XIX International Conference on Water Resources
CMWR 2012
University of Illinois at Urbana-Champaign
June 17-22, 2012

THE CATEGORIZATION OF INUNDATION FLOW OVER COMPLEX TOPOGRAPHY

Ryota Tsubaki [*] and Yoshihisa Kawahara[†]

[*] Hiroshima University
Department of Civil and Environmental Engineering
1-4-1 Kagamiyama, Higashi-Hiroshima, 739-8527 JAPAN
e-mail: rtsubaki@hiroshima-u.ac.jp, web page: https://sites.google.com/site/rtsubaki/

[†] Hiroshima University
Department of Civil and Environmental Engineering
1-4-1 Kagamiyama, Higashi-Hiroshima, 739-8527 JAPAN
e-mail: kawahr@hiroshima-u.ac.jp, web page: http://home.hiroshima-u.ac.jp/civil/laboratories/staff/Kawahara.pdf

Key words: Flood inundation prediction, high-resolution flow model, complex topography

Summary: The spatial-resolution and accuracy of floodplain topography data, practically available for inundation simulations, has been improved as a result of innovations in remote sensing and data processing technologies. The use of detailed topographical data in flood inundation analyses enabled us to evaluate flood propagation over complex and realistic topography. In this work, inundation flow was categorized into four types based on general topographical situations and flow patterns. Here, four representative inundation flow modeling approaches - 'simplified', 'large-scale', 'integral' and 'detailed' - are defined and their suitability for each inundation type is discussed.

1 ADVANCES IN INUNDATION MODELING

The spatial-resolution and accuracy of floodplain topography has been improved as a result of innovations in remote sensing and data processing technologies. Recently, detailed topographical data, with a horizontal resolution of less than one meter, and accuracies in elevation of a few centimeters, have become available. The use of detailed topographical data in a flood inundation analysis enabled us to evaluate flood propagation over complex and realistic topography.

Based on a computational grid size and a modeling approach, a two-dimensional flow model for inundation simulations can be categorized. In the past, due to limitations of computational resources and topographical data resolution, a grid size ranged from 10 to 100 m has been used. In this work, this type of simulation is denoted as 'large-scale'. Another approach that uses detailed topographical data and directly resolves flow at the street scale is referred to as 'detailed' type model. Examples of the 'detailed' approach are found in literatures[1,2,3,4,5]. An additional approach that considers detailed topography data also exists. For this type, a larger grid size is used but the effect of detailed topography is accounted for in the sub-grid model and is referred to as the 'integral' type[6,7]. 'Integral' models are more economical in calculation than 'detailed' calculations. The difference between 'integral' and 'large-scale' simulations is the manner of sub-grid model parameterization. The 'large-scale' approach determines model parameters empirically (e.g. based on land surface categorization), while the 'integral' type accounts for sub-grid scale effects based on more physical and kinematic manners. A small amount of literature is available that compares 'detailed' and other approaches[8,9].

2 THE CATEGORIZATION OF INUNDATION FLOW BASED ON TOPOGRAPHICAL SITUATIONS AND FLUID DYNAMICS

2.1 The categorization of inundation flow

Modern society has witnessed many fluid dynamics-related disasters, including floods, tsunamis, and storm surges. The fluid motion of these events can be described based on the conservation of momentum in one-dimensional space, as follows:

$$\frac{1}{g}\frac{\partial}{\partial t}\left(\frac{Q}{A}\right)+\frac{1}{2g}\frac{\partial}{\partial x}\left(\frac{Q}{A}\right)^2+\frac{\partial h}{\partial x}-i_0+I_f=0 \tag{1}$$

where Q is the flow rate, A is the cross-sectional area, h is the water depth, i_0 is the bed slope, I_f is the energy slope, and g is the gravitational acceleration. The relative contribution of each term in equation (1) depends on the flow situation. For examples, kinematic wave model and diffusion wave model are derived by neglecting some terms in equation (1) (see Table 1). Important to note is that energy loss includes not only friction loss but also a pressure drag due to topography and structures.

