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NUMERICAL MODELLING OF BASIN-WIDE FLOOD FLOW USING VARIABLE FLOW-RESISTANCE COEFFICIENTS

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ABSTRACT: In a populated metropolitan area situated in a tropical/subtropical river basin, interposed between the coastal sea and steep upstream terrains, such as the Tamsui River Basin in the greater metropolitan Taipei region, severe and repeated floods inflict grave life casualties and extensive property damages. To assess the past damages, grasp the rampaging flood waves, and predict inundation hazards, it is desirable to build a reliable numerical model capable of rendering hindcast, real-time, and forecast simulations of tide-affected, basin-wide flood flows. Furthermore, the model must be fairly responsive to the changes in flow resistance, which is evident along the reaches in the basin and at the rising and falling of the flood stages. The channel flow resistance, n (or η), as a function of longitudinal distance, x, and flow depth, h, *i.e.*, $n = n\{x, h(x,t)\}$, is implemented in the present model. Successful simulation results and useful model calibration techniques and experiences have been reported herewith.

Keywords: Unsteady river-channel flow, Multimode method of characteristics, Tamsui River Basin, Urban flood, Variable flow-resistance coefficient.

1. INTRODUCTION

This study aims at flood flows occurring in the Tamsui River Basin. In the past, the numerical modeling of unsteady open-channel flow addressed to the dynamic-wave flood flow was first applied to short or long mono-channels, sometimes referred to as single- or multiple-reach channels (Amein and Fang, 1970; Baltzer and Lai, 1968; Fread, 1978; Lai, 1967). As computer technology progressed and modeling skills improved, the simulation applications grew more sophisticated, and began to encompass complicated and expansive channel configurations with intricate flow patterns (Schaffranek *et al.*, 1981). The scope of applications has reached eventually to an entire river basin, as seen in those simulation models that have simulated several typhoon-caused floods over the entire Tamsui River Basin.

The Tamsui River Basin is located in Northern Taiwan, of which the lower section is bounded by the coastline of Taiwan Strait and is constantly under tidal influence. The upper sections, on the other hand, are covered by steep terrain, through which three major tributaries: Tahhan Stream, Sintain Stream and the Keelung River, each threads its way to meet the Tamsui River, which leads all water to River Mouth. This scenic basin is characterized by rapid urbanization, large-scale disaster prevention work, and above all, repeated catastrophic damage inflicted by severe typhoon floods.

To highlight this last feature, the Central Weather Bureau (CWB) of Taiwan has the following weather records to report: there were 391 typhoons that struck Taiwan from 1897 to 2009, amounting to an average of 3 or 4 typhoons a year. Taiwan's typhoon season is generally from July to September (out of the above 391 typhoons, 304 fell into these 3 months). According to rainfall statistics, during the period of 1900/1~2007/7, there were forty months of monthly rainfall exceeding 300 mm. Two ultra-high monthly precipitation totals recorded were: one in October, 1998, with about 995 mm accumulation, caused by Typhoons Zeb and Babs, and the other in September, 2001, of about 1490 mm, caused by Typhoon Nari. Both broke historical records for the past 110 years (Wang *et al.*, 2008).

The foregoing overview of the critical weather conditions prevailing in the Tamsui Basin and a brief review of the numerical model developments for unsteady open-channel flow have served as an impetus for researchers in the Hydrotech Research Institute (HRI) of National Taiwan University (NTU) to undertake a series of basin-wide modeling works for unsteady flow, including tidal flow, flood flow, and naturally-occurring and/or man-induced transient flow. Already, some research results reflecting special uses or particular interests, have been published (e.g., Lai and Wang, 2005; Lai *et al.*, 2009).

The present article focuses on the numerical modeling of basin-wide flood flows and the effects of using variable flow-resistance coefficients in such form of unsteady flow simulation. Basin-wide unsteady flow generally connotes the time-dependent flow prevailing in a complicated dendritic and network channel system. Considering unsteady single-reach open-channel flow as the beginning of the unsteady one-dimensional free-surface flow modeling, the unsteady flow in a basin-wide river system should serve as the end of such flow modeling. Determination of the flow resistance force in an unsteady flow model is one of the most important and difficult tasks among measurements or quantifications of other model parameters; it is all the more difficult, when the object to be determined is of non-constant value parameter(s).

In the following sections of this paper, a more extensive review of the above two aspects: development of channel configurations and improvement of flow resistance evaluation, both for unsteady-flow conditions, will be given first. The governing partial differential equations, the characteristic equations, and the attendant boundary conditions are organized and examined. The algorithm for formulating variable resistance coefficients are derived and discussed. Applications to the study area are expounded by varied forms of illustration such as figures, maps and sketches, and by other media such as charts and tables.

2. BACKGROUND

It is amply clear that to pursue a numerical modeling study dictated by the subject matter, two aspects of theoretical/technical reviews or considerations must be followed, they are:

2.1 Aspect of Numerically Modeling Basin-wide Unsteady Flows

The advent of modern electronic computers introduced and enabled a new approach to numerically solve, compute and simulate unsteady open-channel flow (Stoker, 1953; Preissmann and Cunge, 1961; Liggett and Woolheiser, 1967). The engineering of unsteady river-channel flow modeling and simulation began with the numerical solution of the equations of continuity and of motion, generally referred to as the Saint Venant equations, and then applying this technique to a single or simple river channel flowing under unsteady state (Lai, 1965; Amein, 1966; Baltzer and Lai, 1968). The application was soon extended to longer river sections or multiple reaches (Lai, 1967), and then to dendritic or network channel configurations (Schaffranek *et al.*, 1981; Fread, 1973), and eventually to the entire river basin.

This last step of entering the basin-wide flow simulation generally requires a considerable increase in programming complexity, computational difficulty, and hardware demands for capacity, capability, and attendant resources. Thus, to achieve the feasibility of basin-wide simulation, the use of large-scale matrix operations is compelled, oversimplified reach/segment schematization is necessitated, and a time-pinched large Δt is inevitably employed.

The numerical scheme adopted by HRI of the NTU for the use in the above simulation is called "Multimode Method of Characteristics of the Second kind" – MMOC-II (Lai, 1988b). This particular scheme is designed to operate in the explicit mode for all the interior nodes, that is, to compute unknown variables at one interior grid point at a time, while junction (or internal boundary) points and the exterior (or terminus) boundary points are computed orderly one after one by some trial and error method. These two groups of computation can be carried out independently, *i.e.*, either group may be computed first within one time step of computation. Moreover, with the use of a multimode scheme, optimum balancing of the size of Δt and the computational resolution may be made. Therefore, it is considered to be particularly suitable for the basin-wide unsteady flow computation.

2.2 Aspect of Evaluating Flow-resistance Coefficients in Unsteady Flow

In an earlier time of unsteady open-channel flow computations, the frictional resistance coefficient was assumed the same as that of steady flow, and hence, could be approximated from the Chezy or Manning equation. Among past investigators (Daily and Jordaan, 1956; Schonfeld, 1948; Baltzer and Lai, 1968; Ragan, 1966), some bore out the above assumptions and some correlated the frictional resistance coefficients to other variables such as the Reynolds number or lateral inflows.

More recently, Yen (1992) compiled a good number of research works on channel flow resistance. There were three articles, though small in number among all papers in the volume, which dealt with the flow resistance coefficient in unsteady flow. They are: Lai *et al.* (1992), which discussed the effects of flow resistance to depth/stage and to discharge, under different combinations of time-dependent boundary variables; Fread (1992), which discussed the selection and calibration of the Manning n for flood routing models, and also touched upon the combined frictional effects of dynamic alluvial bed-forms and overbank vegetation; and Lebosse (1992), which presented an iterative method for estimating the values of the Manning-Strickler roughness coefficient in the Saint-Venant equations.

