5.2 Run-off and Inundation Analysis

5.2.1 Development of Run-off and Inundation Model

The Nadi River Basin is divided into run-off area in the mountainous area and inundation area in the low land area by its run off characteristics. Therefore, the integrated discharge basin and inundation area model which can analyze the basin as a unit is to be established.

(1) Selection of Model

Run-off and Inundation Model is developed to facilitate the following functions:

- Simulation of the flooding of both inland water and external water, reflecting the features of the basin (topography, land use, etc.)
- Evaluation of the effectiveness of various flood control measures such as integrated measure for rainfall, river improvement and so on, which will be implemented in the basin.

As for analytical measures of discharge from basin, concentration model such as rational formula, tank model, storage function model and so on, have been applied so far. The required parameters of these models are average value or represent value in the basin, and the results derived from those models are limited to the information at the end of the basin. However, continues record of water level and velocity of all points in the basin is required in recent years. Since the concentration model cannot meet those requirements, distribution model is proposed as the alternative model.

The characteristics of the Distribution Model are as follows:

- The whole basin is separated into micro grid.
- Differences of the topography, geology, and land use and so on are reflected in the grid.
- Rainfall is given to each grid directly
- Flows among grids can be traced

Distribution Model is applied to analyze the run-off and inundation in this project due to the following reasons:

- The analyses of rainfall discharge and inundation at every location of the basin are required.
- The effectiveness of the various flood control measures are to be verified

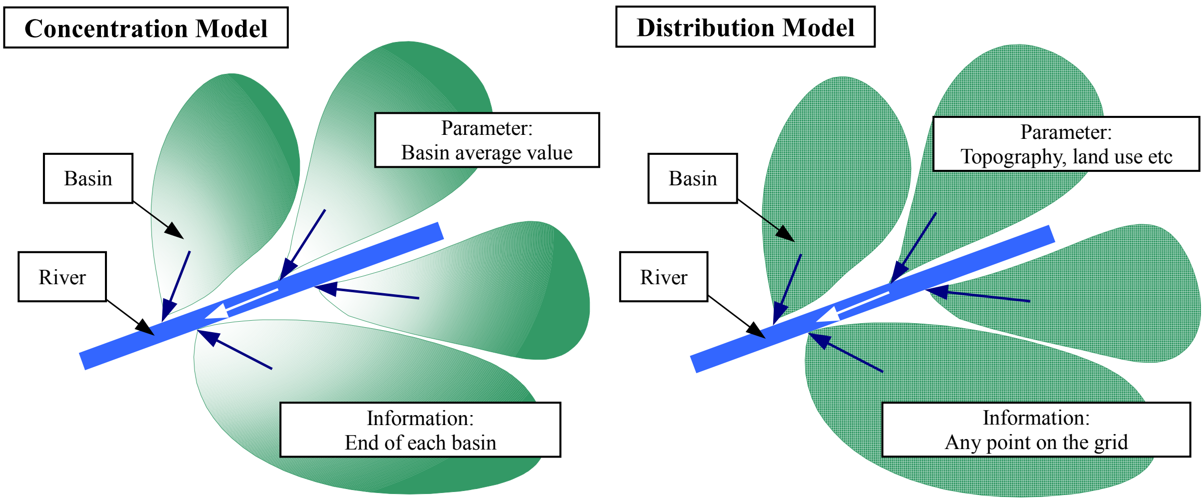


Figure 5.2-1 Image of Concentration Model and Distribution Model

Flood inundation model in the basin shall be separated into two based on the topographical features of the basin: one for the mountain and hill area as discharge basin and the other for the lowland area as inundation area. General description of each hydraulic model is as provided below.

- Model of Run-off Area

Kinematic Wave Method is applied, which presents flow on the slope without influence from downstream water level. The model of discharge basin is to be distribution type run-off analysis model which has same grid structure in discharge area and the inundation area in order to give discharge to micro grid in the inundation area and to trace each flow on the grid along topographic gradient.

- Model of Inundation Area

Dynamic Wave Method, which can show the influence of topography and structures such as drains on flow, is applied to analyze the flow in the inundation area.

Two-Dimensional Un-Steady Flow Model which can model the phenomena of inundation in detail is selected for the whole model.

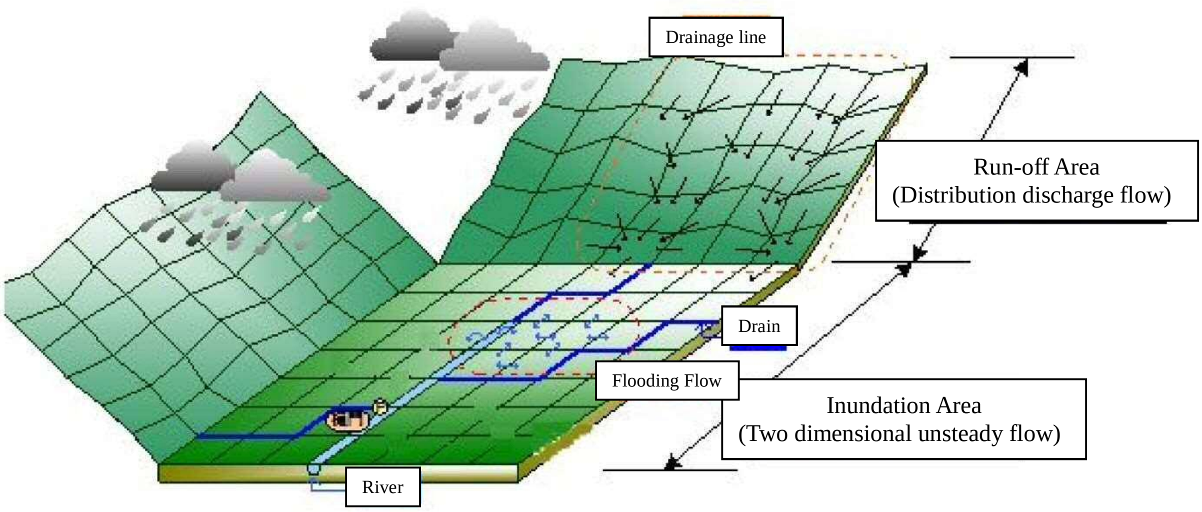


Figure 5.2-2 Outline of Run-off and Inundation Analysis Model

■ Run-off and Inundation Pattern according to Topographic Characteristics

Topography	● Upstream area is mountainous and the gentle slope continues up to the lowland area. ● Downstream is lowland area.
Rainfall	● Rainfall flows down on the slope of the mountain slope, gentle of middle reach to the lowland area. ● Drainage ability declines because of the sea.
Prospected inundation	● Inundation water flows down along river in the uphill area. ● Inundation is spread under the influence of water level of downstream in the lowland area.

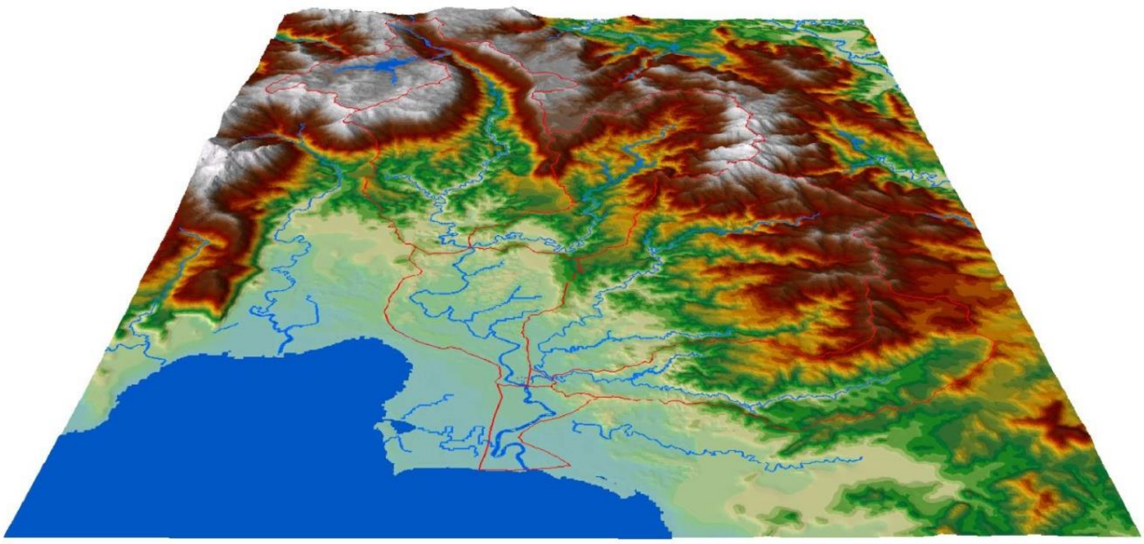


Figure 5.2-3 Topographic Feature of the Nadi River Basin

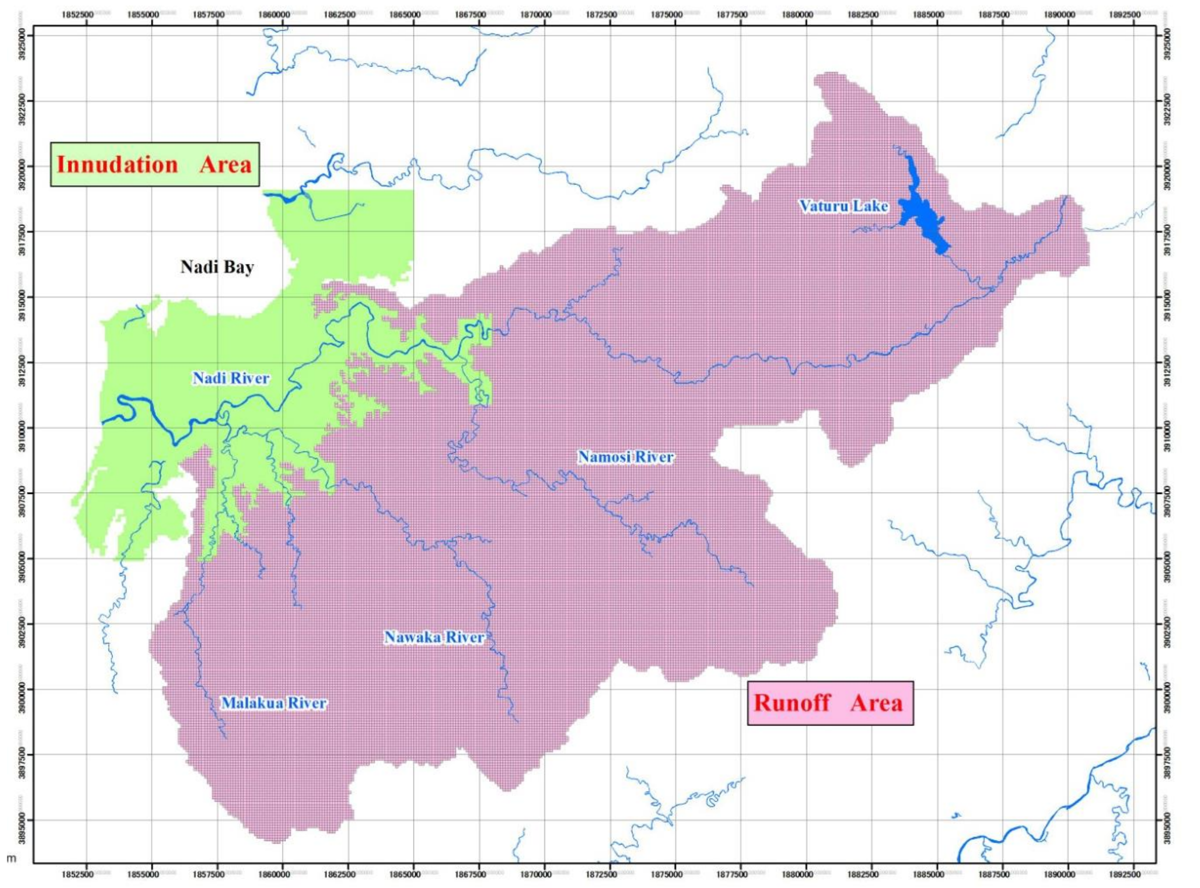
(2) Segmentation of grid in the entire basin

The entire basin is segmented into 100 m * 100 m grid in order to analyze run-off and inundation, and flow condition is to be traced in each grid.

The total number of grids in the basin is 56,894 out of which 46,680 grids are in the runoff area and 10,214 grids are in the inundation area as shown in Table 5.2-1.