Table 1: The inundation flow model categorization based on neglecting terms in the momentum equation (based on Kuriki et al.[10])

$$\underbrace{\frac{1}{g}\frac{\partial}{\partial t}\left(\frac{Q}{A}\right)}_{\text{Unsteady}}+\underbrace{\frac{1}{2g}\frac{\partial}{\partial x}\left(\frac{Q}{A}\right)^2}_{\text{Advection}}+\underbrace{\frac{\partial h}{\partial x}-i_0}_{\text{Pressuregradient}}+\underbrace{I_f}_{\text{Frictionslope}}=0$$

**: considered, *: simplified, -: neglected

	Unsteady term	Advection term	Pressure gradient term	Friction slope term	Advantages and Drawbacks
Storage function, Muskingham method	-	*	*	**	A fast calculation but not applicable for large area inundation
Overflow pond model	-	*	**	*	Not suited for a mild slope basin
Inundation pond model	*	-	**	**	Propagation in the transverse direction is not represented
Two-dimensional unsteady model	*	*	*	**	High accuracy but a long calculation time

Our society utilizes the ground's surface as the area of human activity (e.g. for settlements, food production, industries, and economies). The majority of the population and property are located in flat land. On the other hand, most flat or mild sloped ground is formed as a result of fluvial process, including sedimentation during flooding. As a result, our society has the significant and indispensable potential of becoming inundated. Despite longstanding efforts in river engineering and coastal engineering, the risk of inundation in the space utilized by humans has yet to become completely managed. The potential for suffering inundation seems, unfortunately, to be increasing in many places on the planet as a result of climate change.

Figure 1 depicts three inundation types segmented by general ground slope and fluid motion type. In the flat basin located within low-lying areas, three types of inundation are possible. Storm surges cause disasters as a result of water elevation rise due to a combination of low pressure weather, wind shear, and tidal motion. The driving force of the storm surge inundation propagation is the water gradient, and damage intensity can be estimated using water stage. Tsunami waves also cause high tide in coastal regions but have a large momentum as compared to storm surges. Tsunami inundation is an unsteady phenomenon and propagation should be described in a hydrodynamic manner. Due to a large inflow momentum and an instantaneously high water level, tsunamis can propagate to adversely sloped ground. In cases where the power of the tsunami is relatively small, inundation is limited in low-lying areas since the water, with a small kinetic energy, is not able to propagate in the adverse-sloped direction. A flood is a fluvial process shaping the ground's surface. The driving force behind flooding is the pressure gradient. Water is accelerated by gravity and propagates to the area far from the river or along the river's course (see Figure 2). Large velocity is observed due to the ground's slope, and the large velocity causes destructive damage.

