# Dimensionless width and depth and sediment transport rate in stable rivers

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## Abstract

The author, using data from Japan's natural River in the1880's, natural rivers in Canada, and basic policy channels for river improvement of Class A Japanese rivers, demonstrates that a dynamic relation equation between a river's dimensionless width, dimensionless depth, and dimensionless channel-forming discharge obtained with dimensional analysis using flood flow and channel properties in the river basin is a guideline for river management that is sound in terms of both flood control and environmental considerations; that the dimensionless bed load equation is determined within the dynamic relations in which stable dimensionless river width and dimensionless depth, etc., are determined; and that these relation equations play an important role in close-to-nature river management that achieves harmony between flood control and the environment.

## 1. Introduction

A river is a natural object in which natural phenomenon occur and therefore requires proper maintenance in order to carry out the functions desired of it. This paper will consider, from a goal of managing rivers comprehensively in terms of flood control, water utilization, and the environment, how a river as a natural object should be viewed and managed, how to minimize the flooding damage feared from global warming, and how to resolve the issues of river planning in properly implementing river management.

River width and surface width are particularly important aspects of a river's cross-sectional form: these control flood flows, including sediment transport at the river bed. Despite the dynamic and topographic means by which river width, water surface width, depth, and other river cross-section variables are determined being fundamental issues in river studies and river engineering, the author knows of almost no research that addresses river channel formation dynamically and systematically[1)]. Instead, domestic and foreign river engineering research in general discusses flood flows, sediment transport, and other hydraulic phenomena with river width treated as a given.

Ikeda et al. have proposed an expression for determining channel width and depth that is based on hydraulic considerations, but it cannot account for broadly changing flood flows and river conditions[2)].

Numerous empirically derived regime theories have been published on the stable channel cross-sectional forms of irrigation channels and alluvial rivers. However, equations derived from regime theories have inadequate dynamic consideration and are empirical with no general applicability. Yamamoto, assuming the channel-forming discharge in a Japanese alluvial river to be mean annual maximum discharge, has considered main channel width, river cross-sectional area, and velocity using national river survey data[3)] However, the Yamamoto equation cannot represent dimension properly. Theses reflect that when discussing channel scale and bed stability, external forces and the responses to them must be discussed in terms of dimensionless external forces and dimensionless river width, for instance. In addition, although relatively small scales of external force such as annual mean maximum discharge are used as the main channel's channel-forming discharge , in view of the coming increase in flood discharges, channel-forming discharges that determine the entire river width and entire cross-sectional area must be discussed in the context of river management, rather than just the channel-forming discharge determining the main channel's width.

The transport of water and sediment in a channel involves many phenomena relating to flood control, water utilization, and the environment, and is the foundation of river planning. The workings of sediment transport during flooding is far less understood compared to flood flows because of the relative difficulty of measuring it, necessitating the use of sediment discharge equations to estimate the amount of sediment transported. Current sediment discharge equations do not account for river width. As stated above, river width is the most important determinant of flood flow and sediment discharge in a river. Furthermore, current sediment discharge equations are woefully imprecise for rivers with complex channel topography. This has resulted in a lag in technically addressing sediment transport in the context of preventing river disasters and protecting riverine environments, calling for efforts to develop, from a new perspective, a method for estimating sediment transport. One effective method of estimating is to utilize the fact that sediment transport volume is determined by the same mechanism—discussed later—that determines river width and cross-sectional form.

## 2. Learning from Nature: Close-to-Nature River Development and Maintenance from a Basin-Wide Perspective

In principle, river development and management should be based on the concept of "close to nature". Thus , close-to-nature river development means managing rivers in such a way as to achieve harmony between flood control and the environment, taking the river's natural functions into account. Current close-to-river development, however, does not achieve harmony between the environment and flood control based on the realities of flooding. Although research inside and outside of Japan in recent years has studied rivers' natural flow regimes and the effects of flood discharge change on ecosystems, true close-to-nature river development cannot be said to be in place without a discussion of near-natural river width and cross-sectional form and design discharge from a basin-wide perspective.

Achieving a river channel in harmony with flood control and the environment requires placing at the forefront the issue of river width, water depth, and cross-sectional form. Such a channel cross-section should be close to that of a natural river. The characteristics of a river made by nature are evident in such aspects as planform, profile, and cross-sectional form; river width and cross-sectional form are determined by nature's laws of dynamics. When considering, for instance, what channel cross-section would be stable and achieve harmony between flood control and the environment, it is therefore important to keep in mind the structure of natural rivers and consider the current structure of a river being impacted by human activity. Such an approach can also lead to river design and management techniques that are widely applicable for a broad range of channel and flood scales.