Table 5.2-1 Number of Grids in the Model

Item	Number of Grids	Area (ha)
Inundation area	10,214	10,214
Run-off area	46,680	46,680
Total	56,894	56,894



Source : JICA Study Team

Figure 5.2-4 Segmentation of Grid in Basin

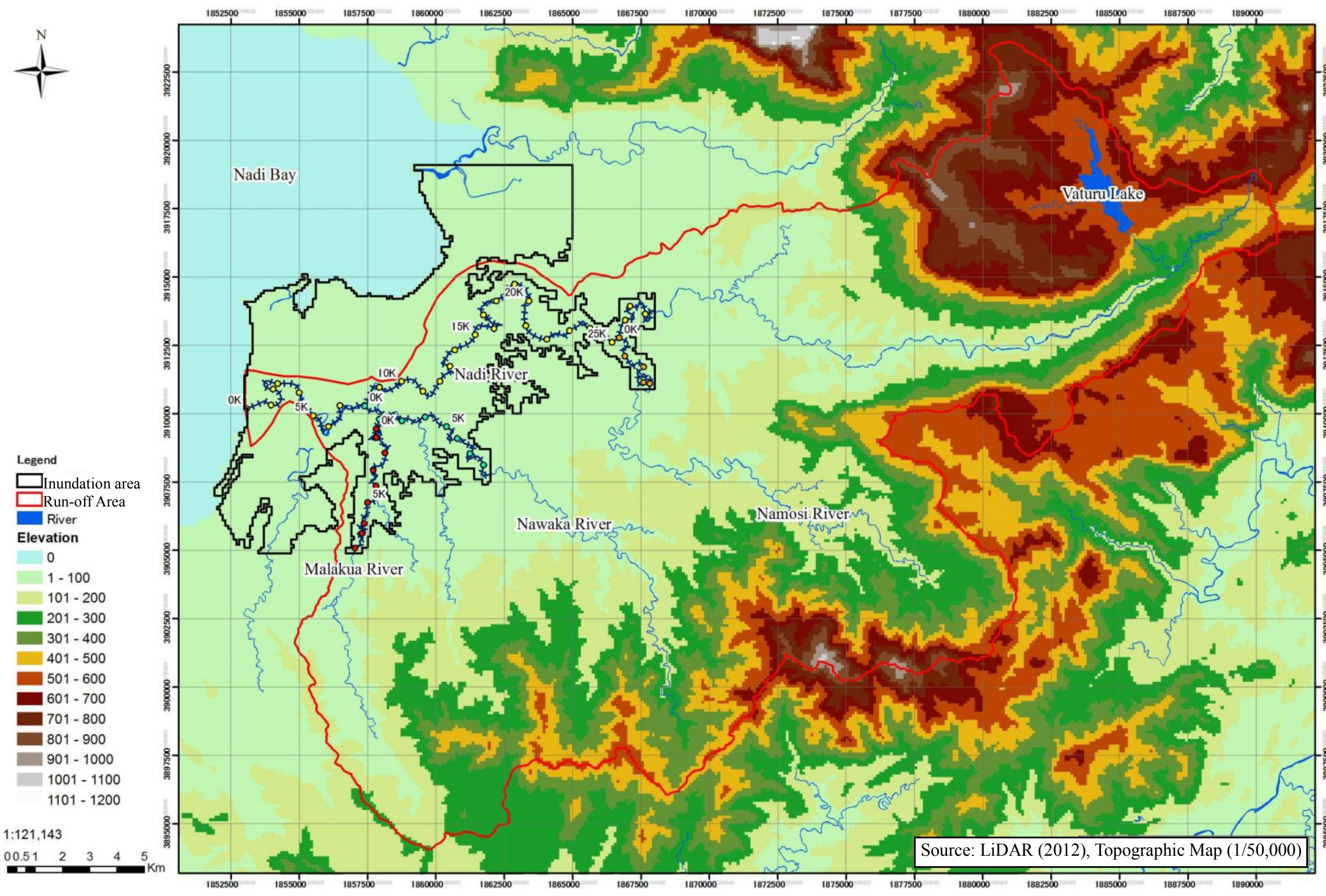
(3) Setting of runoff area and inundation area

As mentioned above, the run-off and inundation model in the basin is separated into a model for the run-off area and another for the inundation area.

In general, the maximum inundation area is defined by the topographical conditions. Also, it is defined by the artificial structures such as river dike adjacent to the inundation area. In this study, topographical and artificial conditions will be considered for the designation of the target inundation area.

In the Study, target inundation area is determined by the maximum potential inundation area based on the actual inundation records and LiDAR elevation data.

The distribution of run-off area and inundation area is shown in Figure 5.2-5.

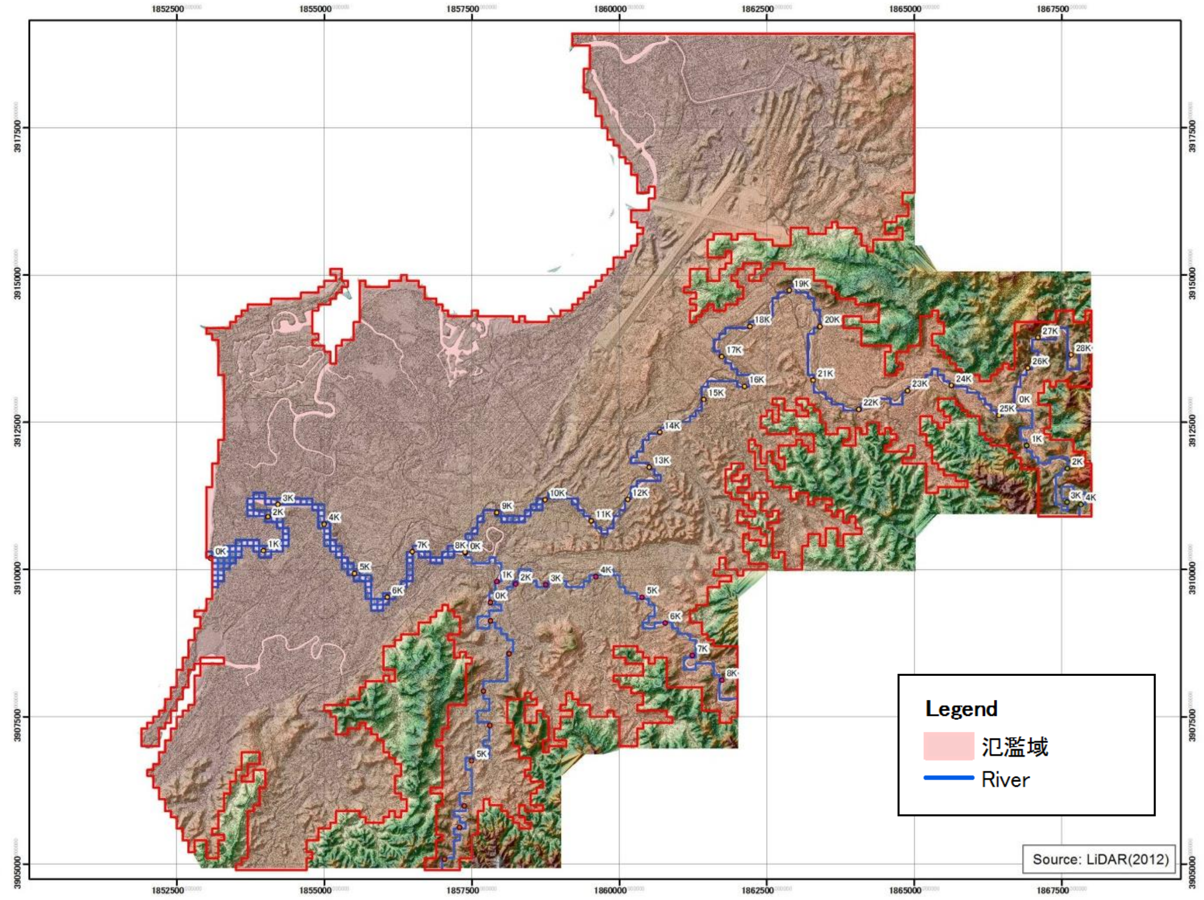


Source : JICA Study Team

Figure 5.2-5 Run-off Area and Inundation Area

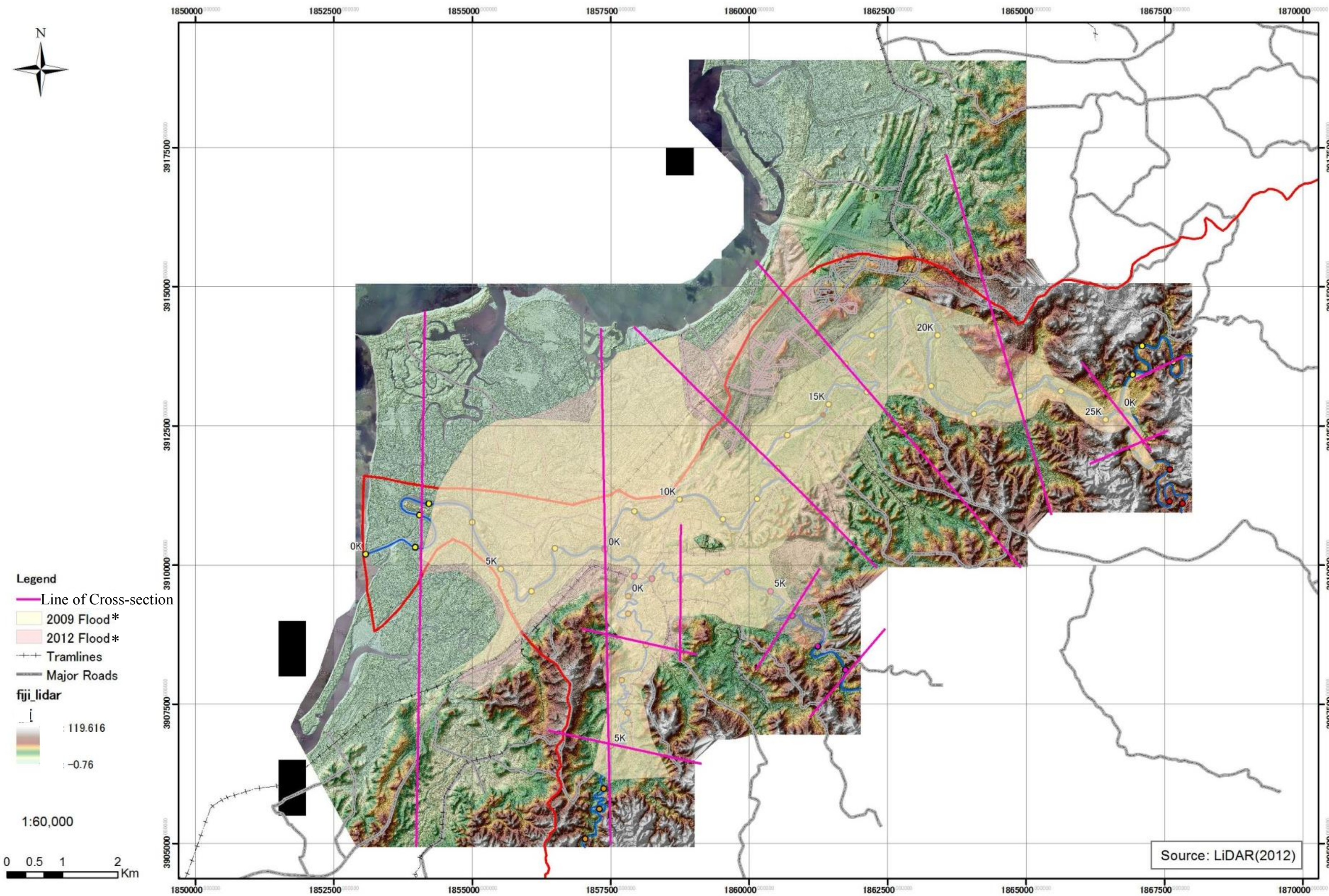
Setting of inundation area

Target inundation area is set based on elevation map, which is produced using LiDAR data (1m * 1m grid), and actual inundation record surveyed by SPC/SOPAC (refer to Figure 5.2-7). The maximum inundation area is set as “surveyed actual / assumed inundation depth + 5m” here. Detail cross-sections of the inundation area are shown in Figure 5.2-8 to Figure 5.2-12 and the set target of inundation area is shown in Figure 5.2-6.