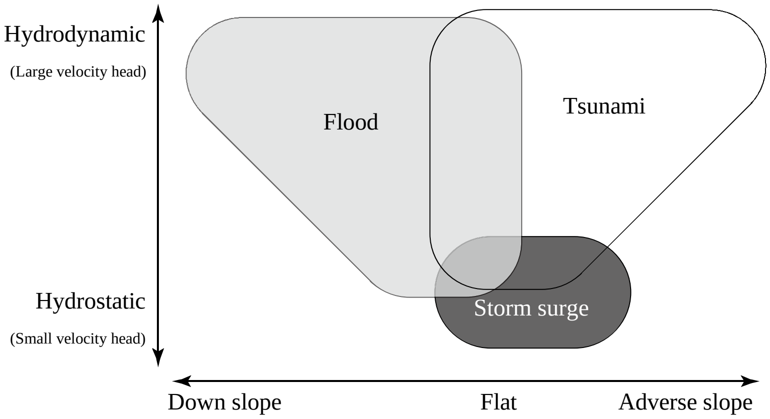
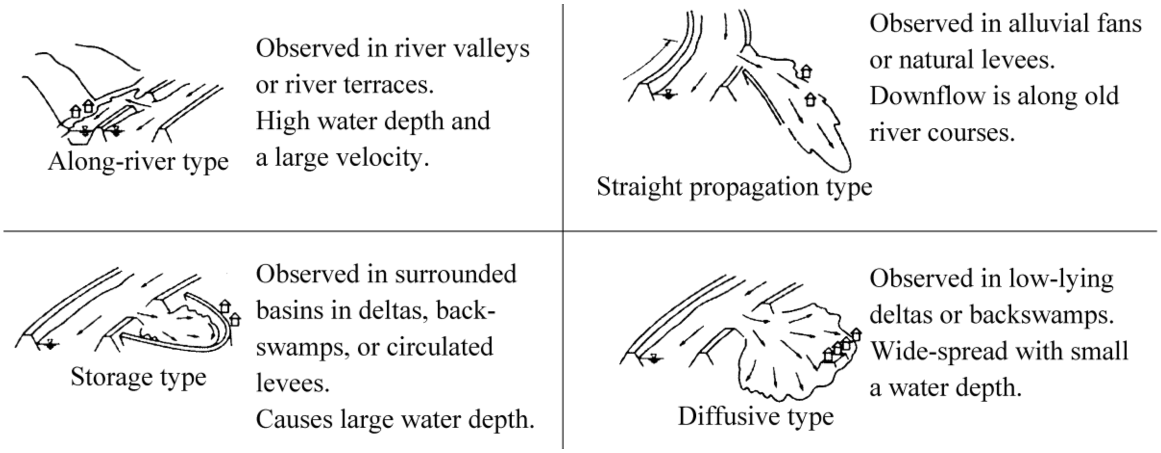


Figure 1: A categorization of inundation based on ground slope and the relative intensity of momentum.



Observed in river valleys or river terraces. High water depth and a large velocity.

Observed in alluvial fans or natural levees. Downflow is along old river courses.

Observed in surrounded basins in deltas, back-swamps, or circulated levees. Causes large water depth.

Observed in low-lying deltas or backswamps. Wide-spread with small a water depth.

Figure 2: An inundation flow categorization based on the type of propagation (based on Yamamoto et al.[11])

2.2 Hydrostatic inundation

Inundation categorized as hydrostatic in Figure 1 can be described well using simplified momentum equations, e.g. the storage cell model and/or by adopting the local equilibrium assumption between the water surface gradient and friction loss[12,13]. In the following discussion, the approach is referred to as ‘simplified’. Improvement in the spatial-resolution and the accuracy of topography directly increases the accuracy of estimated water depth. Detailed topographical information improves the shape of each storage cell (*h*-*V* relation) and the connection between the surrounding cells. The topographical data refinements contribute to an improved accuracy of inundation prediction[14,15]. The full hydrodynamic ‘detailed’ approach is, of course, applicable for hydrostatic type inundation[16], but a more economical model can be used if key hydraulic factors such as embankments and flood defense walls are treated carefully. The inundated water in a flat, but surrounded basin, tends to remain for long periods. Inundated water is drained by a sewer system or a drainage channel[17-21], so the accuracy of the inundation estimation is regulated by the accuracy of the drainage capacity estimation.

2.3 Hydrodynamic inundation

Representing hydrodynamic type inundation requires a hydrodynamic model. A distinct difference exists between down-slope and adverse-slope inundations for the dynamics of inundation propagation. In down slope inundation, local flow is strongly regulated by the local balance of the momentum sink and the water surface gradient. Momentum sink is caused by friction at the ground’s surface and by the pressure drag surrounding obstacles such as vegetation and structures. A trans-critical flow characteristic is more dominant for detail of the inundation flow. In adverse-slope inundation, the inflow boundary condition and the mass, as well as momentum influxes, regulate the flow; and local energy loss does not so much affect the general propagation pattern of the inundation. Comprehensive bed gradients and momentum loss determine the area to be inundated, but the inundated water with a large-momentum is able to bypass local flow blockage. The effect of local and discrete flow disturbances (e.g. ground undulation and flow obstacles) is limited to the area surrounding disturbances.

