modeling of maximum monthly flow

$ARIMA(p,0,q)(P,1,Q)_{12}$  models. For identifying the best model, all models should be examined. In this

research, all  $ARIMA(p,0,q)(P,1,Q)_{12}$  models with different self returnable heights and seasonal or nonseasonal slope mean ( $P, Q, p, q = 0, 1, 2, 3$ ) are evaluated using MNITAB 15 software (totally 35 models). Finally from all the models passed parameters sensibility test, type selection test and independent of residuals test, because of parsimony in parameters  $ARIMA(1,0,1)(0,1,1)_{12}$

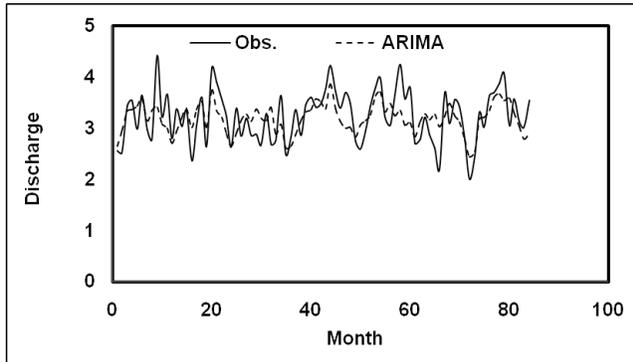
model that has the minimum AIC (Akaike Information Criterion) and SBC (Schwartz Bayesian Criterion) is chosen for the maximum monthly flow time series modeling. For certainty about the chosen model the maximum monthly flow time series values in validation period, together in a month evaluated using error evaluation standards including MSE, RMSE, SSE, MAE, and MAPE.

Finally  $ARIMA(1,0,1)(0,1,1)_{12}$  was the best model.

Figure 4, shows the relationship between 2000-2007 years of monthly data at Yonezo gauge station and predicted data for the same years by using the best models from ARIMA for each gauge station.

It is obvious that except a few occasions, predicted values are close to the maximum monthly values observed in Yonezo station that proofs models suitability. In fact, hydrologic phenomenas of time series models are stochastically and performing accurate values is difficult.

Comparison of observed data to predicted data using are presented in Figure 5.

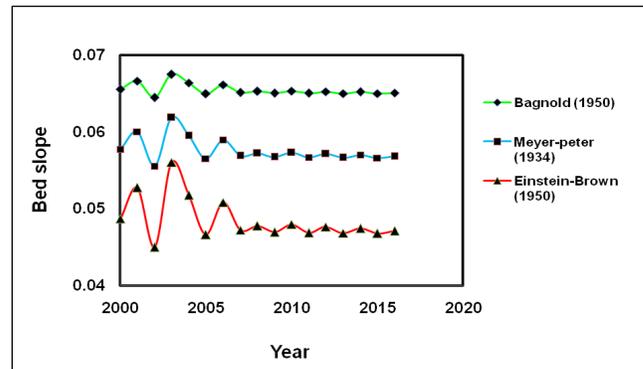
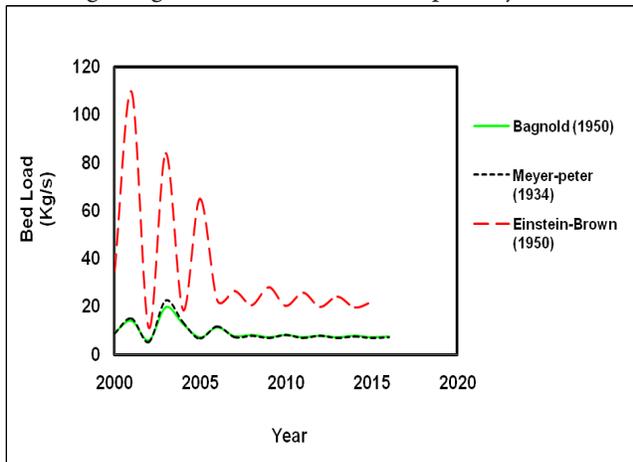