Among the three articles above, the study of channel flow resistance was made for both forward and reverse flows in the first article (Lai *et al.*, 1992), but it was made for only the downstream direction in the other two. Much more recently, Hsu *et al.* (2006) conducted another channel flow resistance study with typhoon floods in the Tamsui River Basin in real time. Because they made their study during the high water flow when no reverse flow existed and also neglected the effects of tributary flows, the end results should be the same as that made for only downstream direction, *i.e.*, the flood routing model study of the second article (Fread, 1992); and the iterative scheme they used resembled that of the third article (Lebosse, 1992). However, together with Lai *et al.* (2009) and their preceding project reports (e.g., Lai *et al.* 2007), the work of Hsu *et al.* would help elevate the Tamsui River system as one of the most real-time studied objects in hydraulic engineering.

Later Lai and his research colleagues extended their work on the relationship between flow resistance and boundary-variable combination to another paper (Schaffranek and Lai, 1996), in which the influence of the reach length was incorporated to the above findings. If the effects of other non-homogeneous terms (than the frictional-resistance term) in the equations (Lai *et al.*, 1987; Schaffranek and Lai, 1994) are considered, it can be clearly perceived that these terms (*i.e*., other non-homogeneous teams) also affect model performance. If a numerical model is calibrated by neglecting a certain non-homogeneous term or condition that should be placed in there to adequately represent the prototype function, the frictional resistance term is forced to absorb any discrepancy. This is the reason why the numerical simulation must be carried out by the same model that was used for calibration. This is also the reason why the authors often use η (for representing "flow resistance coefficient") in place of n, which only means "roughness factor/coefficient", in the unsteady flow model.

In some reaches, the use of a constant η appears satisfactory, in others; a variable flow-resistance coefficient is preferable or necessary. Lai (1986) listed several key parameters, such as the Reynolds number, R, the Froude number, F, the temperature, T, the flow depth, h, and the discharge, Q, that each may be correlated to the η value, or be used as a functional variable of the η. In recent basin-wide flow models that the writers operate, the model user is allowed to employ a parameter of choice from the above list, for the variable η.

In view of the highly variable stage through which the flood water must rise and return, the η value in this study is programmed to vary with depth, h, in addition to its ordinary variation along the reach; *i.e.*, $\eta = \eta(x, h) = \eta(x, h(x, t))$. This variation in depth is mainly derived from change in the cross section (e.g., the main channel and over-bank section), and change in vegetation and bank texture along the depth. Fread (1992) has noted the similar observation in his flood routing modeling.

3. FLOW MODEL

A basin-wide, unsteady, river-channel flow model has been developed from a general unsteady open-channel flow model by the Hydrotech Research Institute (HRI), National Taiwan University (NTU) (cf. Lai, 1999; Lai *et al.*, 1998 a;b), and subsequently modified by the Hydroinformatic

R&D Team of the same Institute for real-time flood forecasting, with a specific application to the Tamsui River Basin in mind (cf. Lai *et al.*, 2007). The prime mover of the above-mentioned general unsteady flow model is the very numerical solution of the St. Venant-type unsteady open channel flow equations having water depth and flow velocity as two unknowns (Lai, 1986):

$$h_t + uh_x + Hu_x + \frac{u}{B}A_x^h = \frac{q}{B} \tag{1}$$

$$u_t + uu_x + gh_x = g(S_b - S_f) - \frac{qv}{A} \tag{2}$$

in which the independent variables are distance, x, and time, t. $A = A[h(x,t), x]$ is cross-sectional area, B, channel top width, $H = A/B$, hydraulic depth of the cross section, $A_x^h = (\partial A/\partial x)|_h$, the rate of change of cross sectional area with respect to x with h held constant ($=0$, if prismatic); q is the lateral inflow per unit length of x, S_b and S_f are the bed slope and frictional slope, respectively. The symbol g signifies the gravitational acceleration, and $v = u - u'$, where u' stands for the x component of lateral inflow.

The method of characteristics transforms the above set of partial differential equations (PDEs), (eqs. (1) and (2)) into a set of ordinary differential equations comprising of two characteristic and two compatibility equations:

$$\left(\frac{dx}{dt}\right)_\pm = u \pm \sqrt{g\frac{A}{B}} = u \pm c \tag{3}$$

along $C_\pm$

$$\left(\frac{Dh}{Dt}\right)_\pm \pm \frac{c}{g}\left(\frac{Du}{Dt}\right)_\pm + F_\pm = 0 \tag{4}$$

in which, $F_\pm = \left(\frac{u}{B}\right)A_x^h \mp cS_b \pm cS_f - \left(\frac{q}{B}\right)\left[1 \mp \left(\frac{v}{c}\right)\right]$, $c = \sqrt{gH}$ = celerity of gravity wave, $\frac{D}{Dt} = \frac{\partial}{\partial t} + \frac{dx}{dt}\frac{\partial}{\partial x}$. The unknown quantities h and u must be integrated along the corresponding characteristic curves (C_+ and C_-). Equations (3) define two families of characteristic curves C_+ and C_- on the (x, t) plane (Lai, 1986), and the compatibility equations (4) describe the two unknowns behave along the curves of $C_\pm$.

The Multimode Method of Characteristics of the Second kind (MMOC-II) has been chosen as the numerical scheme of solution. This is a powerful numerical scheme belonging to the Method of Characteristics (MOC); it merges the temporal reach-back, spatial reach-back, spatial reach-out, temporal reach-out (only at the boundaries), and classical schemes into one large scheme. The advantages of this scheme are: 1) No limitation in size of time step, Δt, is imposed by the Courant condition, the grid of several time and space increments can be taken into consideration during numerical integration; the interpolation can always be performed and the extrapolation can be avoided; and 2) The underlying computational modes are all in the explicit form (Lai, 1988a,b).

4. INTERNAL BOUNDARY POINTS AND CHANNEL JUNCTIONS

The model applied in this study includes one-way, two-way, and up to four-way junctions, and the corresponding number of reaches that meet at these junction points. The one-way junction represents the generalization of an external boundary point; and the other types of junction each act as a varied form of internal boundary point. The mass continuity and energy balance must be satisfied at each junction. At the end of every reach, there are two unknowns, say Q (discharge) and Z (water-surface elevation). Thus for N reaches meeting at an N-way junction, there are $2N$ unknowns at this point. Hence, $2N$ equations are needed to solve for these $2N$ unknowns. Of these, N equations come from the compatibility equation at each end of total N reaches. The other N equations can be derived from the internal boundary conditions, such as

$$\sum_{i=1}^{N} Q_i = 0 \tag{5}$$

and

$$H_1 = H_2,\ H_2 = H_3, \ldots\ldots H_{i-1} = H_i, \ldots\ldots H_{n-1} = H_n \tag{6}$$

where $H_i = Z_i$ or $H_i = Z_i + (1+\alpha_i)\dfrac{u_i^2}{2g}$, subscript $i = 1, 2, \ldots, N$ indicates junction number, H = total head, and α = head-loss coefficient (= 0, for inflow). See (Lai, 1999) for more details.

5. ALGORITHM FOR VARIABLE FLOW-RESISTANCE COEFFICIENTS

Some model parameters have great impacts on the calculated results of a numerical model, and for that reason, performance testing and sensitivity analysis for the related class of parameters are necessary before application of the model. At present, the determination of river roughness coefficients is usually based on inspection of photographic pictures obtained from the actual survey, or consulting with some standard open-channel books such as by Chow (1959) or Barnes (1967). In this study, choice of an appropriate roughness-coefficient value is relied mainly on the Chow's book.

As explained in the previous investigations (e.g., Baltzer and Lai, 1968; Schaffranek and Lai, 1996) and briefly restated earlier, the flow-resistance coefficient usually contains more factors than the roughness factor alone, though the roughness still behaves as a dominant factor. For this reason, the term flow-resistance coefficient instead of roughness coefficient is used normally by the writers. For the sake of simplicity and convenience, however, in the following analysis the writers' algorithm development is largely based on the frictional-resistance arguments.