In the next section, in the context of close-to-nature river development from a river basin perspective, I discuss, using findings from studies of natural Japanese and foreign rivers, the dynamic relationship between flood flows and channel characteristic quantities in a river basin that determine the important close-to-nature river parameters of river width, water surface width, water depth, and cross-sectional form[1)].

## 3. Dimensionless Channel-Forming Discharge that Determines Dimensionless River Width and Dimensionless Water Depth

River width, water depth, and other aspects of a river's cross-sectional form are thought to be a product of the effects of the external factors of channel-forming discharge, river basin topography and geology, channel slope, and bed material (size distribution) experienced over the course of countless large floods over the river's history (Figure 1).

A channel's cross-sectional form and water surface width can be considered essentially dynamically stable toward flood flows below the channel-forming discharges that created the river as it exists today. Here, a dynamically stable channel is defined as one that returns to its original stable state even after changes caused by the external forces of flooding. Once it becomes stable, a channel's cross-sectional form remains in equilibrium even as it changes and fluctuates because of the interaction between floods, the channel's planform and longitudinal and cross-sectional form, and sediment transport, as indicated by the arrows in Figure 1. Normal bed change is a phenomenon that results from this interaction.

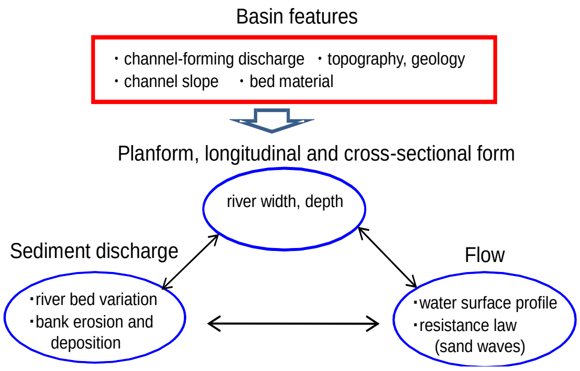


Figure 1 Dynamic relation of stabe channel formation

Before achieving this stability, the channel cross-sectional form changes because of the interdependence between river width, water depth, discharge, slope, and bed material size, but these parameters become mutually independent once channel-forming discharge results in stability. Furthermore, the effects of geology and topography on channel formation can, except in special circumstances, be represented as bed material size and bed slope.

When a channel's cross-sectional form is represented with river width and water depth, stable cross-sectional form is determined by eight physical quantities, including channel-forming discharge, bed slope, and bed material properties, as follows:

$$f(Q, B, h, I, d_r, g, \rho, \sigma) = 0 \tag{1}$$

where $Q$ = discharge, $B$ = river width, $h$ = water depth, $I$ = riverbed slope, $d_r$ = representative diameter, $g$ = gravitational acceleration, $\rho$ = water density, and $\sigma$ = bed material density. Using the $\pi$ theorem, we derive the following dimensionless relationship:

$$\phi\left(\frac{Q}{\sqrt{gId_r^{\,5}}}, \frac{B}{d_r}, \frac{h}{d_r}, I, \frac{\sigma}{\rho}\right) = 0 \tag{2}$$

The first term is dimensionless discharge, which indicates the state of the flood; the second is dimensionless river width; and the third dimensionless water depth. For the representative material diameter $d_r$, I used 60% ($d_{60}$) in this research. Thus, nondimensionalization allows a dynamically standardized explanation of stable channel cross-section regardless of the scale of the channel or of the flooding. This is discussed in greater detail in the next section.

## 4. The Relationship among Dimensionless River Width, Water Depth, and Channel-Forming Discharge in a Natural River

Let us first consider the relationship among dimensionless river width, water depth, and channel-forming discharge (equation 2) in light of data from Japanese and Canadian natural rivers and data on channel-forming discharge from channel-widening experiments conducted in the field and in the laboratory.

For the Japanese natural river, I used flood flow data from channel sections in the upper and middle reaches of the Tone River in the Meiji Period (1868–1912).[4)] Figure 2 is a rapid survey map of the river's upper reaches obtained from surveying done in 1884. The Tone River channel of that time retained the cross-section it had in the preceding Edo Period (1603–1868) and, having only discontinuous levees (where any were present), was essentially in its natural state, with overtopping from the channel occurring during floods. Dashed lines in the figure indicate the channel as of 1885,