Source : JICA Study Team

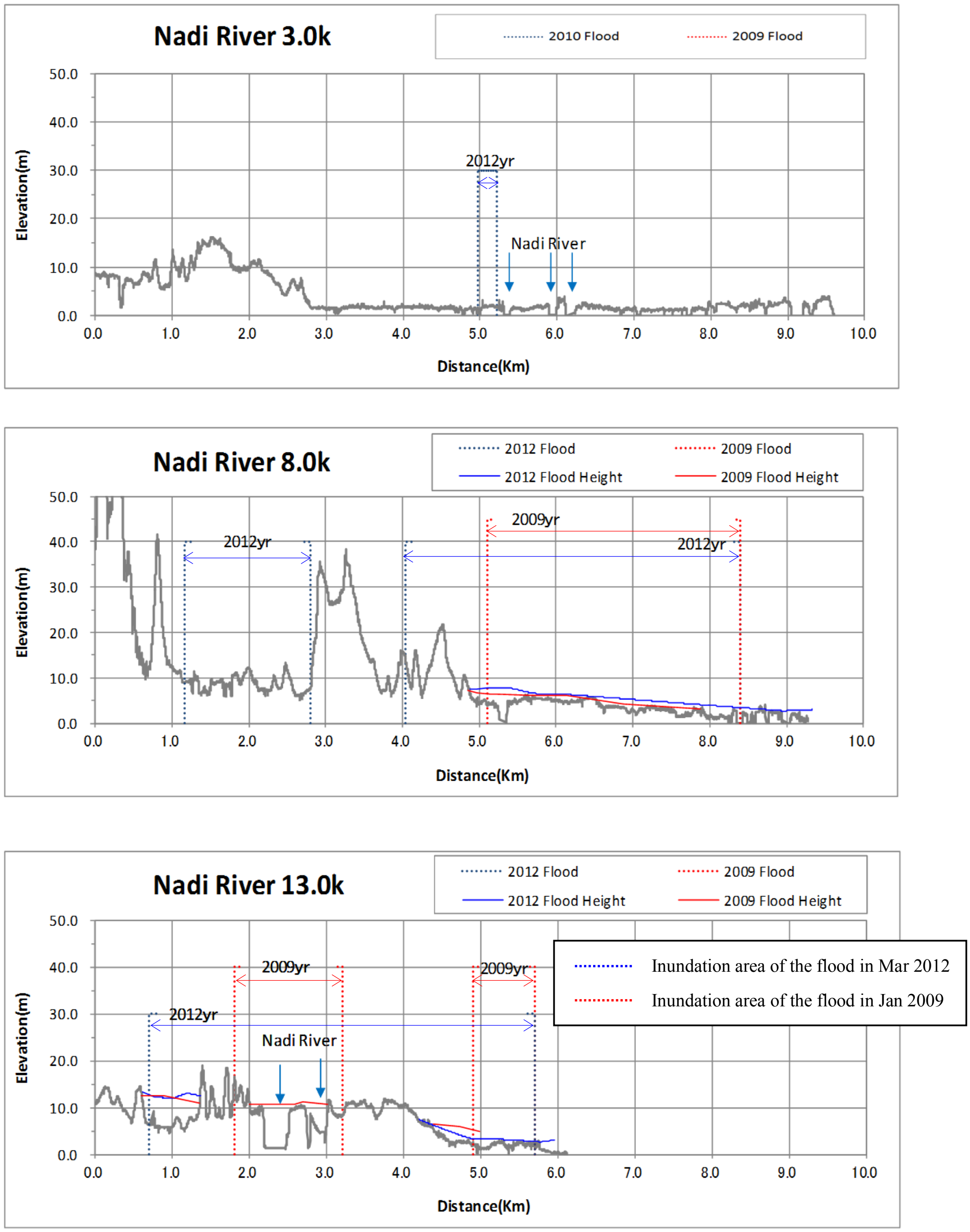
Figure 5.2-6 Target Inundation Area



Source : JICA Study Team

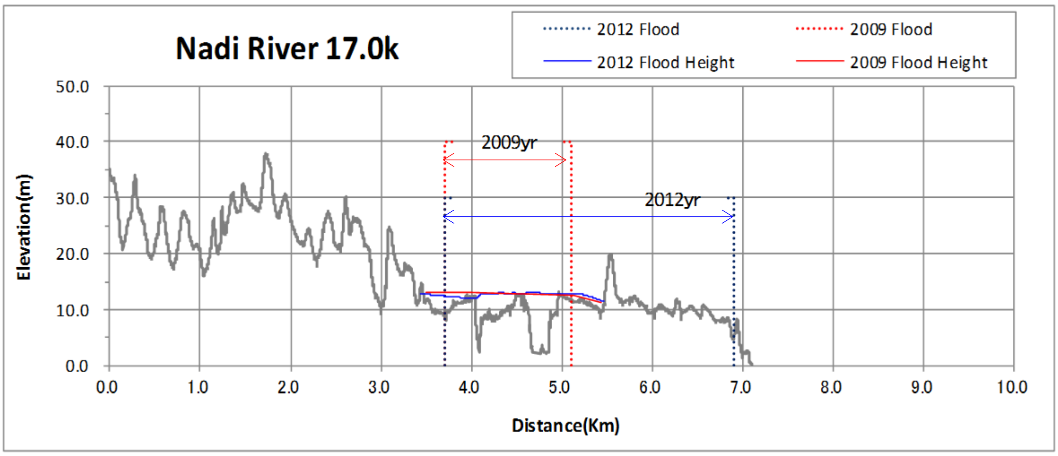
*Actual inundation record was surveyed by SPC/SOPAC

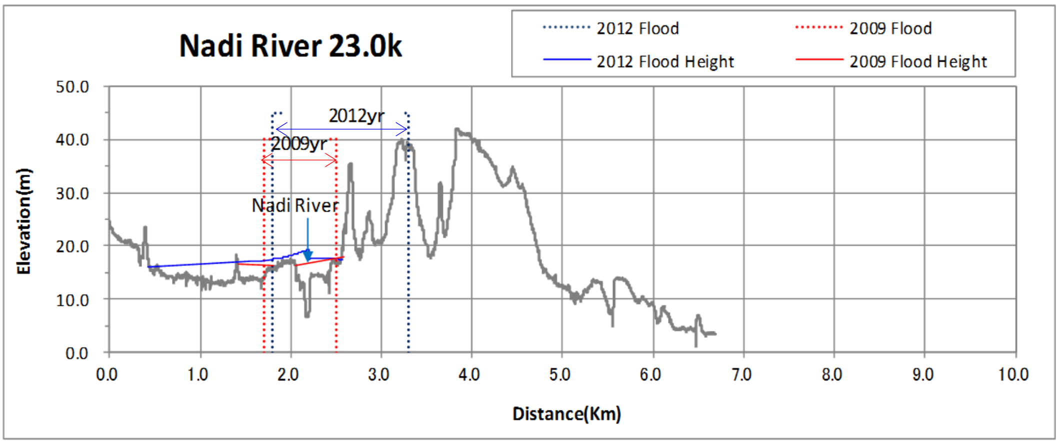
Figure 5.2-7 Actual Inundation Record and Lines of Cross-section

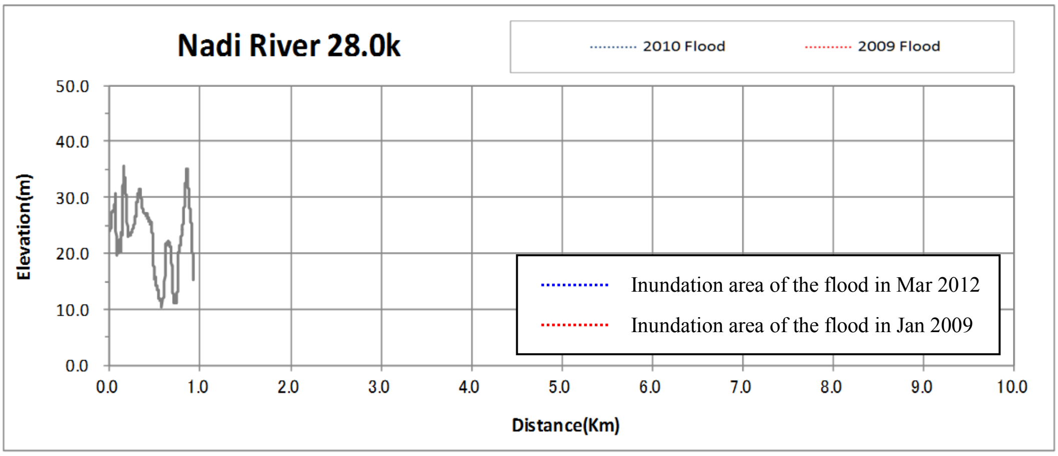


Source : JICA Study Team

Figure 5.2-8 Inundation Area on Cross-section (1/5)

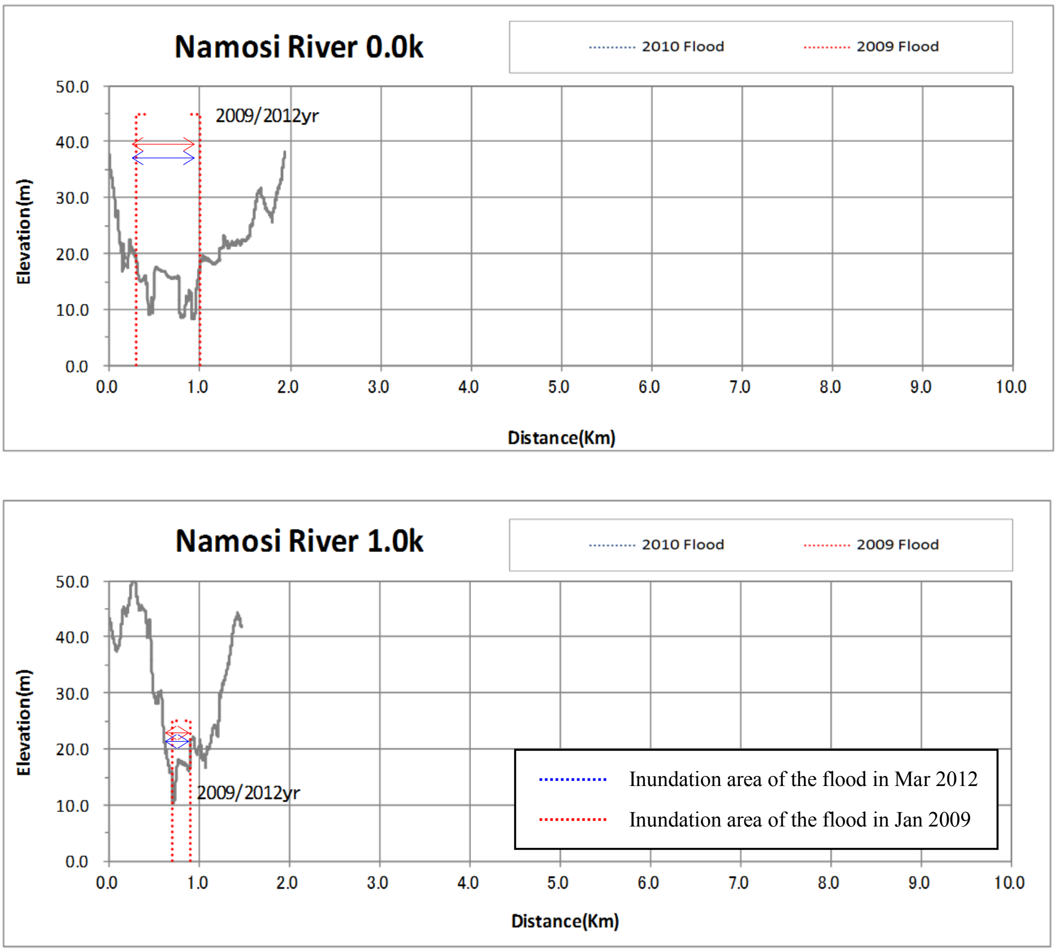






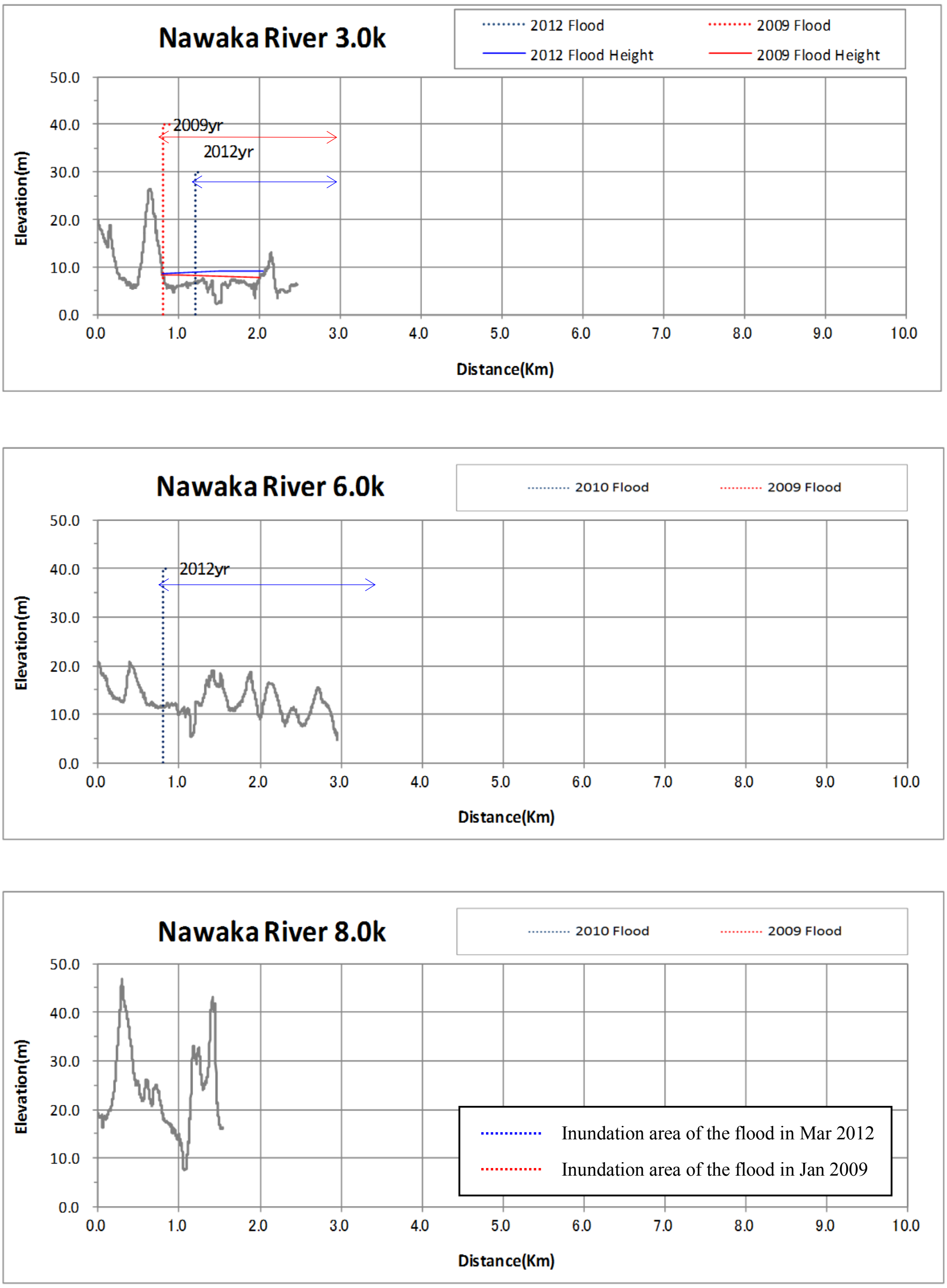
Source : JICA Study Team

Figure 5.2-9 Inundation Area on Cross-section (2/5)