As asserted previously, the flood stage would rise far above the flood plain, and $n(\approx \eta)$ value is assumed to vary against stage, z, in the following manner, which is derived partly from the field observation:

$$\begin{aligned} n &= n_{ub} && \text{if} \quad z \geq z_{ub} \\ n &= f(z) && \text{if} \quad z_{lb} > z > z_{ub} \\ n &= n_{lb} && \text{if} \quad z \leq z_{lb} \end{aligned} \tag{7}$$

in which the flow-resistance coefficient, η, is approximated by Manning's n, z_{ub} and z_{lb} are the upper and lower limits of the varying stage, respectively, and n_{ub} and n_{lb} are the roughness coefficients corresponding to, respectively, stages of z_{ub} and z_{lb}.

If the frictional resistance is assumed to increase linearly from the minimum stage (z_{lb}), at which the stage is far below the flood plain level, to the maximum stage (z_{ub}), at which the flood plain is totally submerged in the flood. The $n = f(z)$ equation can then be explicitly written as

$$n = n_{lb} + m(z - z_{lb}). \tag{8}$$

in which m is the slope, $m = (n_{ub} - n_{lb})/(z_{ub} - z_{lb})$.

In this study, the values of n_{ub}, n_{lb}, z_{ub} and z_{lb} were calibrated according to the measured stage values (z) of ordinary and flood stages separately. Figure 1 gives a schematic diagram of the linearly varying roughness coefficient.

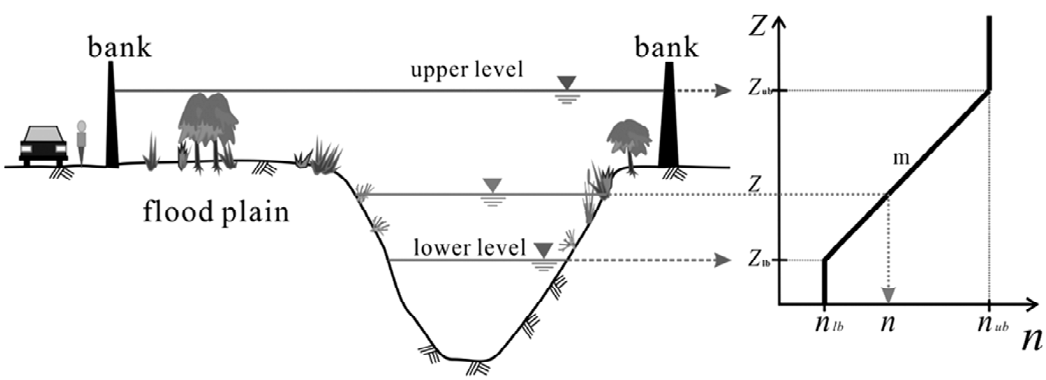


Figure 1: Schematic Drawing of the Variable Roughness Coefficients

6. STUDY AREA AND CHANNEL SCHEMATIZATION

A general description of the Tamsui River Basin has been given in the Introduction section. Figure 2 shows a map of the Tamsui River system, which well covers the study area of this article. The river system, with its longest limb having a length of 159 km, ranks the third largest river in Taiwan. Because many reaches of the Tamsui River are situated in low-lying areas near sea-level, they are strongly tide-affected. On the other hand, the tributary Keelung

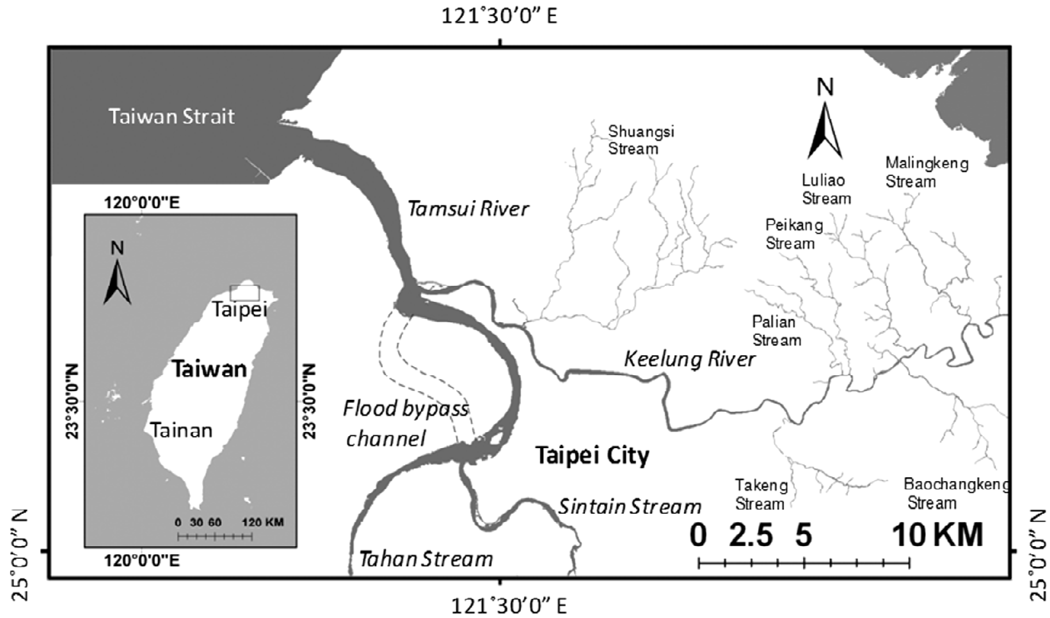


Figure 2: Map of the Tamsui River Basin

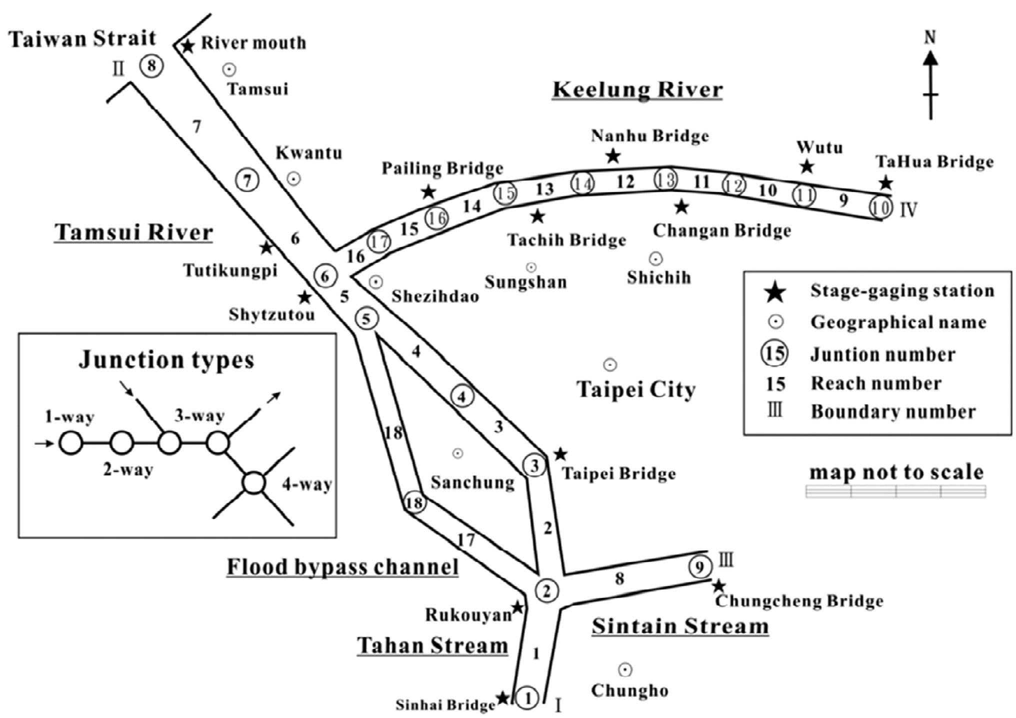


Figure 3: Channel Schematization of the Tamsui River Basin

River has a very winding course and a highly variable gradient. These conditions are further aggravated by rapid urban development along its banks, resulting in amplified magnitude of peak flows, increased frequency of flood occurrences, intensified inundation of adjacent areas, and shortened time of flood-peak arrival. All these factors make the Keelung River the most notorious flood-prone branch in the system.