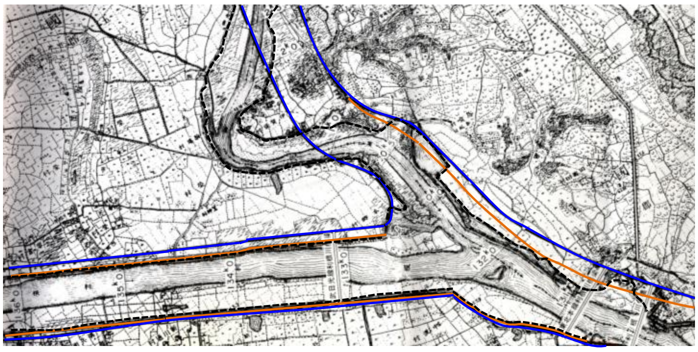

Figure 2 Upper reach Tone river by 1884 surveying (rapid survey map)

Table. 1 Flood discharge and probability scale in the Meiji period (1868-1912)

| Year | Discharge($m^3/s$) | Reference point | Probability scale |
|---|---|---|---|
| 1895 | 3780 | Menuma | 2-3 years |
| 1898 | 3750 | Menuma | 2-3 years |
| 1910 | | | |
| 1911 | | | |

Fig. 4 Correlation of dimensionless water surface width and water depth to dimensionless channel-forming discharge

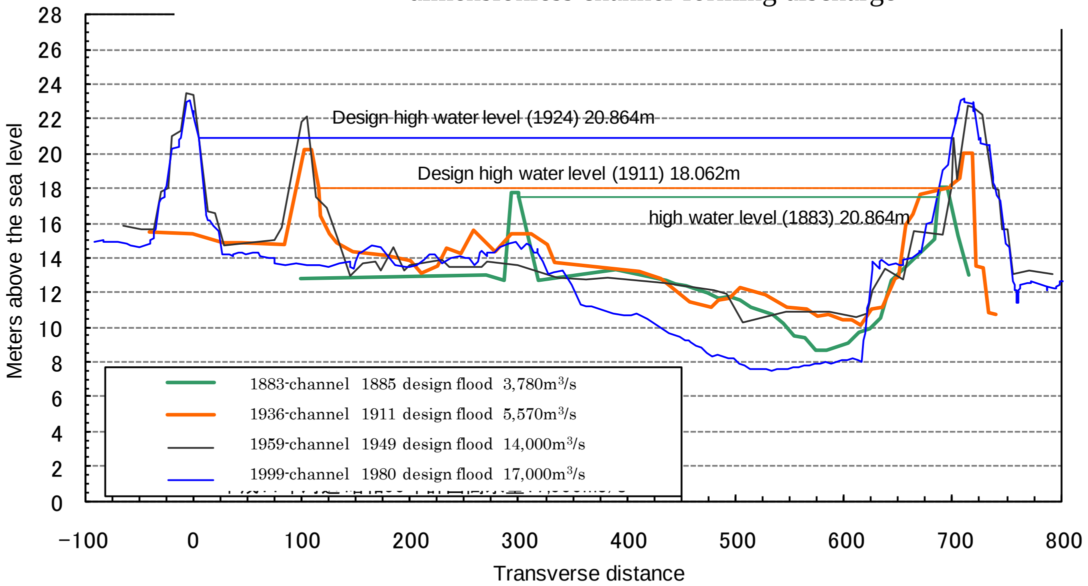


Figure 3 Channel cross-sections at Kurihashi point in each flood year[4)]

Table-2 Data used for the investigation

| | d (mm) | B (m) | h (m) | Q ($m^3/s$) | 1/I |
|---|---|---|---|---|---|
| Tone river in Meiji period | 0.3~40.0 | 340~840 | 4.0~6.6 | 2240~6960 | 470~5000 |
| Natural river in Alberta | 19.0~145.0 | 14~545 | 0.4~6.9 | 6~8212 | 67~4545 |
| Joganji river field experiment | 80~125 | 7.8~9.6 | 0.5~1.2 | 3.2~14.4 | 130 |
| Channel-widning experiment[23)] | 0.83 | 0.84 | 0.02 | 0.0048 | 60 |
| Channel-widning experiment[24)] | 0.67 | 0.34 | 0.02 | 0.002 | 400 |

the orange lines the planned channel in 1891, and the solid blue line the planned channel alignment in 1948. The river experienced large floods in 1885, 1898, 1910, and 1911; Table 1 lists each flood's discharge and probability scale. During the Meiji Period, the 2- to 10-year probability discharges were roughly equivalent to the design scale discharge, indicating a discharge that formed the main channel of the time. Figure 3 is channel cross-section at the Kurihashi Point on the Tone River in each flood year. Bed slope and representative bed material size at that point is assumed to be unchanged today from the Meiji Period, and so the current channel's slope and bed material representative size are used.