An important point to note is that continuous blockages have a definite impact on inundation propagation. Continuously elevated ground such as embankments for inundation protection or for transportation suspends the propagation of inundation[22]. The consecutive vegetation belt in coastal areas or planted along river courses, decelerates inundation flow[23] and deposits garbage and sediment particles transported by inundation flow.

3 MODELING STRATEGIES FOR DIFFERENT INUNDATION TYPES IN DATA-RICH ENVIRONMENTS

3.1 Suitable flow modeling approaches

The optimal inundation modeling approach depends upon the type of inundation to be estimated. Inundation types distinguished by flow characteristics are categorized in Figure 3. Areas A, B, and C in Figure 3 require a full hydrodynamic model for describing the propagation of inundation, but simplified modeling is sufficient for modeling a D type inundation. In area A, an inhomogeneous flow is formed as a result of the local unbalances among the terms of momentum equation so the 'detailed' model is suitable. On the other hand, in case there is a specific direction for the large-scale ground slope, the general propagation pattern of inundation can be reasonably estimated using a large-scale point of view (e.g. the along-river type and the straight propagation type in Figure 2). In this context, for estimating the area to be inundated and the travel-time of inundation, an 'integral' or well-tuned 'large-scale' inundation model[24] can be utilized. For estimating local and flow related damage during inundation (e.g. the structural damage or the deformation of land), resolving detailed flow directly by considering local topography and the effect of obstacles is required. Moreover, in many cases, the transition between subcritical and super-critical flows surrounding obstacles and specific points arises, and this flow transition sometimes strongly regulates local flow and inundation propagation. Such aspects strongly depend on local topographic detail[1], so it is difficult to generalize and to treat a sub-grid model of the 'integral' model. Accordingly, resolving detailed flow directly by using the 'detailed' model is essential and beneficial for representing the inundation flow categorized in area A.

For area B, the approach discussed for area A is, in general, applicable. However, the routing of inundation propagation becomes more sensitive to the detail of the topography because the large-scale ground slope is almost flat. Thus, the 'detailed' or, at least, the 'integral' type model is required in order to ensure the accuracy of the prediction. If inundation lasts over a longer duration, a careful estimation of drainage performance is more essential than flow modeling.

In area C, the contribution of the inflow condition to inundation propagation is larger, in general, than the local topography, so the 'integral' model is suitable for describing the propagation of inundation. Utilization of the ‘detailed’ model for this type of area provides a more realistic and detailed process for inundation, but may not improve the accuracy of the general pattern of inundation propagation as compared with results estimated using an ‘integral’ approach. Continuous topographic features are a key factor regulating inundation propagation, so these features should be evaluated precisely in inundation simulations. ‘Detailed’ approaches directly represent the effect of this feature. Careful treatment of this feature in ‘integral’ models (e.g. by considering the anisotropy of sub-grid topography[25,7] is required.

In area D, a mass balance, including drainage ability, is essential for inundation prediction. The ‘simplified’ model is suited for predictions in this area because dynamic processes have a limited impact[26]. Water level can be estimated in practice using a comparatively rough spatial resolution model. Local water depth can be calculated afterward using a detailed elevation distribution.

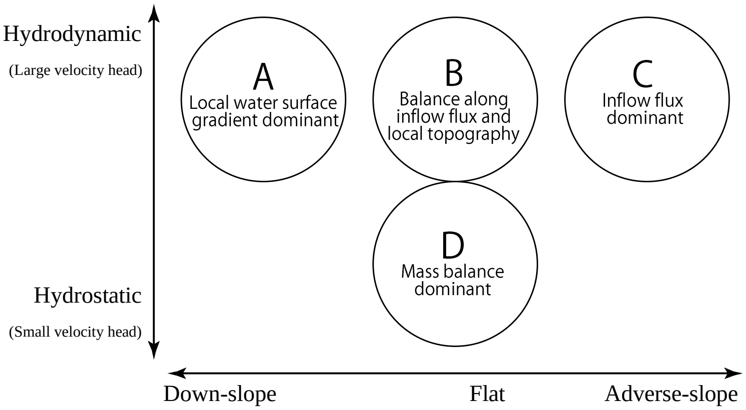


Figure 3: Suitable approaches for different inundation categorizations.