The natural river, stream, and channel system shown in Figure 2 can be schematized to a geometrically simple, program-wise amenable, and modeling-wise operable configuration such as exemplified in Figure 3. It has various types and shapes of terminus, junction, and confluence, for which some typical forms have been mentioned earlier. It can serve as a convenient chart and worksheet for preparing initial values, boundary conditions, and other model parameters.

7. COLLECTION OF HYDROLOGIC AND GEOGRAPHIC DATA

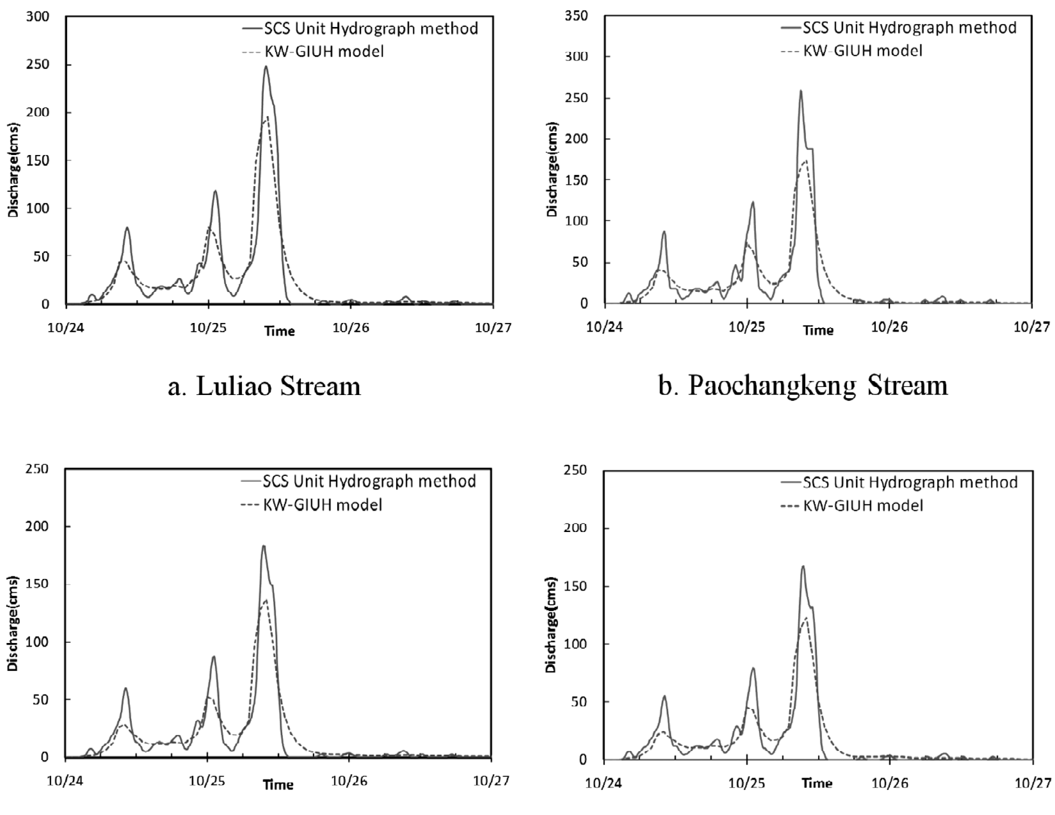
In order to build a numerical model that could simulate the typhoon flood events of the past and to reconstruct water-level changes for each typhoon flood, the cross-sectional data in the Tamsui River system since the year 2000 and water-stage station monitoring information, which contains 40 water stage stations, were obtained from The Tenth River Bureau, Water Resources Agency, Ministry of Economic Affairs (MOEA). In addition, water stage monitoring information, which includes as many as 60 stations, was also secured from the Conservation Department of the Taipei City Government. At the same time, the data of all tidal measurements in the Tenth River Management Office were gathered for the data basis used for model verification. In this study we also acquired cross-sectional data from the Tenth River Bureau, Water Resources Agency, MOEA, amounting of total 165 cross-sections, of which 49 from the Tamsui River and Tahhan Stream, 9 from Sintain Stream, 97 from the Keelung River, and 10 from the flood bypass channel.

8. INFLOWS FROM SMALL SUB-WATERSHEDS

The tributary inflows along the banks of the Keelung River could contribute a non-negligible amount of flow as to affecting accurate calculation of the flood water. In order to extend the calculation range up to the Tahua Bridge, the tributary inflows along the Keelung River should be included up to this bridge. This is important to keep the computational accuracy to the degree required, especially at the times when the typhoons are prevailing in the area. In this study, two methods were employed to estimate the tributary inflows: 1) Empirical formulae: SCS Unit Hydrograph method and 2) Kinematic-wave based geomorphic instantaneous unit hydrograph model (KW-GIUH model, Lee and Yen, 1997). The related geographic parameters for tributary flows can be used directly to estimate the inflows of each tributary with the aid of actual rainfall records. Four tributary inflows during the Nock-Ten typhoon were evaluated by these two methods (see Figure 4): Comparing the runoffs in Luliao Stream, Paochangkeng Stream, Peikang Stream and Palian Stream, it can be found that the estimated runoff curves on flow and peak value through the two different methods match each other. The study finally adopted the KW-GIUH model to complete calculation of the runoffs for all tributaries of the Keelung River.

9. CALIBRATION OF AND FLOW VERIFICATION WITH VARIABLE ROUGHNESS COEFFICIENTS

Using the past recorded data through daily observation as well as from some serious floods, the Manning's roughness coefficients calibration and verification were conducted in this study. A data set of stage and discharge measured during a complete tidal cycle was also used to verify the applicability of the present simulation model.



a. Luliao Stream

b. Paochangkeng Stream

c. Peikang Stream

d. Palian Stream

Figure 4: Comparison of Four Tributary Inflows of Keelung River; Each Estimated by Two Different Methods

The lower-bound values, n_{lb}, were calibrated using non-flood time, daily observed stages of three continuous days, e.g., from 2004/08/16 to 2004/08/18. Then, two periods of three continuous days, 2004/09/16 to 2004/09/18 and 2004/10/16 to 2004/10/18, were selected randomly for model verifications. It is to be pointed out that there was no rain in the watershed during these periods. Figure 5 displays the calibration results of the simulation model at several