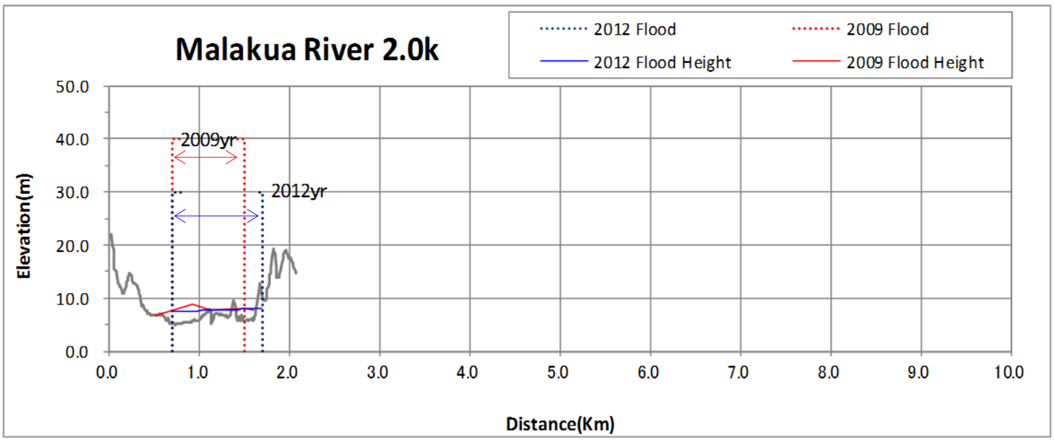
Source : JICA Study Team

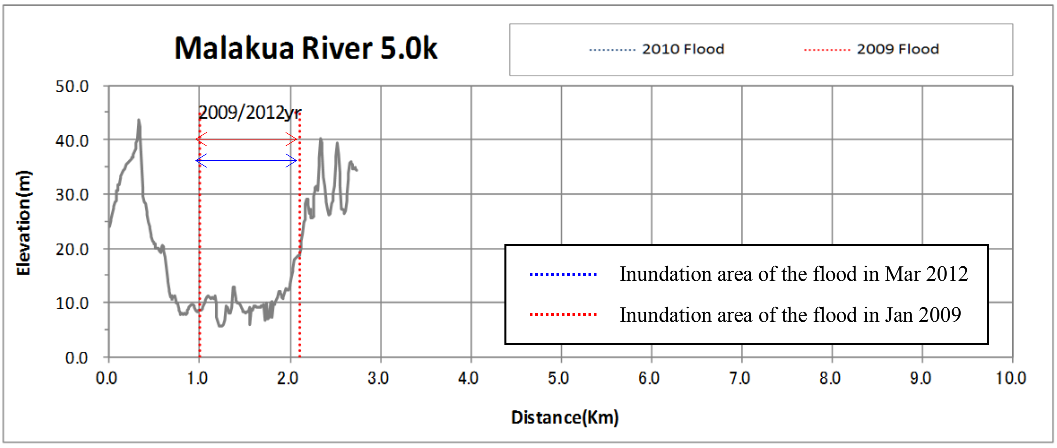
Figure 5.2-10 Inundation Area on Cross-section (3/5)



Source : JICA Study Team

Figure 5.2-11 Inundation Area on Cross-section (4/5)





Source : JICA Study Team

Figure 5.2-12 Inundation Area on Cross-section (5/5)

(4) Basic Structure of the Flood Inundation Model

Basin characteristics are as described below, and they should be reflected in the flood inundation model as a basic structure of the model.

- The basin can be separated into 2 areas, mountain and hill area as run-off area, and lowland area as inundation area
- Rainfall flows down on the slope of the mountain, gentle slope of middle reach to the lowland area through the main rivers, such as the Nadi River and its major tributaries.
- Large-scale floods occurred in Jan 2009 and Mar 2012 and the occurrence frequency of inundation is high
- Inland flooding occurs in the lowland area due to the poor drainage system

Required functions for building up the Run-off and Inundation Model are as follows:

- Representing the combination of the inland flooding and external flooding.
- Analyzing discharge and flooding simultaneously for the same area.
- Obtaining time series of fluctuation of river water level taking into consideration of the water level at downstream edge of the river, discharge volume from the discharge basin and the influence of the bridges.
- Areal expansion and propagation velocity of inundation flow can represent flow resistance, reflecting the land use and density of houses.
- Taking into account the effects of micro topography and drain embankment and securing high accuracy and precision.
- Analyzing the flow of the sewerage conduit and channel (How the conduit/channel flows?), and representing surface flows, and urban drainage system.
- Analyzing flood retention facility so that its function in the flood control can be presented.

To satisfy above function, analytical models described blow are required.

- Rainfall Model - Rainfall falls on each grid in all basins by time series distribution
- River Channel Model - River water level is presented by the time series fluctuation using one dimension unsteady flow model which can present the overflow and dike breaks, reflecting forced drainage to river and sea water level.
- Run-off Area Model - Distribution Discharge Model (Kinematic Wave) which can trace the discharge along the river channel following the feature of topography is applied.
- Inundation Area Model - Two dimension unsteady flow model which can trace the propagation of inundation flow under the influence of drainage system composed of channel, pumps, and embankment, besides topographical features is applied.

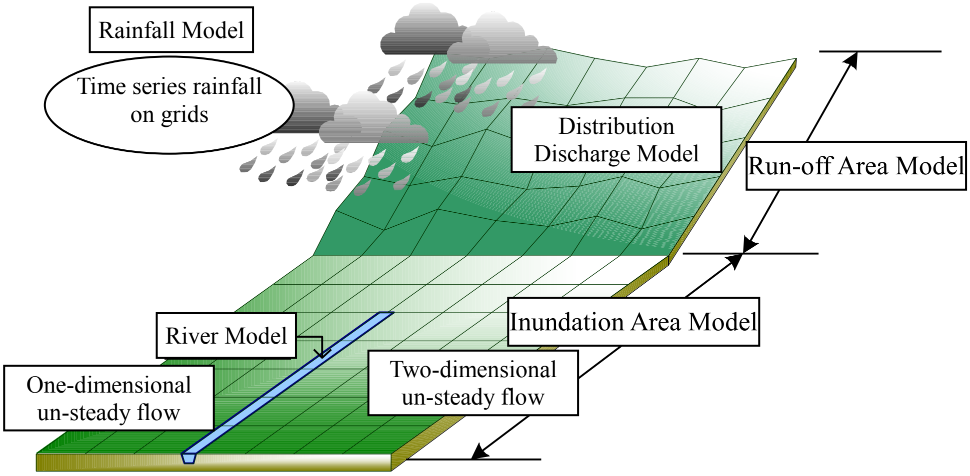


Figure 5.2-13 Basic Structure of Run-off and Inundation Analysis Model

5.2.2 General Description of Each Model

(1) Rainfall model

Rain falls on each grid in all basins by time series distribution. Spatial distribution is set by Thiessen method. Figure 5.2-14 shows an example of segmentation of Thiessen, targeting the flood in March 2012.

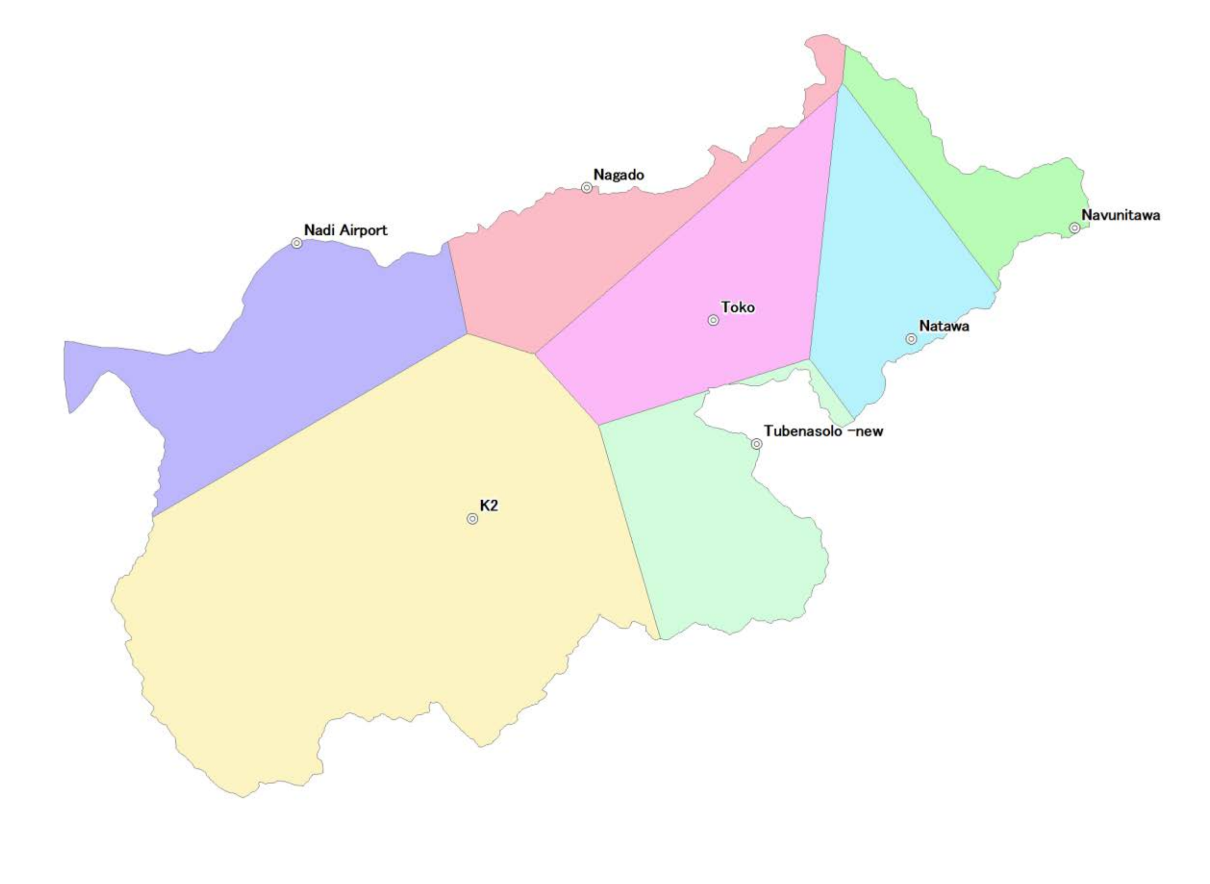


Figure 5.2-14 Example of Segmentation of Thiessen (Hourly rainfall of Mar 2012)

(2) Model of Run-off Area

Distribution flow model is applied to the run-off area. The Kinematic Wave Method used to mode the flow distribution which is segmented by square grid taking into consideration of loss of rainfall, and tracing the flow from grid to grid. The Kinematic wave method is explained as follows.

1) Composition of Distribution Flow Model

Basic formula of Kinematic Wave Method

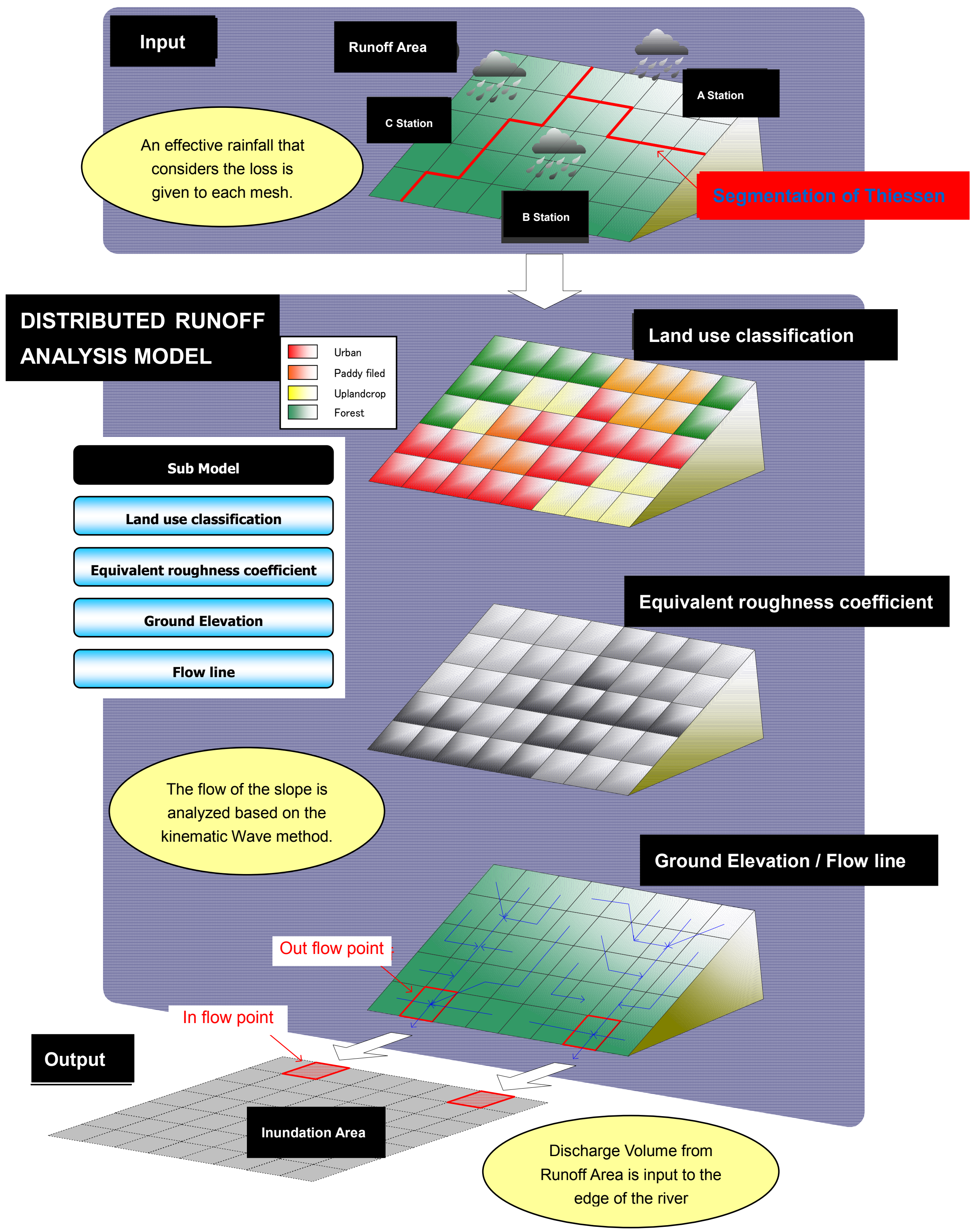
$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r_e \quad (0 \leq x \leq L)$$

$$q = \alpha h^m$$

Where, t: time, x: distance from the top of slope, h: water depth, q: unit flow on slope,
L: length of slope, r_e: effective rainfall
α, m: numerical constant which are defined below,