As the foreign natural rivers, let us consider 67 river data from Bray et al. for rivers in Canada's Alberta Province.[5),6)] These natural rivers are comprised of a floodplain and a main channel, which is said to be formed by the 2-year probable discharge, i.e., the main channel bankfull discharge. This

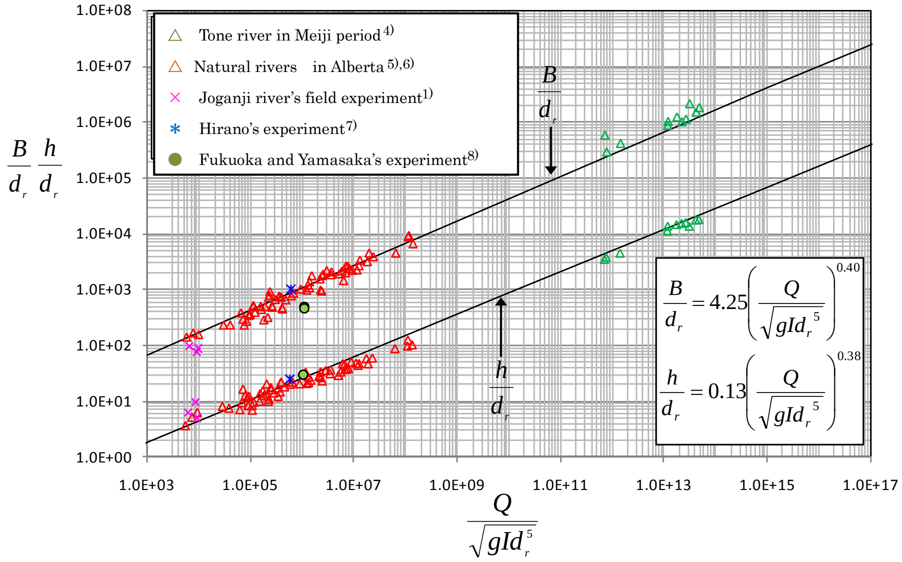


Figure 4 Correlation of dimensionless water surface width and water depth to dimensionless channel-forming discharge

work also uses the 2-year probable discharge. For details on the data, see references 5 and 6. The data used are listed in Table 2. Table 2, in addition to data on the Tone River and Canada's natural rivers, also gives the results of three experiments: one by the author and others with a large, stony-bed compound waterway (length 190 m, total width 8 m, main channel width 3 m, water surface slope 1:130, representative bed material size 8 cm) built in the bed of the Joganji River[1)] and having straight and meandering sections, and channel-widening experiments conducted by Hirano[7)] and by Fukuoka and Yamasaka[8)] with straight channels.

Figure 4 plots the correlation of dimensionless water surface width and water depth to dimensionless channel-forming discharge in the Meiji Period Tone River, Canadian natural rivers, and river-widening experiments in actual and experimental waterways. As the figure shows, within the broad dimensionless range of dimensionless river width and water depth ($10^2$–$10^6$ and $10^0$–$10^4$, respectively) on the vertical axis and dimensionless discharge ($10^3$–$10^{14}$) on the horizontal axis, these variables are determined by dimensionless channel-forming discharge, which in turn is determined by the combination of channel-forming discharge, bed slope, and representative bed material size, and can be represented with equations (3) and (4), the results of which are indicated by straight lines in the figure.

$$\frac{B}{d_r} = 4.25\left(\frac{Q}{\sqrt{gId_r^{\,5}}}\right)^{0.40} \tag{3}$$

$$\frac{h}{d_r} = 0.13\left(\frac{Q}{\sqrt{gId_r^{\,5}}}\right)^{0.38} \tag{4}$$

Equations (3) and (4) are called "Fukuoka equations", hereafter. This indicates that the dimensionless width and water depth of a stable channel are governed by dimensionless channel-forming discharge $Q/\sqrt{gId_r^{\,5}}$ as represented with channel-forming discharge, bed slope, and representative bed material size.

## 5. The Relationship among Dimensionless River Width, Water Depth, and Channel-Forming Discharge at Japanese Class A River Reference Point