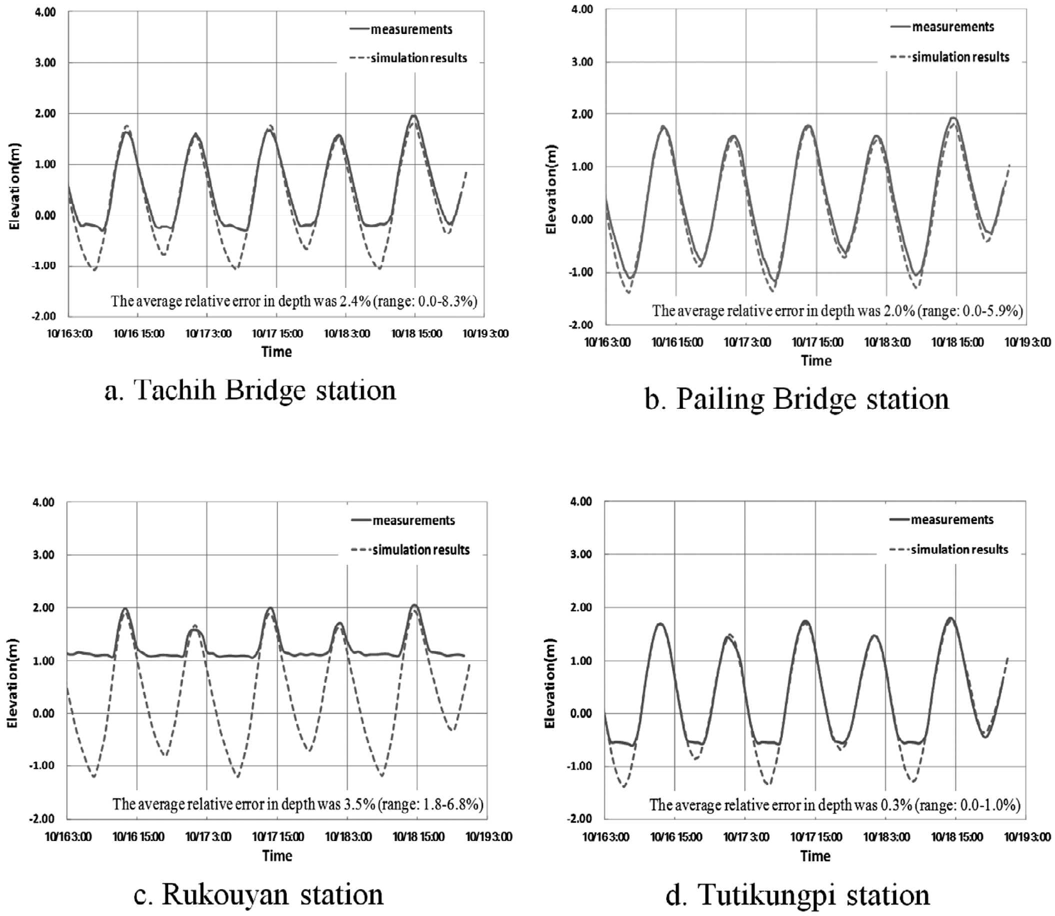
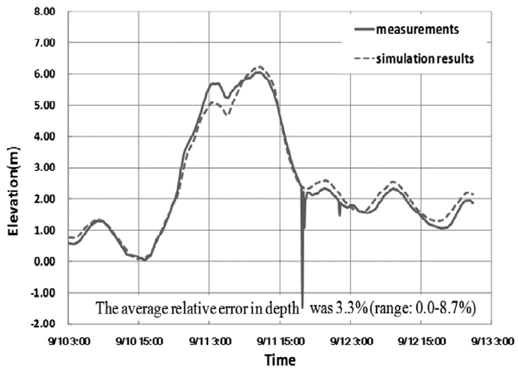
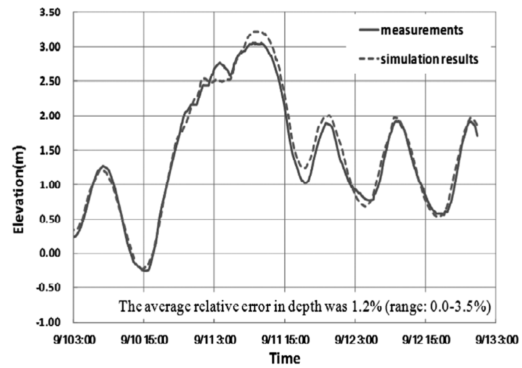


Figure 5: Calibrated Results of Simulation Model

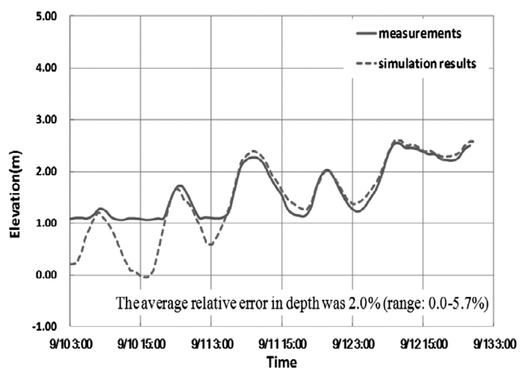
gauging stations along the Keelung River (Tachih Bridge and Pailing Bridge stations) and the Tamsui River (Rukouyan and Tutikungpi stations) during the sampling period indicated above. It is also to be noted that the observational instruments at the Rukouyan and Tutikungpi stage-gauging stations were blocked by silt, rendering the lower stages unable to observe. To calibrate the upper-bound values, n_{ub}, the flood stages induced by the NOCK-TEN Typhoon during the period of 2004/10/24 to 2004/10/27 were used. The simulation model thus calibrated was then verified by using the high-water stage data occurred in HAIMA Typhoon during the period of 2004/09/11 to 2004/09/13. Verification of this simulation model is given in Figure 6. A sudden drop of the measurement curve in Figure 6a is conjectured to be a momentary agitation of the instrument.



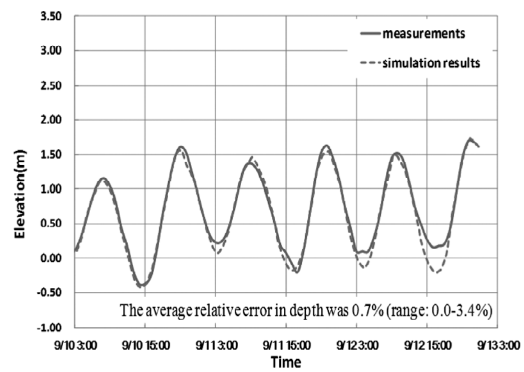
a. Tachih Bridge station



b. Pailing Bridge station



c. Rukouyan station



d. Tutikungpi station

Figure 6: Verification of Present Simulation Model

Figure 7 shows four cross-sectional profiles among the most typical cross sections seen in the study reaches, with their variable roughness coefficients schematically defined (using four parameters, z_{ub}, z_{lb}, n_{ub} and n_{lb}) and graphically displayed at the side. The characteristics of these four cross sections are found to be: 1) A simple section of ecological design (no flood plain); Figure 7a depicts the shape of cross section in Wutu gauging station, the Keelung River. 2) Beside the main watercourse, there is a large tract of parkland functioning as a flood plain; Figure 7b portrays a shape of cross section in the stage gauge of Tachih Bridge, the Keelung River. 3) Wide channel; Figure 7c shows such a wide channel cross section. The section is located at the stage gauging station of Rukouyan, the Tamsui River. 4) Sandbanks formed by silts in a wide water channel; Figure 7d represents the cross sectional profile having a sand

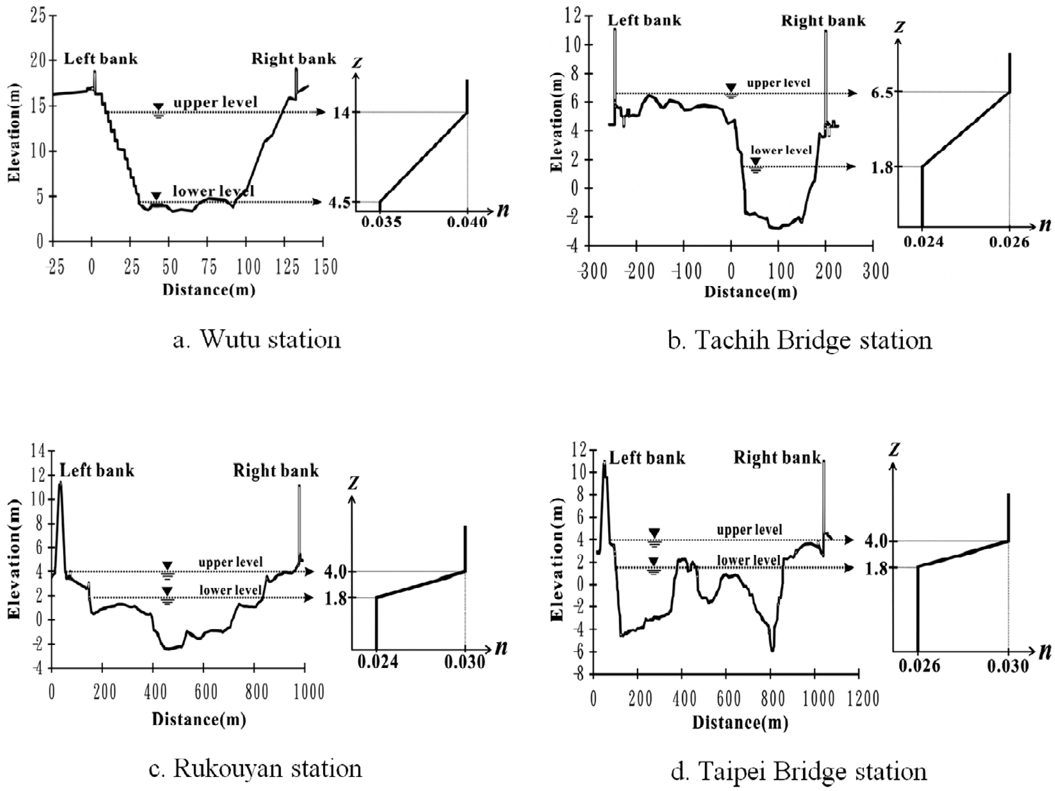
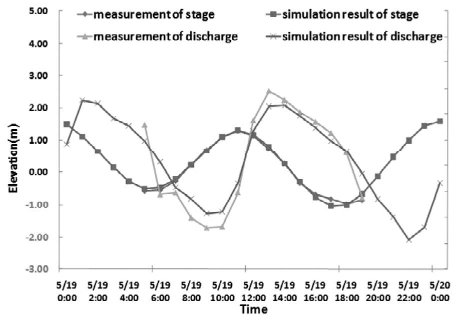