3.2 Prior evaluations, real time forecasting, and data assimilation

The time duration of inundation on steep-sloped ground (including both down and adverse slopes) is comparatively short. For A and C type inundation, the prior evaluation of inundation based on a wide variety of disaster scenarios is essential since it is difficult to conduct a real-time prediction. The counter measure (e.g. evacuation planning) should be carefully prepared before a disaster actually happens. For cases in which inundation has occurred in a comparatively flat domain, inundated areas tend to spread over a large area for long periods, so real-time forecasting of inundation prediction is practical and effective for disaster management. In the forecasting process, an assimilation of inundation flow based on the data obtained from observation stations or satellite data is effective for improving the accuracy of forecasting. To ensure enough lead time (e.g. for evacuation), precise and long-range predictions of the inflow condition, namely a metrological forecasting or a tsunami warning system, is required. Today, the approach is stepping toward practical use, but it is not applicable for A and C type inundation because of those short time duration.

4 CONCLUSION

In this work, inundation flow was categorized into four types based on general topographical situations and flows. The topographical situation was represented by the general ground slope and the differences in flow types were denoted by the balance between the dynamic and static aspects of fluid motion. Four modeling approaches - ‘simplified’, ‘large-scale’, ‘integral’ and ‘detailed’ - were defined and their suitability for each inundation type was discussed. As a result, the significance of the modern inundation flow models, ‘integral’ and ‘detailed’, was determined.

REFERENCES

[1] S. Haider, A. Paquier, R. Morel and J.-Y, Champagne, “Urban flood modelling using computational fluid dynamics”, *Water & Maritime Engineering ICE*, **156**, 129-135 (2002).

[2] D.M. Cobby, D.C. Mason, M.S. Horritt and P.D. Bates, “Two-dimensional hydraulic flood modelling using a finite-element mesh decomposed according to vegetation and topographic features derived from airborne scanning laser altimetry”, *Hydrological Processes*, **17**, 1979-2000 (2003).

[3] P.D. Bates, K.J. Marks and M.S. Horritt, “Optimal use of high-resolution topographic data in flood inundation models”, *Hydrological Processes*, **17**, 537-557 (2003).

[4] S. Soares-Frazão and Y. Zech, “Dam-break flow through an idealized city”, *Journal of Hydraulic Research*, **46**, 648-658 (2008).

[5] K.E.K. Abderrezzak, A. Paquier and E. Mignot, “Modelling flash flood propagation in urban areas using a two-dimensional numerical model”, *Natural Hazards*, **50**, 433-460 (2009).

[6] S. Soares-Frazão, J. Lhomme, V. Guinot and Y. Zech, “Two-dimensional shallow-watr model with porosity for urban flood modelling”, *Journal of Hydraulic Research*, **46**, 45-64 (2008).

[7] B.F. Sanders, J.E. Schubert and H.A. Gallegos, “Integral formulation of shallow-water equations with anisotropic porosity for urban flood modelling”, *Journal of Hydrology*, **362**, 19-38 (2008).

[8] J.E. Schubert, B.F. Sanders, M.J. Smith and N.G. Wright, “Unstructured mesh generation and landcover-based resistance for hydrodynamic modeling of urban flooding”, *Advances in Water Resources*, **31**, 1603-1621 (2008).

[9] N.M. Hunter, P.D. Bates, S. Neelz, G. Pender, I. Villanueva, N.G. Wright, D. Liang, R.A. Falconer, B. Lin S. Waller, A.J. Crossley and D.C. Mason, “Benchmarking 2D hydraulic models for urban flooding”, *Water Management, ICE*, **161**, 13-30 (2008).