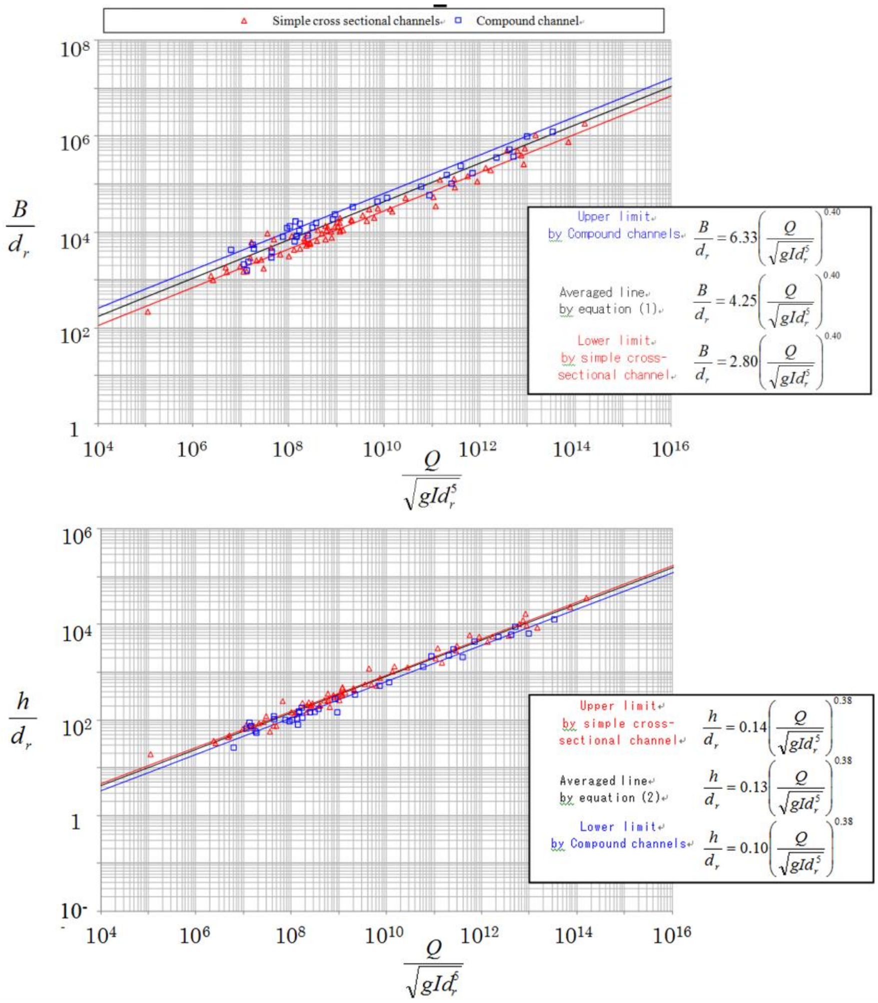


Figure 5: Relationship of dimensionless width and depth in design level of Japanese rivers

Next let us see whether the correlation among dimensionless river width, water depth, and discharge in equations (3) and (4) that holds for natural rivers also holds for flooding at a reference point along a Class A Japanese river. Reference points are important locations for devising high- and low-water plans of Class A Japanese rivers. In the case of a Class A river, various data are collected at references points over a long period, including discharge and water level hydrographs of flood flows, channel cross-sectional form, and bed material size distribution. For bed slope, mean bed slope at the reference point is used. For sections where the bed is nearly flat, such as at the mouth, water surface slope is used instead of bed slope.

The basic policy channel for river improvement is the river planned so as to carry the design high-water discharge below the design high-water level. Cross-sectional area, water surface width, and water depth in the basic policy channel are determined from the design high-water level profile, i.e., the profile at design high-water discharge. Equations (3) and (4) are applied for the design high-water discharge passing each reference point of basic policy channels for river improvement of 109 Class A river systems.  Mean depth is used for the water depth of channels with a compound form.[1)]

Figure 5 shows the correlation of the dimensionless values for discharge to river width and water depth. However, the correlation between the data is not as strong as with the Tone River or the Alberta natural rivers. This is because while reference points on Class A Japanese rivers represent a variety of topographical conditions—e.g., delta marshes, lowlands, and mountainous region. Furthermore, cross-sectional shape (i.e., simple or compound cross-section) is not accounted for in the calculation of dimensionless river width and water depth. In the figure, most of the compound cross-section channels are found above the approximation curve for dimensionless river width, while most simple cross-section channels are found below the curve. Conversely, compound cross-section channels are found below the dimensionless water depth curve and simple cross-section channels above it. Respective approximate equations for the compound channel and the simple cross-sectional channel are shown in figure 5[1].

From the above discussion, it is highly significant that Fukuoka equations hold similarly for floods and channels for a wide range of sizes, including many natural rivers and Japan's basic policy channels for river improvement.

## 6. Calculating Dimensionless Bed Load Transport Rate and Designing Channel Cross-Sections for Sustainable Sediment Transport

This section discusses a method estimating the bed load transport rate as a dynamic phenomenon determined within the stable channel cross-section, that is based on an approach unlike previous ones, and accounts for the mechanism (discussed in the previous section) that determines river width and other stable cross-section parameters. Bed load transport rate is a quantity determined by there being a fixed cross-sectional form and so was not incorporated into equation (1) as an independent quantity for determining river width, water depth, and cross-section. Of course, bed load transport rate is closely involved in the process by which the stable cross-section is created, as large amounts of sediment are transported into the river from the river basin. Once the channel stabilizes, however, bed load transport rate becomes a dependent variable of cross-sectional form and the parameters that determine it.