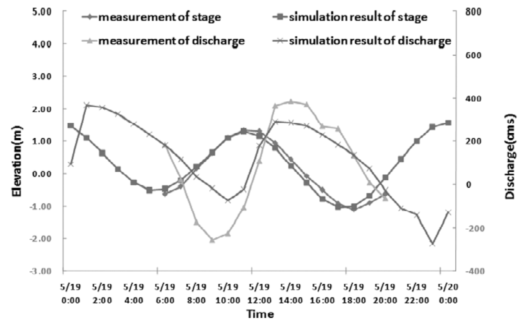
Figure 7: Four Typical Cross Sections and Model Calibrated Variable Resistance Coefficients

bank near the right bank of the channel. This cross section is located at the stage gauging station of Taipei Bridge, the Tamsui River.

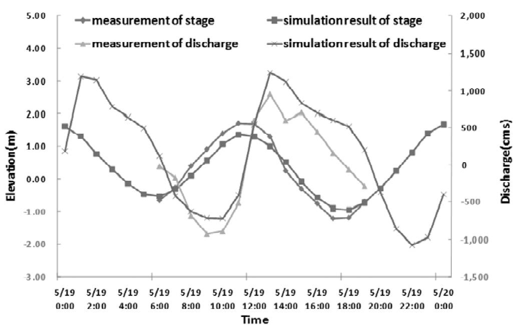
In unsteady-flow modeling, the water elevation is relatively easy to measure and is also easy to give accurate computational results. The discharge, on the other hand, is both more laborious and troublesome to measure and difficult to afford accurate computational results. The Tenth River Bureau, Water Resources Agency, MOEA, made measurements for a complete tidal cycle at several different stations of the Tamsui River system, such as: (1) Kwantu Bridge and Taipei Bridge on the Tamsui River, (2) Pailing Bridge on the Keelung River, (3) Chungcheng Bridge on Sintain Stream, and (4) Sinhai Bridge on Tahhan Stream. The Stages and discharges obtained from the flow measurements of one tidal cycle in 2004 were used to perform rigorous comparisons in Figure 8. It was shown that the agreement between measured (circle) and simulated (square) stages was better than that of measured (triangle) and simulated (cross) discharges. However, both cases demonstrated reasonably good agreements.



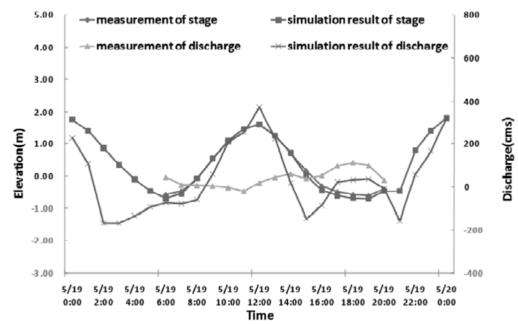
a. Kwantu Bridge station



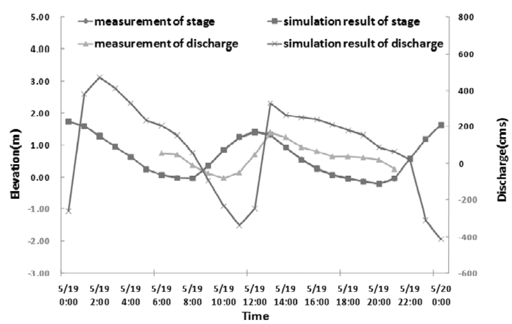
b. Pailing Bridge station



c. Taipei Bridge station



d. Chungcheng Bridge station



e. Sinhai Bridge station

Figure 8: Comparisons of Measured and Simulated Discharge and Stage for One Tidal Cycle

10. FLOOD SIMULATION

In this section, three simulations of actual typhoon-flood events using the enhanced (*i.e.* the variable flow-resistance coefficient) model were carried out; NARI typhoon in 2001, HAIMA typhoon in 2004, and NOCK-TEN typhoon, also in 2004. Among them, the NARI flood had been utilized for the real-time flood forecasting study (Lai *et al.*, 2007; 2009) using the (time-wise) fixed flow-resistance coefficient.

Figure 9 shows the rapid rising of NARI-flood stage causing overtopping of water at lower or breaching points of the bank. The NARI typhoon hit the northern Taiwan in the evening of Sep, 16, 2001; within 6 hours, it reached the embankments and an overflow took place at 22:00 in the vicinity of Nanhu Bridge. The rampage this flood brought about was all too well known, and many detailed accounts of flood consequences have been reported elsewhere. As to some of the differences observed between the simulations by the fixed and the variable flow-resistance coefficients, the reader is referred to a few later paragraphs of this section.

After the government finished the Keelung River sub-basin integrated flood control plan between 2001 and 2004, the most difference evidenced was the topographic changes along the channel, including changes in cross-sectional shape and in elevation of embankments (e.g., note the marked difference in bank profiles before <cf. Figure 9> and after <cf. Figure 10 & 11> the completion of the plan).

Two typhoon-flood events presented in Figures 10 and 11 were caused by rarely seen, extremely heavy rainfalls in 2004. The water level rose very quickly, especially in the case of NOCK-TEN typhoon flood. Recorded at the Tahua Bridge were the water-level risings of 2.81 meters within an hour and of 7.83 meters within three hours. Such a record of water-level rising is indeed amazing. In Figures 9 to 11, the green solid line indicates the elevation of the left bank, the red solid line that of the right bank, and the orange solid line the river bed. The sudden rise of elevation for the right bank in Figure 9 was previously the Neihu Sanitary Landfill Site (nicknamed "Neihu Garbage Mountain"). The red circle is the warning water level at the location shown. The blue solid line stands for the current (real time) water-surface profile and the dotted lines each predict the water-surface profile of the successive hours.

Presented in Tables 1 and 2 are the maximum discharge ($Q_{\max}$) and the maximum water level ($Z_{\max}$) occurred at each gauging station for the three typhoon floods, NARI, HAIMA and NOCK-TEN. The site of the maximum flood flow for the entire basin was found to be at the Shytzutou or Tutikungpi, the confluence of the Keelung River and the Tamsui River. The maximum discharge in the Keelung River was 3424 m^3/s, that in the Tamsui River, 9144 m^3/s, that in Tahhan Stream, 4770 m^3/s, and that in Sintain Stream, 5106 m^3/s.

The number within the parentheses in the second column, under the heading $Z_{\max}$ of Table 1 and that under the heading $Q_{\max}$ of Table 2 are, respectively, the corresponding water-level data and peak-discharge data of the NARI typhoon flood when the simulation was made with the fixed flow resistance coefficient. It is of interest to observe that the use of a higher η (or n) value results in a reduced Q value except at a boundary point, at which this rule may not follow. This pattern makes one recall the case of z-z boundary combination in the study of friction term response (see Schaffranek and Lai,1996). In short, with the present model that is implemented with a variable flow resistance coefficient, a more realistic (which is higher) frictional resistance value at the flood stage is used, and thus a better simulated discharge is obtained, while the use of a fixed resistance value results in over estimation of flood discharges.