Manning : $\alpha = \sqrt{i} / n$, $m = 5/3$

Where, i: slope gradient. n: coefficient of kinematic wave



Source : JICA Study Team

Figure 5.2-15 Outline of Model of Run-off Area

2) Rainfall Loss Model

Rainfall is given to each grid by the depth of effective rainfall which is obtained reducing rainfall loss from the total rainfall, and the rainfall loss is the rainfall infiltrates to ground and is reserved to reservation facilities and is not to contribute to run-off.

Image of effective rainfall and primary runoff ratio of each land use pattern and saturated rainfall is shown in Figure 5.2-16, and primary values of f1, Rsa and fsa are shown in Table 5.2-2.

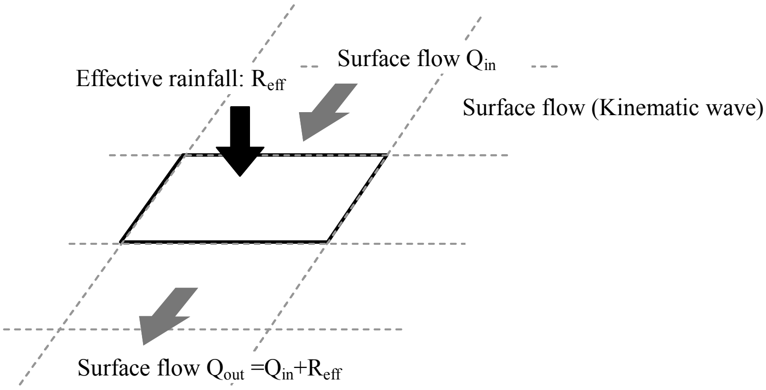


Figure 5.2-16 Image of Effective Rainfall

Table 5.2-2 Primary Value of f1, Rsa, fsa (f1: initial runoff ratio, Rsa: saturation rain and fsa: runoff ratio at saturated situation)

Landuse classification	f1	Rsa	fsa	Application
Grassland	0.15	300	1	Grasslands
				Grazing
				Mandarine
Farmland	0.15	300	1	Bananas
				Fallow
				Idle former cane areas
				Mixed vegetables
				Others
				Pawpaw
				Pineapple
				Root crops
				Sugarcane
Water area	1	0	1	Pond
				Vaturu dam
Paddy field	0	50	1	Rice
Urban area	0.7	55	1	Airport
				Commercial/Industrial
				Nadi Town
				Residential
				School
Forest	0.25	150	1	Forests
				Land reclamation
				Mangroves
				Pine
Golf Course	0.15	300	1	Golf Course

3) Topography Model

a) Setting of elevation

Elevation is set in the topography model. Average elevation of each 100m grid in inundation area is set based on the LiDAR survey data, and elevation of run-off area is set based on 1/50,000 topography map which is published by the government of Fiji. Detail procedures are as shown below.

*** Inundation area**

By overlapping the LiDAR data on 100m grid, and calculating the average elevation of LiDAR data contained in each 100m grid.

*** Run-off Area**

By interpolating the counter line (20m interval) of 1/50,000 topographic map and rasterizing it to 50m square pixels, and overlapping the raster data on 100m grid, and calculating average elevation of raster data contained in each100m grid.

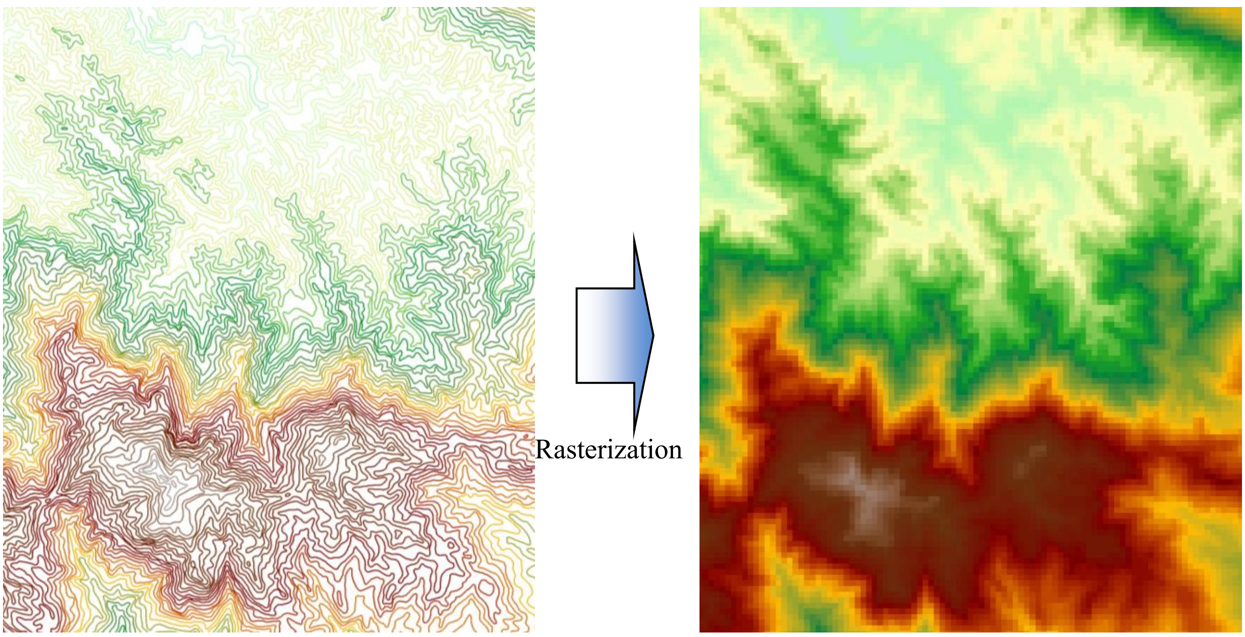


Figure 5.2-17 Rasterization of Counter Line

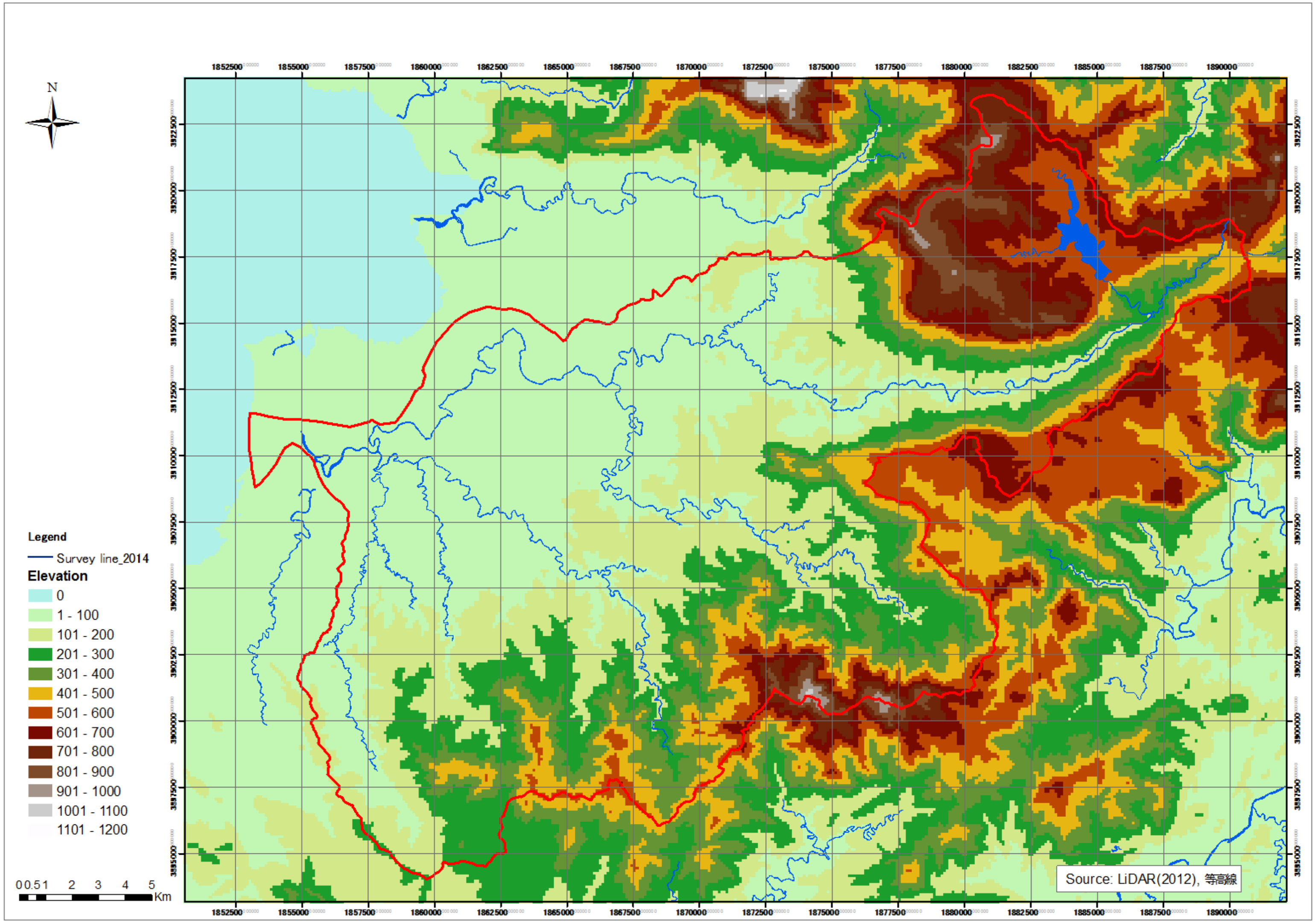


Figure 5.2-18 100m Grid Elevation

4) Equivalent Roufhness Coefficient

Equivalent roughness coefficient is defined by land use. Equivalent roughness coefficient is as shown in Table 5.2-3 depending on land use.

Land use map is as shown in Figure 5.2-20.

Table 5.2-3 Land use and Equivalent Roughness Coefficient

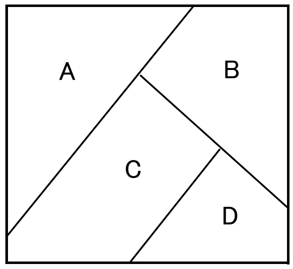
Land use	Equivalent Roughness Coefficient※ $n(m^{-1/3}s)$
Water	0.0
Forest	0.7
Dry field, Open area	0.3
Paddy field	2.0
Urban area	0.005-0.1

Source: Handbook for management of medium and small size rivers (draft)

Equivalent roughness coefficient can be set as combined coefficient by the area ratio of land use in each grid as shown in Figure 5.2-19 and the primary value is set as shown in Table 5.2-4.