Thus bed load transport rate is determined by the dynamic interrelation between mutually independent quantities that form the stable channel cross-section, and so it can be calculated from the interrelations in equation (5):

$$Q_B = f\left(Q, B, h, I, d_r, g, \rho, \sigma\right) \tag{5}$$

where $Q_B$ is bed load transport rate. Applying the dimensional analysis, we derive the dimensionless interrelationship of equation (6):

$$\frac{Q_B}{\sqrt{sgId_r{}^5}} = \phi\left(\frac{Q}{\sqrt{gId_r{}^5}}, \frac{B}{d_r}, \frac{h}{d_r}, I, \frac{\sigma}{\rho}\right) \tag{6}$$

as $s = (\sigma - \rho)/\rho$. Equation (6) accounts only for bed load transport, not for suspended sediment, which is strongly affected by factors such as bank erosion and sediment yield in the mountain area. Because the 2nd and 3rd terms on the right side of equation (6) can be represented as the dimensionless form of the 1st term on the right side of equations (3) and (4), equation (6) can be rewritten as follows:

$$\frac{Q_B}{\sqrt{sgId_r{}^5}} = \phi\left(\frac{Q}{\sqrt{gId_r{}^5}}, I\right) \tag{7}$$

The bed load data used to derive the functional relationship of equation (7) is listed in Tables 3 through 5. The variable $d_m$ in the tables represents mean grain diameter and here is used as $d_r$. Except for data from Japan's Civil Engineering Research Institute for Cold Region, all of the data are direct measurements made with bed load transport measurement instruments. Table 3 contains 50 data points collected by Nakato for America's Mississippi River[9)10)]. Of the bed load data in Table 4, which Williams et al.[11)] collated from U.S. Geological Survey data collected with a Helley-Smith bed load sampler, we used 127 data that were usable with equation (7). Table 5a contains data obtained with a large-scale experimental waterway (length114m, width 1.76m, 0.78m) at Japan's Public Works Research Institute (PWRI)[12)] while Table 6b gives bed load data from a large-scale experimental waterway (length 24m, width 1.0m) at the Civil Engineering Research Institute for Cold Region

Table-3. Bed load data measured in the Mississippi river[9)10)]

| River | d (mm) | B (m) | h (m) | Q ($m^3$/s) | 1/I | $Q_B$ ($m^3$/s) |
|---|---|---|---|---|---|---|
| Mississippi R. | 0.25~0.85 | 86~880 | 1.4~7.0 | 46~4500 | 1400~5500000 | $4.37\times10^{-7}$~$2.15\times10^{-2}$ |

Table-4. Bed load data of USGS[11)]

| river | $d_m$ (mm) | B (m) | h (m) | Q ($m^3$/s) | 1/I | $Q_B$ ($m^3$/s) |
|---|---|---|---|---|---|---|
| Tanana River at Fairbanks | 40 | 107~469 | 1.4~2.9 | 345~2020 | 1900~2400 | $2.3\times10^{-4}$~$3.4\times10^{-2}$ |
| Wisconsin River at Muscoda | 0.5 | 219~310 | 0.7~3.4 | 87~1240 | 1900~4500 | $4.0\times10^{-4}$~$1.8\times10^{-2}$ |
| Black River near Galesville | 0.6 | 72~122 | 0.55~1.9 | 13~256 | 2800~9000 | $7.1\times10^{-5}$~$1.5\times10^{-3}$ |
| Chippewa River near Caryville | 8.0 | 124~247 | 0.89~2.8 | 31~779 | 4000~11000 | $2.0\times10^{-5}$~$5.1\times10^{-3}$ |
| Chippewa River at Durand | 0.8 | 153~244 | 0.61~3.2 | 51~884 | 2800~4300 | $2.2\times10^{-4}$~$1.1\times10^{-2}$ |
| Chippewa River near Pepin | 0.5 | 171~277 | 0.75~1.8 | 70~399 | 1700~5900 | $6.4\times10^{-4}$~$5.5\times10^{-3}$ |

Table-5. Bed load data obtained by large-scale model tests

(a)Experimental data by Public Works Research Institute[12)]

| | $d_m$(mm) | h(cm) | Q (l/s) | 1/I | $Q_B$ ($m^3$/s) |
|---|---|---|---|---|---|
| 36 | 1.038 | 19.3～43.7 | 43～200 | 613~4545 | 0.10~25.25 |
| 64 | 2.21 | 11.4～51.5 | 28～350 | 63~1538 | 0.01~66.94 |
| 63 | 2.62 | 19.6～51.3 | 90～325 | 340~1667 | 0.21~54.31 |
| 52 | 3.76 | 18.1～51.8 | 80~400 | 352~1111 | 0.22~57.66 |
| 31 | 4.58 | 19.4～42.3 | 80~350 | 431~800 | 0.39~18.97 |
| 21 | 10.0 | 21.0～50.5 | 395~1443 | 172~245 | 0.80~192.80 |
| 14 | 18.1 | 23.1～50.2 | 540~1630 | 133~183 | 1.53~270.31 |