On the other hand, the use of a variable flow resistance coefficient did not alter the simulated water levels as much as it did for the discharge values, except possibly at or near the confluent points, such as Shytzutou or Tutikongpi. This pattern can likewise be checked from Schaffranek and Lai (1996), which (the pattern) endorses the earlier statement made for the case of (easier) z agreement in response to η variation. Thus, the flood forecasting performed by the fixed η (e.g., Lai, *et al.* 2009) appear as good as the flood stage profile computed by variable η (Figure 9). The rather large discrepancy in $Z_{\max}$ values at a confluent point (seen in Table 1), may be due to some other reason (say the time of peak arrival has been influenced). Such an influence seems to be felt at a few points near the confluence, also.

Finally, another valuable finding can be brought forth by the above three Keelung River simulations. From the water course shown in Figure 12, it appears that the protrusion of the Yuanshan tract could force the flow of the Keelung River to make an unduly detour around the area. Because of this obstruction, proposals as to drill a water tunnel or to build a bypass channel to cut through the protrusion, or even to construct a linking canal nearby to lead flood waters from the Keelung to Tamsui River have been made previously. However, all such "farsighted" worries should look like taking needless trouble if careful studies of Figures 9 to 11, or of the like study of unsteady-flow simulations, had been taken, one would perceive that such a matter would not happen. Any overflow due to floods would take place at the upstream regions, such as Sitze, or Nankang areas, long before the flow could overtop the banks at the Yuanshan tract. Chungshan Bridge is safe at any flood!

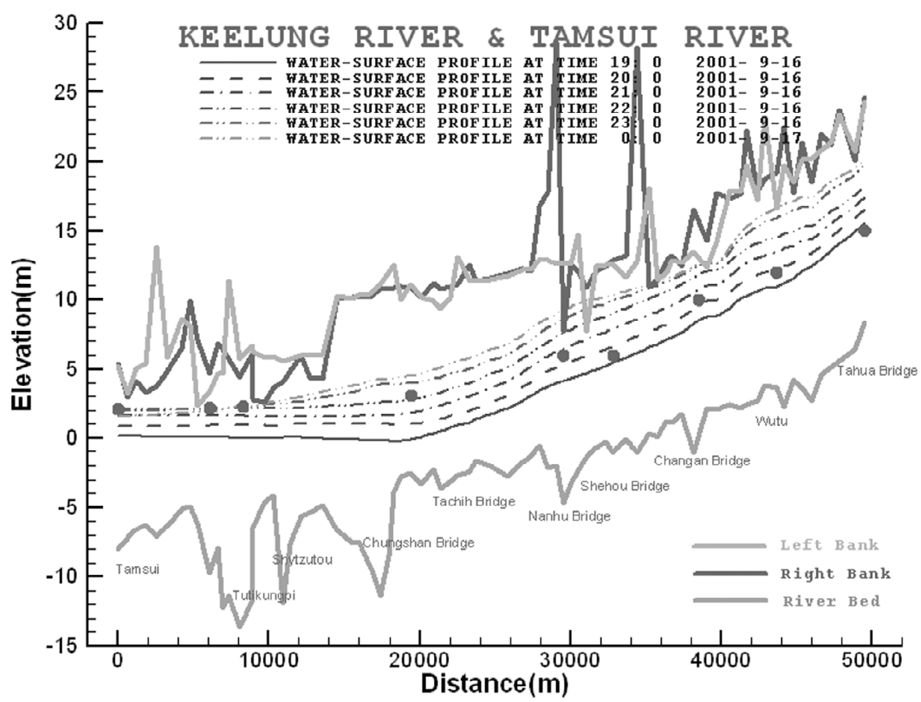


Figure 9: NARI Typhoon Event; the Overflow of the Keelung River

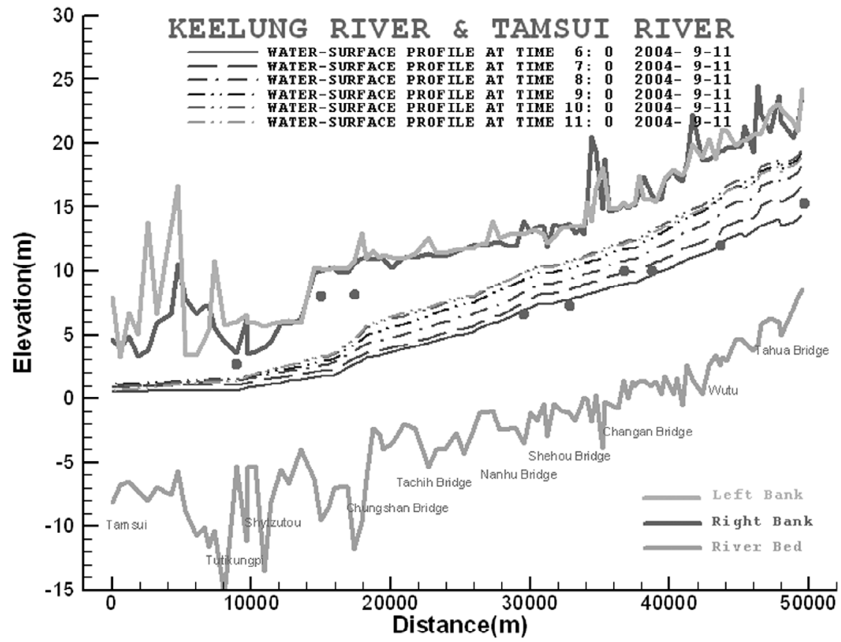


Figure 10: HAIMA Typhoon Event; Sudden Rise of Water Level in the Keelung River & Tamsui River

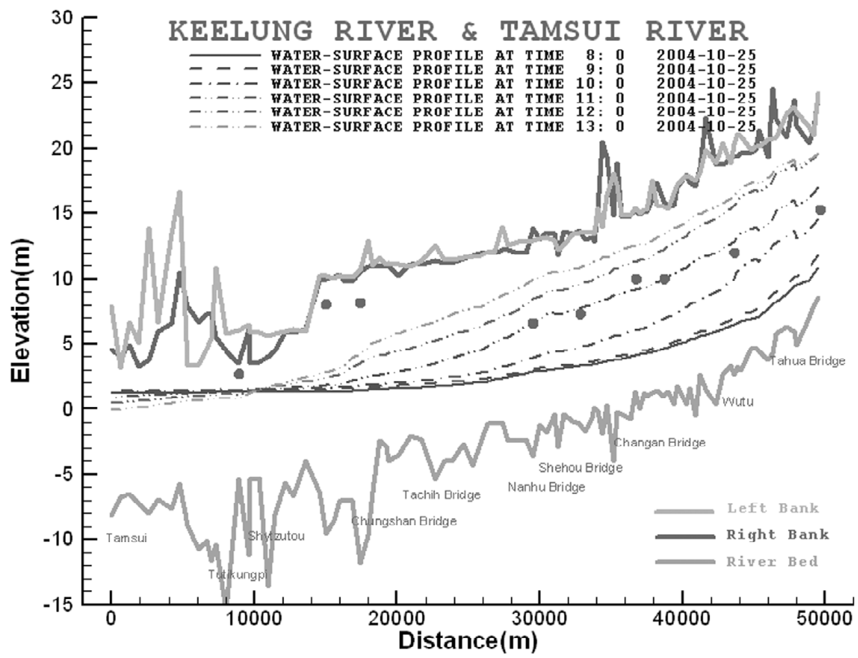


Figure 11: NOCK-TEN Typhoon Event; Sudden Rise of Water Level in the Keelung River & Tamsui River