Table 5.2-4 Equivalent Roughness Coefficient (Primary Value)

Landuse classification	Roughness	Application
Grassland	0.30	Grasslands
		Grazing
		Mandarine
Farmland	0.30	Bananas
		Fallow
		Idle former cane areas
		Mixed vegetables
		Others
		Pawpaw
		Pineapple
		Root crops
		Sugarcane
Water area	0.00	Pond
		Vaturu dam
Paddy field	2.00	Rice
Urban area	0.03	Airport
		Commercial/Industrial
		Nadi Town
		Residential
		School
Forest	0.70	Forests
		Land reclamation
		Mangroves
		Pine
Golf Course	0.3	Golf Course



$$Ng = \frac{Na*Aa + Nb*Ab + Nc*Ac + Nd*Ad}{Aa + Ab + Ac + Ad}$$

N : equivalent roughness coefficient
A : accumulative area

Figure 5.2-19   Combined Roughness Coefficient

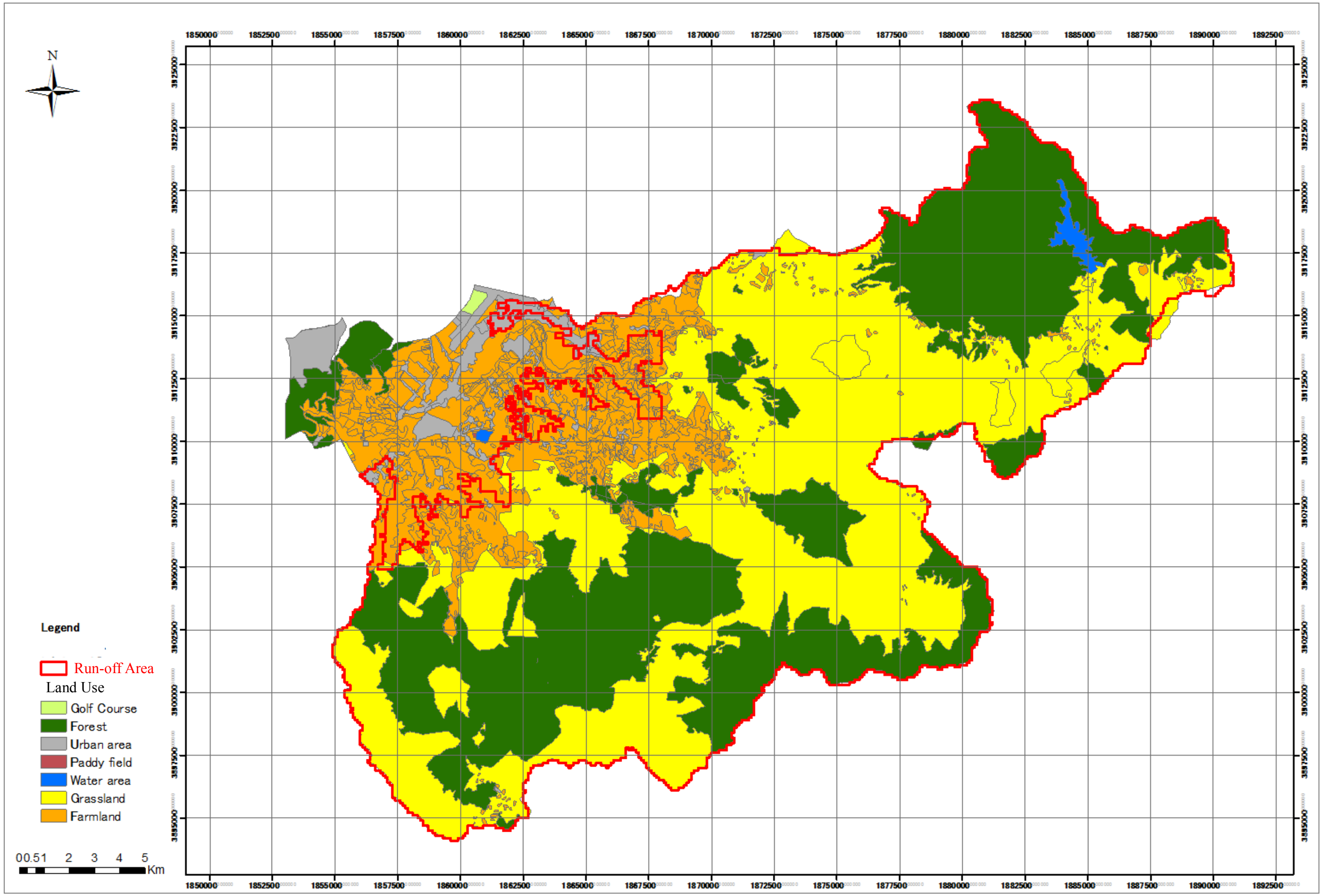


Figure 5.2-20 Land use map (100m grid)

5) Water Falling Line

The water falling line which shows the flow route of discharge is set as follows.

1) Water flows on the steepest line which measured from center of grid to 8 directions (4 directions of lengthwise and crosswise, 4 diagonal directions, refer to Note: Figure shows elevation of each grid

Figure 5.2-22,). Gradient of the grid is set as average value of the grid.

2) In case that elevation of the grid is low relative to adjacent grids (depression), the elevation is checked by topographical map or aerial photo and son. In case that it is not depression, water falling line has to be corrected to the line found by reviewing.

The set water falling line is set as shown in Figure 5.2-23.

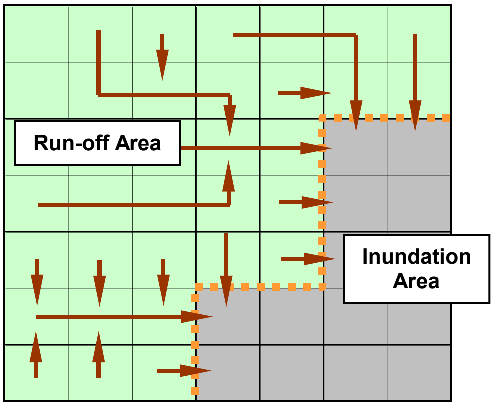
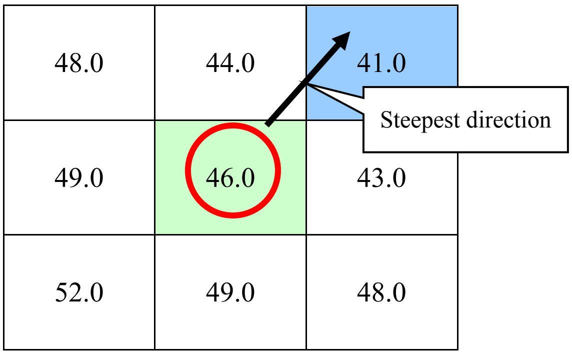


Figure 5.2-21 Example of Water Falling Line



Note: Figure shows elevation of each grid

Figure 5.2-22 Example of Setting of Water Falling Line Direction

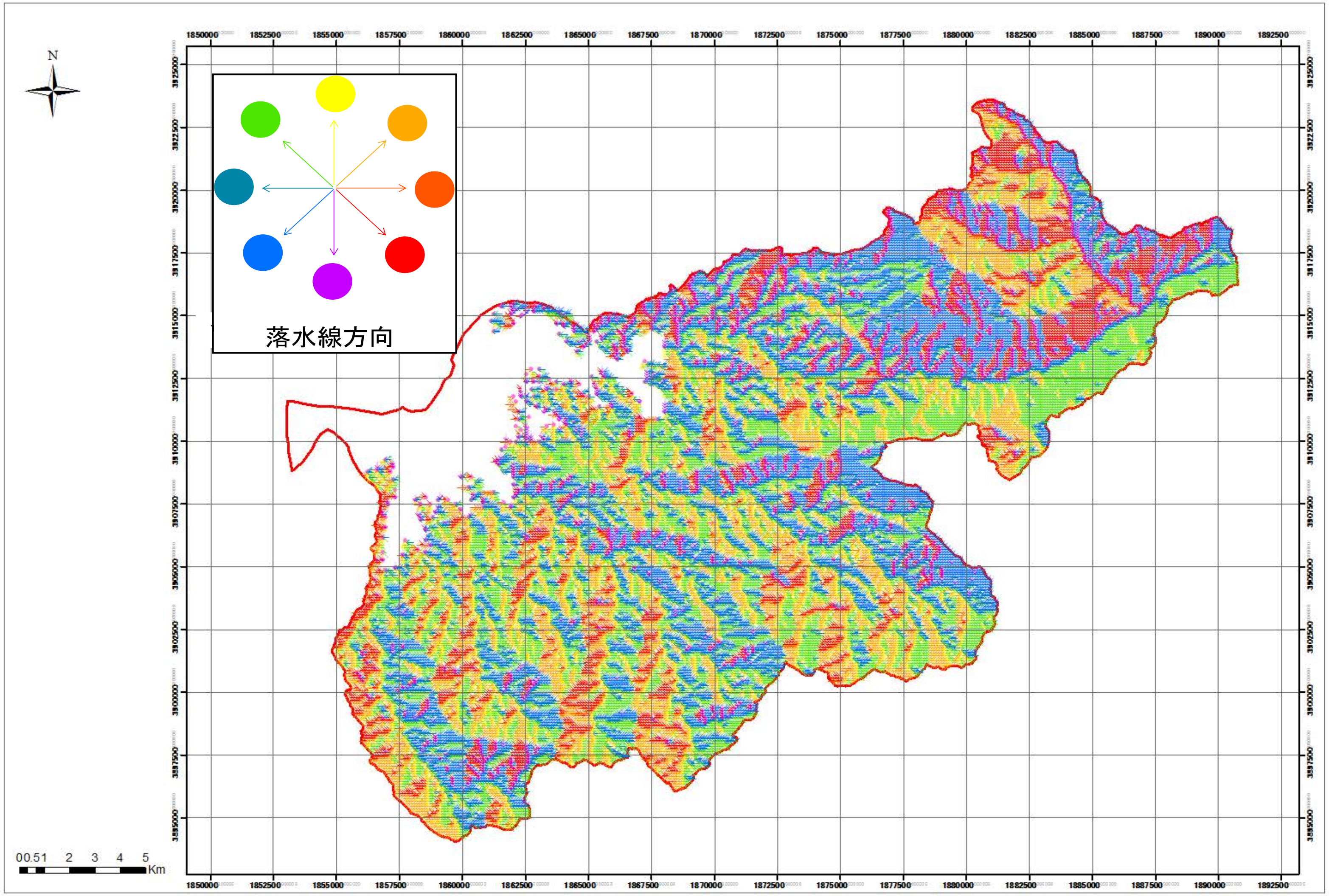


Figure 5.2-23 Map of Water Falling Line

(3) Inundation Area Model

1) Composition of Inundation Area Model

Inundation Area Model should be the model which has the function to trace inundation flow propagation by two-dimensional unsteady flow model under the confluence of the drainage system of channels and sluice, and embankment and so on besides area characteristics.

In this project inundation model is composed of rainfall model, river channel model and inundation flow trace model (two-dimensional unsteady flow model). Image of inundation model is shown in Figure 5.2-24.

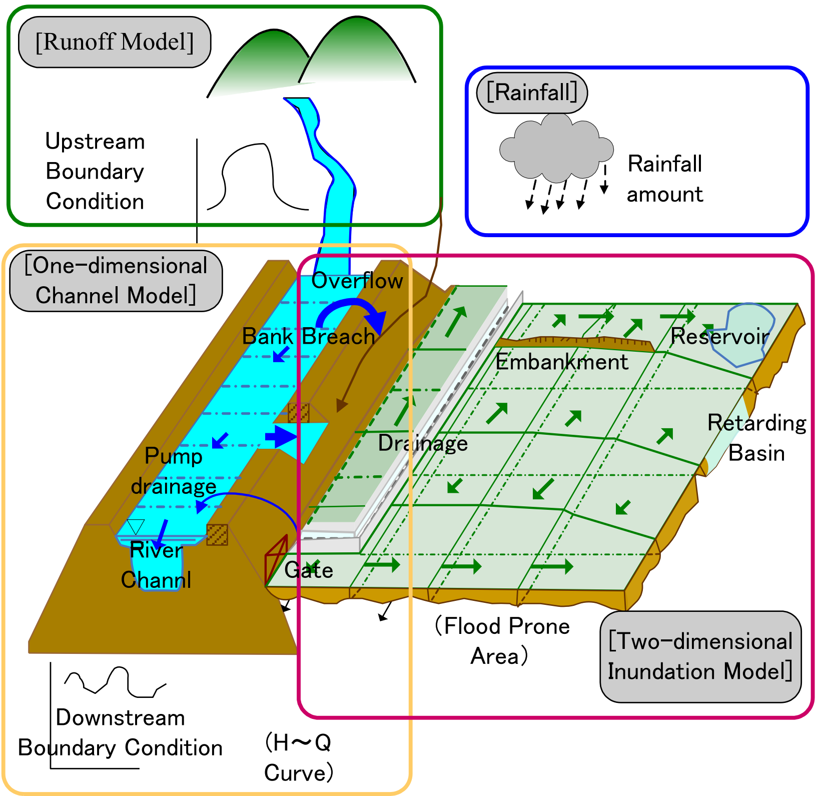


Figure 5.2-24 Image of Inundation Area Model

2) Rainfall loss model

Rainfall loss model is set based on the above mentioned method (refer to 5.2.2 (2), (1).

3) Topography model

a) Setting of elevation

The method of setting of the elevation is the same for run-off are model (refer to 5.2.2 (2), 3), (a). The set elevation of the inundation area is as shown in Figure 5.2-25.