[10] M. Kuriki, T. Suetsugi and H. Kobayashi, “Inundation simulation manual”, *Technical note of PWRI*, No 3400, (1996) in Japanese.

[11] K. Yamamoto, T. Suetsugi and S. Kiryu, “Inundation simulation (2)”, *Technical note of PWRI*, No 2175, (1985) in Japanese.

[12] N.M. Hunter, P.D. Bates, M.S. Horritt and M.D. Wilson, “Simple spatially-distributed mod-

els for predicting flood inundation: A review", *Geomorphology*, **90**, pp.208-225, (2007).

[13] A. Pathirana, S. Tsegaye, B. Gersonius and K. Vairavamoorthy, "A simple 2-D inundation model for incorporating flood damage in urban drainage planning", *Hydrology and Earth System Sciences Discussions*, **5**, 3061-3097 (2008).

[14] D. Yu and S.N. Lane, "Urban fluvial flood modelling using a two-dimensional diffusion-wave treatment, part 2: development of a sub-grid-scale treatment", *Hydrological Processes*, **20**, 1567-1583 (2005).

[15] H.K. McMillan and J. Brasington, "Reduced complexity strategies for modelling urban floodplain inundation", *Geomorphology*, **90**, 226-243 (2007).

[16] T.W. Gallien, J.E. Schubert and B.F. Sanders, "Predicting tidal flooding of urbanized embayments: A modeling framework and data requirements", *Coastal Engineering*, **58**, 567-577 (2011).

[17] M.H. Hsu, S.H. Chen and T.J. Chang, "Inundation simulation for urban drainage basin with storm sewer system", *Journal of Hydrology*, **234**, 21-37 (2000).

[18] X. Zhang, S. Oishi, H. Ishidaira and K. Takeuchi, "Practical aspects in the simulation of flood inundation using 2D shallow water equations on a complex land-cover", *J. Japan Soc. Hydrol. & Water Resour.*, **16**, 501-517 (2003).

[19] O. Mark, S. Weesakul, C. Apirumanekul, S. B. Aroonnet and S. Djordević, "Potential and limitations of 1D modelling of urban flooding", *Journal of Hydrology*, **229**, 284-299 (2004).

[20] K. Kawaike, K. Inoue, K. Toda, M. Noguchi, "Inundation flow analysis due to heavy rainfall in low-lying river basin", *Journal of Hydroscience and Hydraulic Engineering, JSCE*, **22**, 1-14 (2004).

[21] J. Leandro, A.S. Chen, S. Djordjević and D.A. Savić, "Comparison of 1D/1D and 1D/2D coupled (Sewer/Surface) Hydraulic models for urban flood simulation", *Journal of Hydraulic Engineering*, **135**, 495-504 (2009).

[22] R. Tsubaki, Y. Kawahara, T. Sayama and I. Fujita, "Analysis of geomorphic and hydraulic conditions causing railway embankment breach due to inundation owing to heavy rainfall", *Journal of Hydraulic and Hydroscience Engineering, JSCE*, (2012), accepted.

[23] S. Yoshida, Y. Kawahara, R. Tsubaki and Y. Yamada, "The effects of tree belt along levee on levee-break flows", 33rd IAHR Congress, pp.976-983, Vancouver, (2009).

[24] A. Casas, S.N. Lane, D. Yu and G.Benito, "A method for parameterising roughness and topographic sub-grid scale effects in hydraulic modelling from LiDAR data", *Hydrology and Earth System Sciences*, **14**, 1567-1579 (2010).

[25] G. Huang and M. Isobe, "A proposal for flood damage reduction in urban area by 'water pathway' ", *Annual Journal of Hydrauic Engineering, JSCE*, **50**, 571-576 (2006) in Japanese.

[26] P.D. Bates, R.J. Dawson, J.W. Hall, M.S. Horritt, R.J. Nicholls, J. Wicks, M.A.A.M. Hassan, "Simplified two-dimensional numerical modelling of coastal flooding and example application", *Coastal Engineering*, **52**, 793-810 (2005).