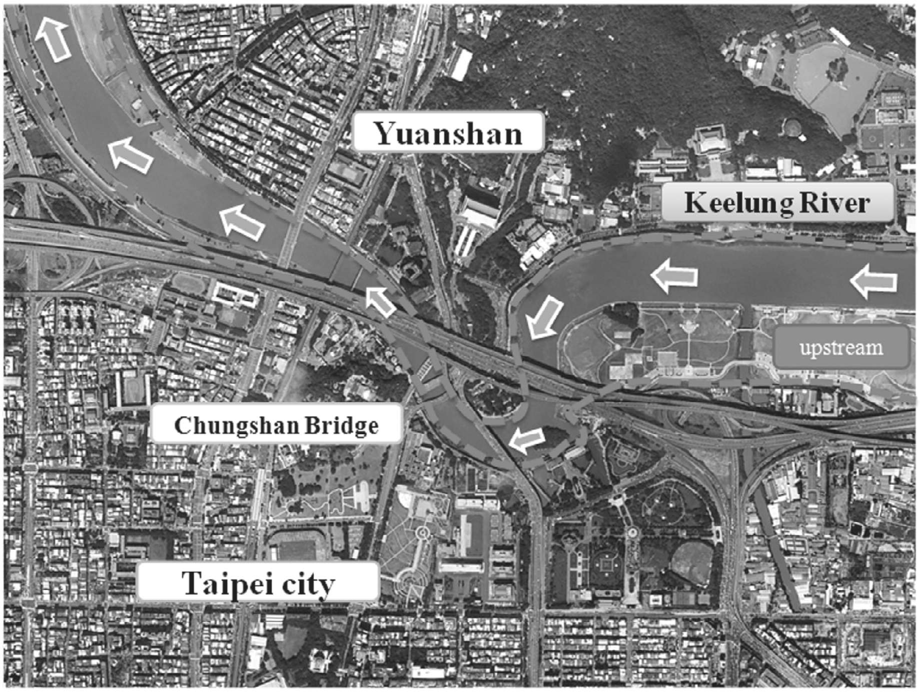


Figure 12: The Obstruction of Yuanshan in the Keelung River

Table 1
Maximum Stages Occurring at Gauging Stations for the Three Typhoon-flood Events
*[Note: * = Boundary Val. Data, (xxx) = Z_{max} Computed with Fixed Flow Resistance Coeff.]*

Stage gauging stations	*NARI(2001)* Z_{max} *(m)*	*NARI(2001) Time*	*HAIMA(2004)* Z_{max}	*HAIMA(2004) Time*	*NOCK-TEN(2004)* Z_{max}	*NOCK-TEN(2004) Time*
Sinhai Bri.	5.64 *	9/18 06:00	2.85	9/12 13:00	2.51	10/25 11:00
Rukouyan	4.06 (3.98)	9/17 03:20	2.59	9/11 09:40	2.30	10/25 11:20
Taipei Bri.	3.30 (3.22)	9/17 03:20	2.20	9/12 22:50	1.91	10/25 21:40
Shytzutou	2.90 (3.41)	9/17 11:20	1.79	9/12 22:30	1.71	10/26 09:30
Tutikungpi	2.46 (3.24)	9/17 23:40	1.71	9/12 22:20	1.64	10/26 09:20
River mouth	2.07 *	9/16 22:00	1.56	9/12 22:00	1.55	10/26 09:00
Chungcheng Bri.	6.06 *	9/17 03:40	3.46	9/12 11:00	3.02	10/25 12:00
Tahua Bri.	22.18 *	9/17 01:40	19.39	9/11 10:00	19.69	10/25 12:50
Wutu	18.77 (17.65)	9/17 01:20	16.03	9/11 10:10	16.34	10/25 13:00
Chang-an Bri.	13.52 (15.49)	9/17 00:00	13.19	9/11 10:10	13.49	10/25 13:10
Nanhu Bri.	9.38 (9.25)	9/17 07:00	9.97	9/11 10:30	10.07	10/25 13:20
Tachih Bri.	7.28 (4.80)	9/17 07:40 (04:30)	6.27	9/11 11:10	6.10	10/25 13:50
Chungshan Bri.	5.55 (4.87)	9/17 07:40 (04:45)	3.30	9/11 11:10	2.90	10/25 13:30

Table 2
Maximum Discharges Occurring at Gauging Stations for the Three Typhoon-flood Events
[Note: (xxx) = Q_{max} Computed with Fixed Flow Resistance Coeff.]

Stage gauging stations	*NARI(2001)* Q_{max} *(cms)*	*Time*	*HAIMA(2004)* Q_{max}	*Time*	*NOCK-TEN(2004)* Q_{max}	*Time*
Sinhai Bri.	4770 (4608)	9/18 06:00	1541	9/12 15:50	1105	10/25 11:00
Rukouyan	4073 (4738)	9/17 02:20	3255	9/12 16:00	2514	10/25 12:10
Taipei Bri.	4063 (4765)	9/17 03:20	4001	9/12 16:20	3169	10/25 12:50
Shytzutou	9144 (10685)	9/17 04:00	4870	9/11 11:40	4517	10/25 13:00
Tutikungpi	8829 (10202)	9/17 04:00	5839	9/11 11:40	5455	10/25 13:10
River mouth	8787 (9281)	9/18 02:00	6443	9/11 12:00	6018	10/25 12:30
Chungcheng Bri.	5106 (5124)	9/17 00:40	1621	9/12 13:50	1293	10/25 12:00
Tahua Bri.	3424 (2817)	9/17 01:40	1830	9/11 09:50	2084	10/25 12:00
Wutu	2543 (2744)	9/17 02:00	2189	9/11 10:00	2347	10/25 12:10
Chang-an Bri.	2816 (2787)	9/17 01:00	2271	9/11 10:10	2400	10/25 13:00
Nanhu Bri.	2075 (2204)	9/17 00:00	3078	9/11 10:20	3226	10/25 13:20
Tachih Bri.	1652 (1905)	9/17 07:20 (04:30)	2986	9/11 11:00	3033	10/25 13:50
Chungshan Bri.	1503 (2699)	9/17 07:40 (04:45)	2516	9/11 11:20	2551	10/25 14:00

11. CONCLUDING REMARKS

Taiwan is a country that suffers from frequent flood damages. The damages cause immensely serious economic losses each year. In order to develop a comprehensive as well as effective numerical model that could cope with the problems in the flood stricken areas such as the Tamsui River basin, intensive research was launched.

To pursue such objectives, two aspects of technical considerations were followed: a) Building a numerical, basin-wide, unsteady-flow model, which handles the three basic forms of flows — tidal, flood, and nature/man-induced transient flows; b) Implementing a flow-resistance coefficient that varies with the flow depth which is, in turn, dependent on the flood stage, in addition to, that traditionally varies with the location along the reach.

Tasks required for successful model building and simulation include: (1) collection of the hydrologic and geologic data for the Tamsui River system; (2) formulation of unsteady open-channel flow algorithms, in which a pair of dependent variables, such as flow depth, $h = h(x,t)$, and velocity, $u = u(x,t)$, are selected; (3) schematization of the compound-complex channel system and subsequent computer modeling using the MMOC-II; (4) installation of variable flow-resistance coefficients as stipulated above; (5) calibration of variable roughness coefficients during ordinary days (low water levels) and typhoon periods (flood water levels); and (6) verification of the flow model.

The model simulations conducted for a few major typhoon floods pinpointed where along the banks of the Keelung River reinforcement might be needed. Comparison of the Nari typhoon-flood simulations using the variable and fixed (time- wise) flow-resistance coefficients indicated that the latter case would overestimate peak-discharges, while both cases gave comparable peak stages. This is in good agreement with the earlier sensitive studies made for a simple channel system. Many vulnerable points were found to be still along the banks of upstream sections, such as Nankang, Sitze, and Wutu areas. On the other hand, the narrow conveyance near Chungshan Bridge was found to be hydraulically safe, although some esthetical, structural, and traffic rearrangement and improvement may be of help.

The unsteady flow model described herein is hoped to offer an effective tool for prediction, prevention, or mitigation of flood disasters, and for the long-term planning and management of waterfront environment. Other aspects of investigations and explorations may be tried using the present model. Extended applications of the model to other water bodies in the island, or to hurricane floods in other parts of the world, can be attempted as well. The study may also help in consolidating the management of all basic information and simulation results, perhaps beyond mere flood information processing.

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