(b) Experiment by Civil enfineering Research Institute for Cold Region[13)]

| | $d_m$(mm) | h(cm) | Q (l/s) | 1/I | $Q_B$ ($m^3$/s) |
|---|---|---|---|---|---|
| Run 1 | 28 | 57.1 | 1000 | 214 | 165.49 |
| Run 2 | 27.6 | 55.3 | 1000 | 214 | 386.21 |
| Run 3 | 22 | 59.3 | 1000 | 214 | 230.52 |
| Run 4 | 23.3 | 56.8 | 1000 | 214 | 183.60 |
| Run 5 | 28.4 | 59.2 | 1000 | 214 | 325.10 |
| Run 6 | 24.6 | 58.6 | 1000 | 214 | 83.87 |
| Run 7 | 11.3 | 65.2 | 1500 | 214 | 610.31 |
| Run 8 | 30.3 | 64.2 | 1500 | 214 | 616.21 |

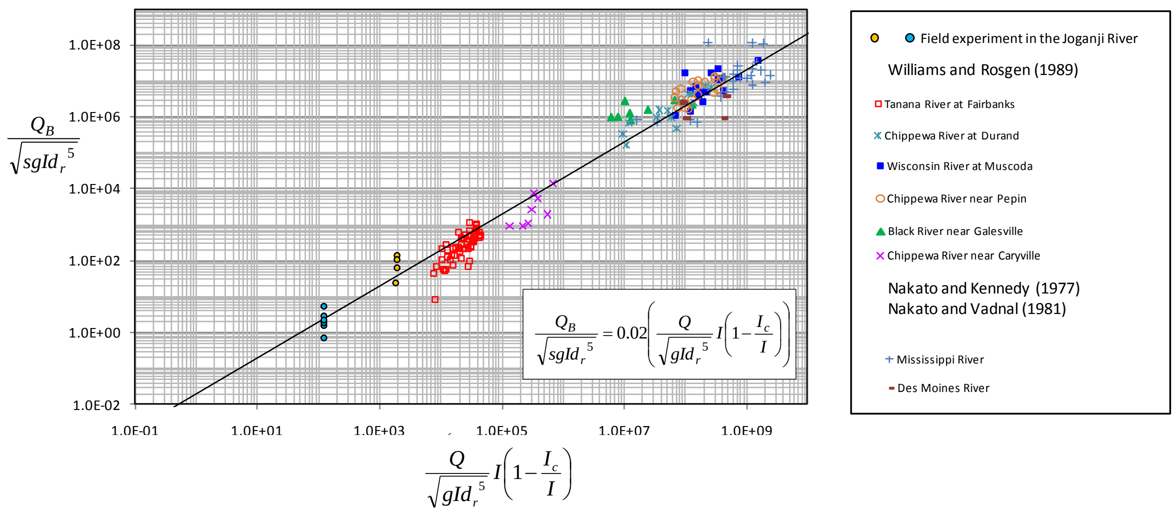


Figure 6: Relationship of dimensionless sediment transport rate and dimensionless discharge

(CERICR) [13)] Of the latter's bed load transport data, those on changes in bed height and sediment transport rate from upstream during running water were used in the calculations.

Figure 6 shows the correlation between dimensionless discharge and dimensionless bed load transport rate determined using the American river bed load data and experimental channel data from the two aforementioned Japanese national organizations. Bed load transport rate is affected by water surface slope ($I$), which is a local hydraulic quantity. To account for this effect, dimensionless bed load is expressed as the product of dimensionless discharge (a determinant of channel cross-section) and water surface slope (a local hydraulic quantity of the channel). Here, dimensionless discharge is multiplied by *I*, which is the value that best fits the dimensionless sediment transport rate data.