**Figure 5.** Comparison of observed data to predicted data.

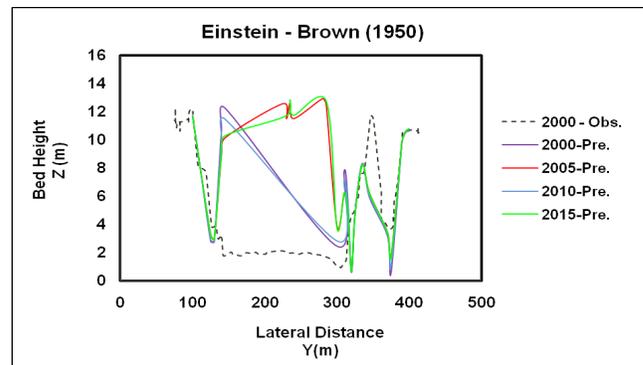
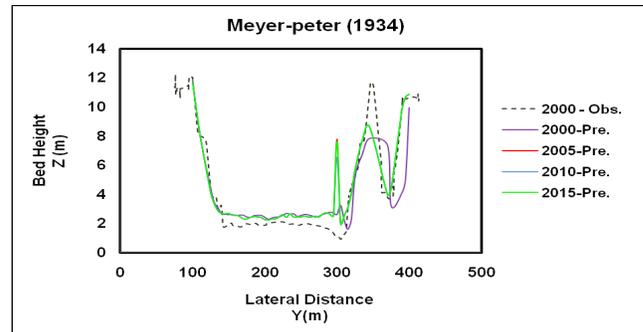
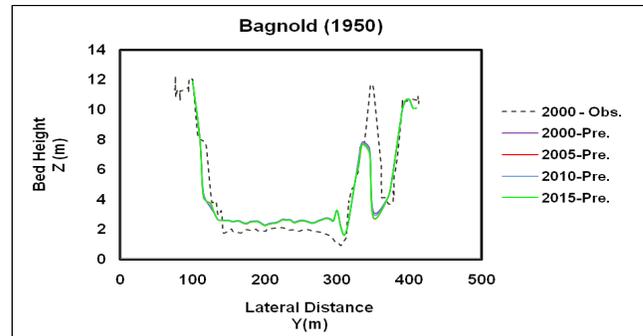
Comparison of observed data to predicted data using are presented in Figure 5.

Maximum stream flow prediction based on  $ARIMA (1,0,1)(0,1,1)_{12}$  model leads to Maximum

bed load and slope prediction using calculated sediment estimation and slope equation. In Figure 6, regarding to equal flow discharge values, predicted bed load and slope calculated with Einstein-Brown estimating calculation comparing with Bagnold and Meyer-peter equation has more variation. The main reason can be more than enough estimation of load using Einstein-Brown equation. In both above figure, because of low difference between predicted values of maximum stream flow discharge after 2007, bed load and slope values have low difference. Using the maximum stream flow, slope and sediment predicted values related to each year in future, we can calculate the predicted cross section of the year in bed height regression models for each point (j).



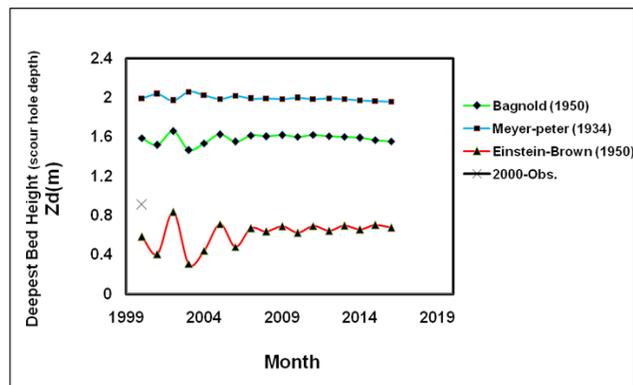
**Figure 6.** Sensitivity analysis of a) maximum bed load and b) bed slope values predicted using Three methods Bagnold (1950), Meyer-peter (1934) and Einstein-Brown (1950).



**Figure 7.** Sensitivity analysis of cross section in Yonezo station using three methods Bagnold (1950), Meyer-peter (1934) and Einstein-Brown (1950).

Comparison between predicted cross section using stochastically model in Figure 7 shows if we use Bagnold and Meer-Peer equation or bed load estimation, the results are more acceptable than using Einstein-brown equation. It can be because of a few number of cross section points (j) that have the best bed height regression equations.

In (Figure 8), the minimum predicted bed height values comparing with the real values in year 2000 are more but the values have a decreasing procedure that this decreasing progress of deepest bed height values is obvious with predicted deepest bed height using method Bagnold and Meer-Peer equation, so by decreasing the minimum predicted bed height, the deformation process from braided to meander will be continued.



**Figure 8.** Sensitivity analysis of Scour hole depth in Yonezo station using three methods. Bagnold (1950), Meyer-peter (1934) and Einstein-Brown (1950).

## 5. Conclusion

The stochastic deepest bed height prediction model based on river morphology changes in a braided rivers shows that in a specific time period (2000-2008) a decreasing procedure is occurred, therefore, the river morphology change from braided to meander continues and the change is obvious while using Bagnold and Meyer-peter methods for bed height estimation. The sensibility analysis of sediment transport analysis in stochastic model proofs using Bagnold equation for bed load estimation leads to more acceptable results. From year 2008 to 2016 because of decreasing the maximum predicted discharge, the river tendency for river morphology changes decrease but by decreasing the minimum predicted bed height, the deformation process from braided to meander will be continued.

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