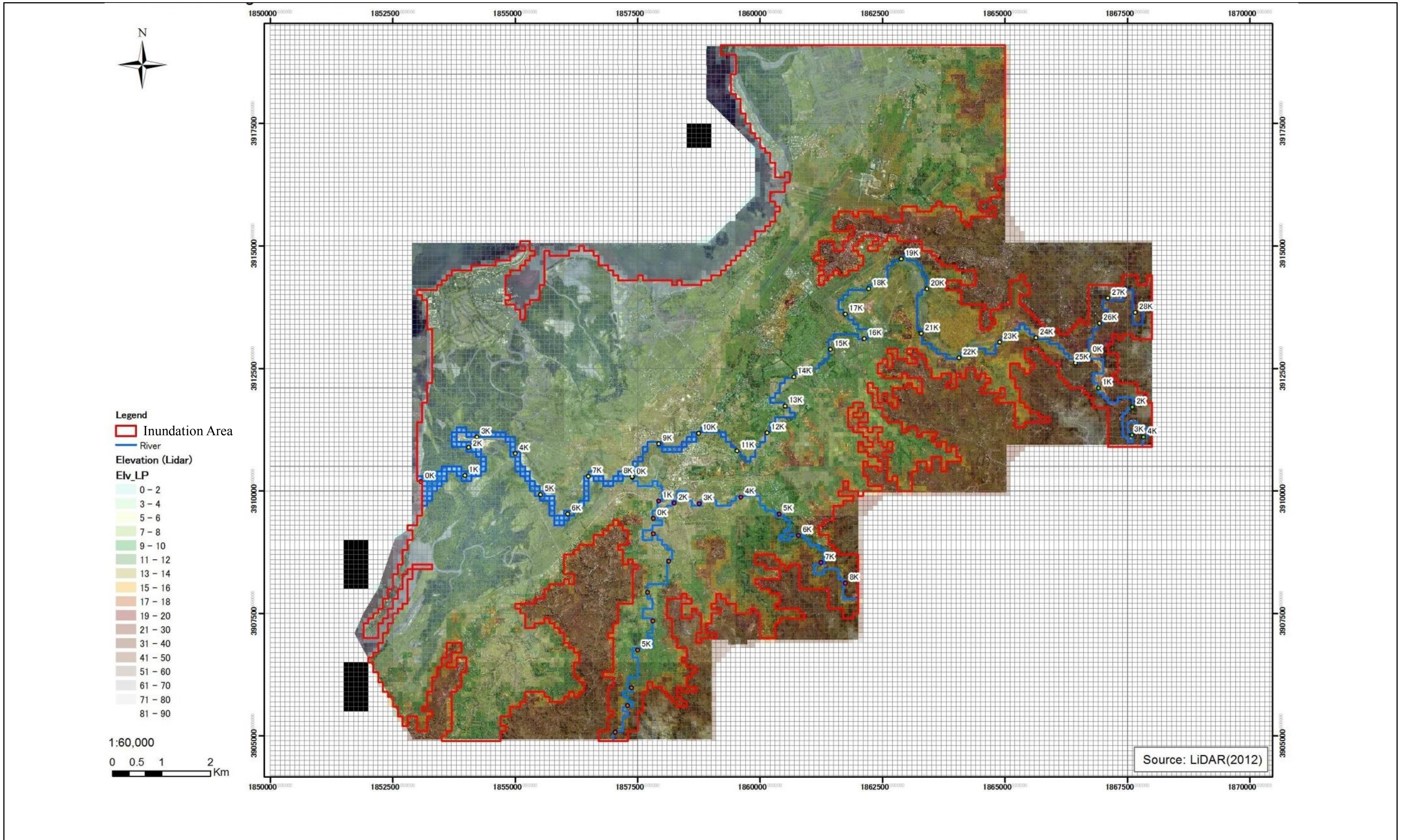


Figure 5.2-25 Inundation Area with 100m Grid Elevation

b) Roughness coefficient of inundation area

Roughness coefficient of inundation area is set based on the following method:

1) Building occupation ratio and coefficient of roughness of each land use are set for each grid.
2) Coefficient of roughness in flooding basin is given by the following equation based on coefficient of bottom surface roughness:

$$n^2 = n_0^2 + 0.02 * (\theta / (100 - \theta)) * h^{4/3}$$

Where; θ: building occupation ratio, h: water depth

Bottom surface roughness except building is given by the following weighted average:

$$n_0^2 = (n_1^2 A_1 + n_2^2 A_2 + n_3^2 A_3) / (A_1 + A_2 + A_3)$$

Where; A_1: farm land area, n_1: farmland roughness = 0.060

A_2: road area, n_2: road roughness = 0.047

A_3: other area, n_3: other roughness = 0.050

Table 5.2-5 Land Use and Roughness Coefficient of Inundation Area

Land use	Land use (subdivision)	Roughness
Building	Urban Area	Calculated by building occupancy ratio
Farmland	Grassland, Farmland, Paddy Field	0.060
Road	Road, Airport	0.047
Others	Water area , Golf course	0.050

Building occupancy ratio is calculated using the data of outline of building (Building surface model), which is one of the output of LiDAR survey, and Figure 5.2-26 100m grid figure shows an example of outline of building and building occupancy ratio near the factory located on the left bank of Nadi River Basin (17.0km). Calculated building occupancy ratio in the inundation area is as shown in Figure 5.2-29

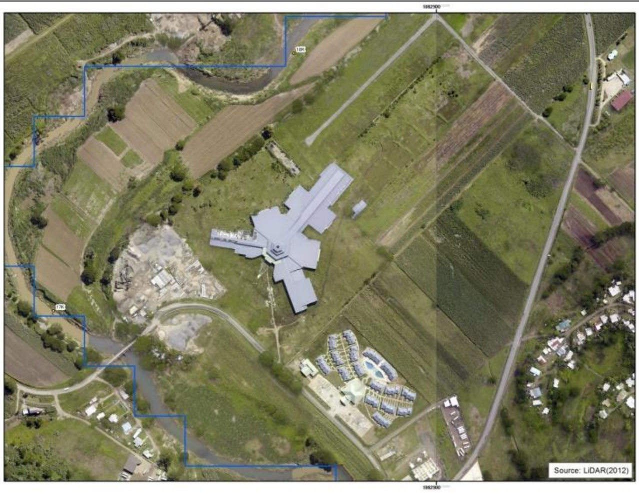
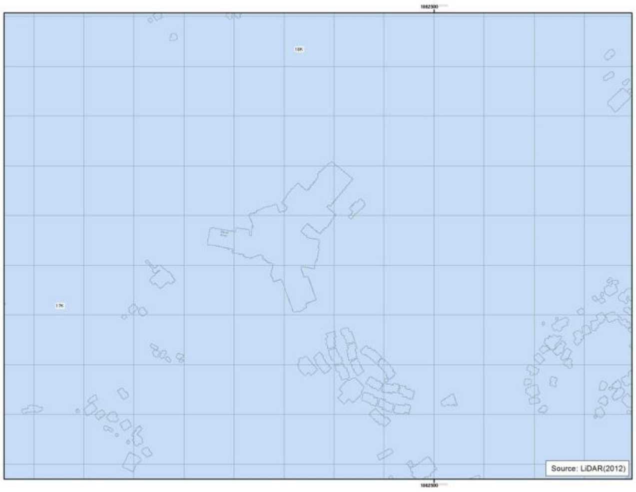
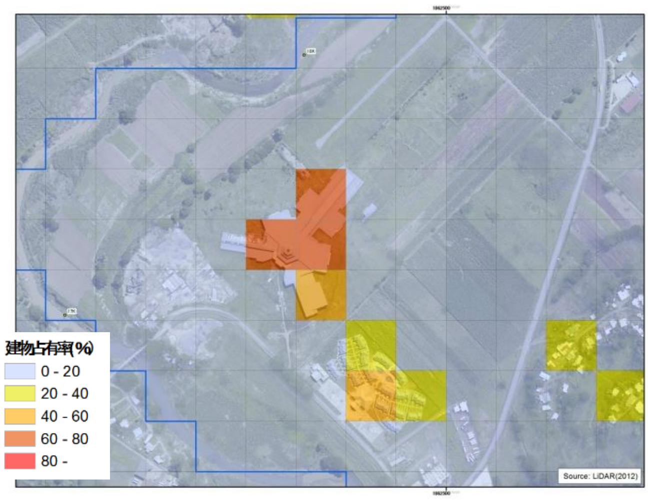
Aerial photo	
Outline of building with 100m grid (Building surface model)	
Building occupancy ratio (100m grid)	

Figure 5.2-26 Outline of Building and Building Occupancy Ratio
(Near the Nadi River 17.0km, Left bank)