Ordinarily, a slope ($I$) that is less than the critical slope ($I_c$) is thought to allow sediment to stay in place. It would therefore be appropriate to express the horizontal axis ($I$) in Figure 6 as $I - I_c$. With a dimensionless critical tractive force ($\tau_{*c}$) of 0.05, $I_c$ can be approximated as 0.083 $d_r/h$. The value of $I_c$ should be accounted for with swiftly flowing rivers where the grain size/water depth ratio is relatively large but is essentially zero in gently flowing rivers. The solid line in Figure 6 is a relation equation (equation (8) below) of dimensionless bed load transport rate.

$$\frac{Q_B}{\sqrt{sgId_r^{\ 5}}} = 0.02\left(\frac{Q}{\sqrt{gId_r^{\ 5}}} I(1-\frac{I_c}{I})\right) \tag{8}$$

Equation (8) is a dimensionless function incorporating dimensionless discharge and bed slope, which determine dimensionless river width and water depth. Conventional dimensionless bed load transport equations incorporate a dimensionless tractive force ($\tau_*$) for the center of a watercourse and calculate bed load without taking river width into account. Equation (8), in contrast, yields a dimensionless bed load that comprises the same parameters that determine dimensionless river width—discharge, bed slope, and grain size—and in this regard is a practical equation for determining dimensionless bed load transport rate. Thus dimensionless discharge not only determines a channel's dimensionless river width and cross-section but is also an important quantity for determining dimensionless bed load transport rate.

A river that satisfies nearly all flood-control and riverine environmental requirements is a channel that looks like a natural river. A natural river, in turn, is one that satisfies equations (3) and (4)—i.e., has a channel with a dimensionless river width and water depth determined by dimensionless channel-forming discharge—and whose flow cross-section roughly complies with Fukuoka equations even for water surface widths resulting from other discharges and water levels. A channel with its channel-forming discharge carries bed load corresponding to cross-sectional form and river width, with the result being that the cross-sectional form is maintained. This suggests that even when flood discharges or water levels are lower, dimensionless bed load corresponding to the water surface width and water depth represented with equation (8) occurs within the cross-section formed by the channel-forming discharge, resulting in a stable channel in which the channel-forming cross-section is essentially maintained. A channel cross-section that provides a desirable relationship between flood flows and bed load transport gives thus a standard of a channel cross-sectional form in harmony between flood control and the environment. Such a channel cross-section is a ship-bottom shaped cross-sectional channel having the sort of continuous wetted perimeter seen in natural rivers[1)].

Thus for a channel with a ship-bottom shaped cross-section, it is possible to define the dimensionless river width, water surface width, and water depth for the dimensionless discharge and, with equation (8), to calculate the resultant dimensionless bed load transport rate.

The ability to calculate dimensionless river width and bed load transport rate for a standard channel cross-section such as a ship-bottom shaped cross-section provides a basic tool for creating a sound cross-sectional form in difficult-to-manage channels with a fixed water path or overgrown vegetation. In many rivers, flows and sediment movement in a cross-section are extremely non-uniform during flooding, while at normal discharges, flow concentrates in the fixed water path; aquatic wildlife exists in locations limited by localized hydraulic and sediment-movement phenomena, meaning that it is not widely applicable to discuss sound riverine ecosystems. Instead, a river section requiring flood control and environmental improvement to correct fixed water path and vegetation overgrowth must be reformed into a ship-bottom shaped cross-section to achieve sound, sustainable flow and sediment movement and a correlation between desirable dimensionless river width (i.e., water surface width), discharge, and bed load transport, after which factors such as desirable bed shape, habitats, and vegetation management can be considered.

## 7. Afterword

This paper has, from the new perspective of learning from natural rivers, derived Fukuoka equations for river development that achieves harmony between flood control and the environment throughout the river basin, such as dimensionless river width, water depth, cross-sectional form, and bed load transport rate. Fukuoka equation demonstrated that an alluvial river's determinants such as dimensionless river width, water depth, and cross-sectional form were determined by the natural laws of river dynamics, and that the equations are universal expression equations for channel formation in a river basin. Close-to-nature river development must fully recognize a river's naturality and understand that a river is the product of interaction between macrostructures—river width, water surface width, cross-sectional form, and other parameters determined by the river basin—and microtopographical features and other elements sculpted by the flood flows and sediment movement within that microstructure.

Fukuoka equations can estimate the required river width, water surface width, water depth, and other factors -even for rivers for which data are sparse- as long as discharge, bed slope and bed material representative grain size are known, and so the equations are highly applicable to river planning and river maintenance.

This paper has discussed dimensionless river width ,water depth, and sediment transport and presented a practical and effective equation for calculating dimensionless bed load transport. Despite its close connection to flood control and riverine environmental management, and despite its importance, bed load transport has been the subject of little research in recent years. Based on the idea that bed load transport is determined in the framework of the mechanism by which flood flows produce a stable river width, the author has studied published results on bed load measured in actual rivers and observed experimentally and has created a practical dimensionless bed load equation that explains these data. The author hopes that this research will renew awareness of the importance of proactively measuring sediment discharge as was done in Japan in the 1950s and 1960s, and will thus lead to widespread measurement of a quantity so important in channel planning.

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