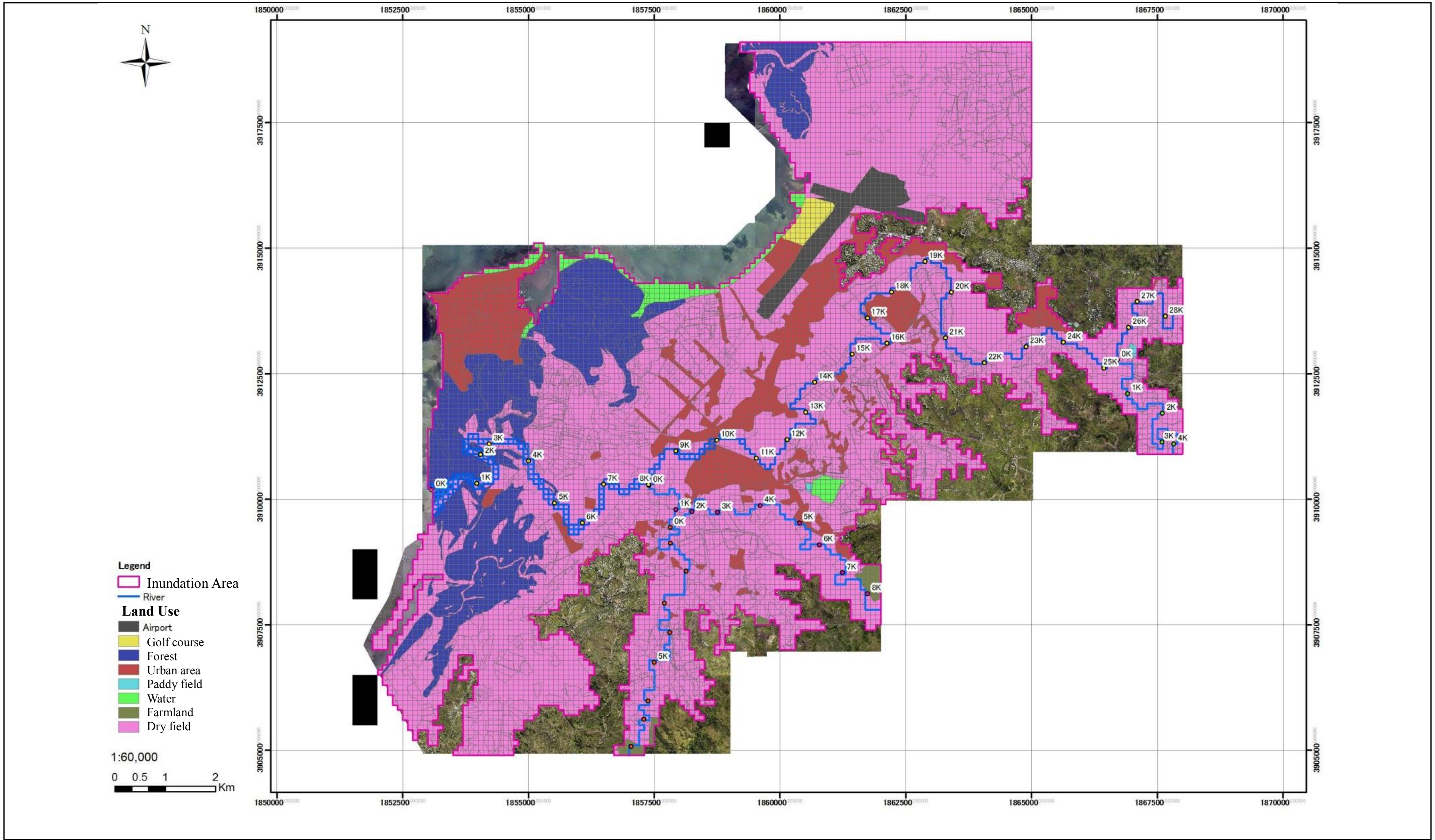


Figure 5.2-27 Land Use in Inundation Area

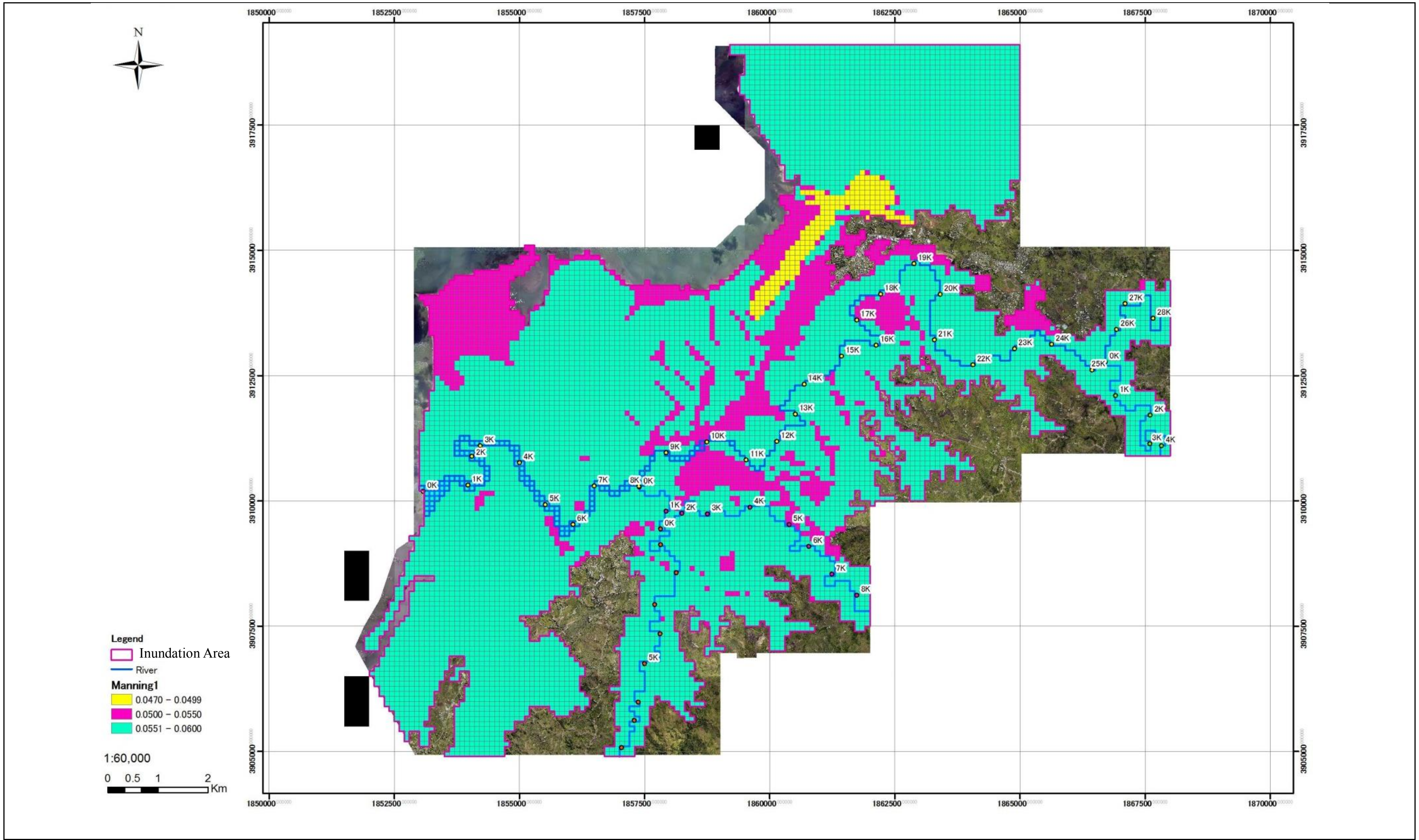


Figure 5.2-28 Bottom Surface Roughness in Inundation Area

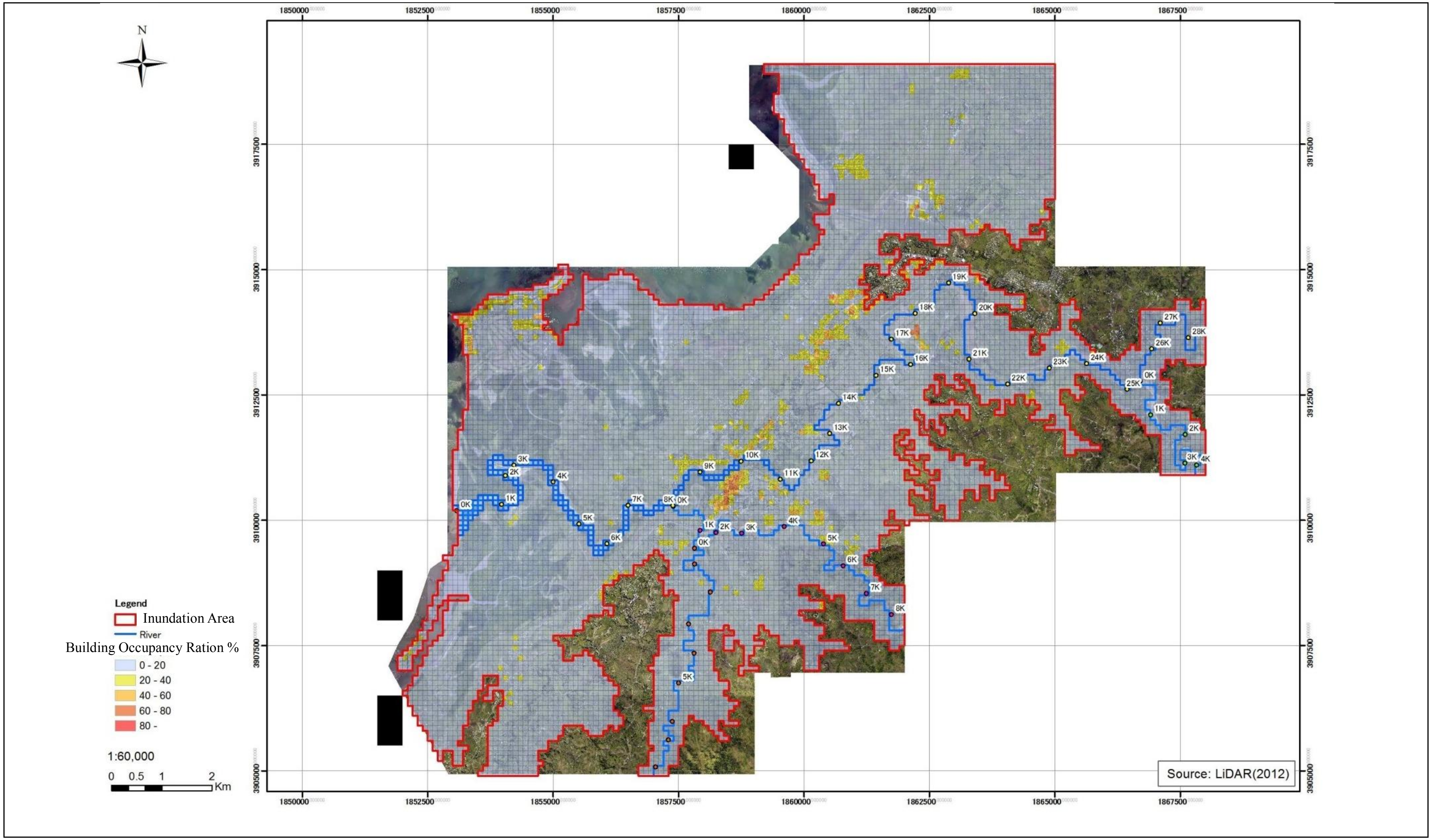


Figure 5.2-29 Building Occupancy Ratio in Inundation Area

4) Inundation Flow Trace Model

a) Outline of inundation analysis model

As to the two-dimensional unsteady flow model applied to inundation analysis, its characteristics are compared with other major inundation analysis model. Relation of unsteady terms between one dimensional open channel unsteady flow equation and major analysis models is as shown in Table 5.2-7.

[One dimensional open channel unsteady flow equation]

$$\underbrace{\frac{1}{gA}\frac{\delta Q}{\delta t}}_{1^{st}\ \text{term}} + \underbrace{\frac{2Q}{gA^2}\frac{\delta Q}{\delta x}}_{2^{nd}} - \underbrace{\frac{Q^2}{gA^3}\frac{\delta A}{\delta x}}_{3^{rd}} + \underbrace{\frac{\delta h}{\delta x}}_{4^{th}} - \underbrace{i_b}_{5^{th}} + \underbrace{\frac{n^2|Q|Q}{A^2R^{4/3}}}_{6^{th}} = 0$$

(Acceleration term) (Inertial term) (Water surface gradient term) (Friction term)

Table 5.2-6 Model and Each Term of Motion Equation

Analysis Model \ Item		Term of Motion Equation 1st	2nd	3rd	4th	5^{t}	6th	Remarks
One-dimension al	Storage function method	×	×	△	×	○	○	Same as river channel model
	Muskingum method	×	×	△	△	○	○	
	Simple one dimensional unsteady flow model	×	×	×	○	○	○	Omit of Acceleration term and Inertial term
Two dimensional	Overflow pond model	×	△	△	○	○	△	Use constant of inertial term together with friction term t
	Inundation pond model	○	×	×	○	○	○	Omit of acceleration tem and roughness coefficient is function of water depth
	Open channel pond model	○	×	×	○	○	○	Omit of acceleration term and roughness coefficient by land use
	Two dimensional unsteady flow model	○	○	○	○	○	○	Motion equation in X and Y direction

Note)○:Term considered、△:Term approximately considered、×:Not considered
Source: Public Works Research Institute, Ministry of Construction, Inundation Simulation

To present wide and planar inundation two dimensional model is appropriate, among which the two dimensional unsteady flow model used in recent year for estimation of prospective inundation area has a little restriction compared with other models since there is no calculation terms omitted.

Advantage and disadvantage of Two-dimensional unsteady flow model are as follows.

Advantage

1) Constraints from topography features are not so many due to any calculation terms omitted.
2) Modeling is easy because modeling is formed by standard grid.
3) Grid elevation is given by the condition of topography, so no need of forecasting the actual flow

condition.

4) Embankment and drainage channel is easy to build in the inundation area.
5) Inundation spreading process in the area can be presented.

Disadvantage

1) Calculation time is longer than other models due to two direction calculations (X and Y) and any calculation term omitted.
2) Stability of calculation is a little low due to the complex calculation.

Based on the above characteristics, two dimensional unsteady flow models is to be applied to this Study, which model can represent the inundation flow propagation most in detail.

The issues to apply this model are not problems since the capacity increase of computer and real time calculation results are not required.

The outline of the model is as shown below.

(i) Tracking technique inundation analysis

Two-dimensional unsteady flow model is consisted of (1) continuity formula and (2), (3) of momentum conservation formula.

✧ continuity formula

$$\frac{\partial H}{\partial y}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \quad \cdots\cdots (1)$$

✧ x direction momentum formula

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}(uM)+\frac{\partial}{\partial y}(vM)=-gh\frac{\partial H}{\partial x}-\frac{1}{\rho}\tau_{bx} \quad \cdots\cdots (2)$$

✧ y direction momentum formula

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}(uM)+\frac{\partial}{\partial y}(vN)=-gh\frac{\partial H}{\partial Y}-\frac{1}{\rho}\tau_{bx} \quad \cdots\cdots (3)$$

Where; h: water depth, H: water level, g: gravitational accelerate, ρ: water density

M ＝uh: x direction discharge flux, N＝vh: y direction discharge flux

u: x direction current velocity, v: y direction current velocity

τ_b: Bottom friction in running water, using the Manning formula

$$\tau_b = \rho g n^2 \sqrt{(u^2+v^2)}\cdot u/h^{1/2} \quad \cdots\cdots (4)$$

In actual calculation, unknown figures of M,N, h calculation points are arranged in staggered grid, then (5) and (6), (5) and (7) formulas are solved by finite difference approximation in explicit expression to time direction (refer to Figure 5.2-30).

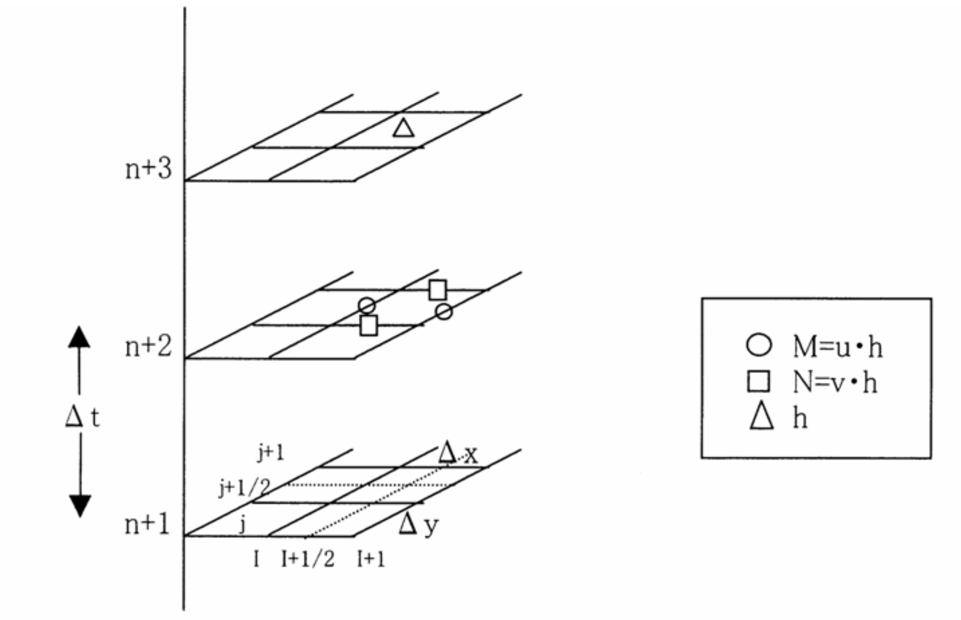


Figure 5.2-30 Finite Difference Grid in Continuity Formula

Continuity formula in finite difference equation

$$\frac{h^{n+3}_{I+1/2,j+1/2} - h^{n+1}_{I+1/2,j+j+1/2}}{2\Delta t} + \frac{M^{n+2}_{I+1,j+1/2} - M^{n+2}_{I,j+1/2}}{\Delta x} + \frac{N^{n+2}_{I+1/2,j+1} - N^{n+2}_{I+1/2,j}}{\Delta y} = 0 \quad \ldots (5)$$

Where, h ; water depth、H ; water level、u、v ; x, y is the average velocity of the vertical direction, M = uh, N = vh. n ;Manning roughness coefficient.

X direction momentum formula

$$\frac{M^{n+2}_{I,j+1/2} - M^{n}_{I,j+1/2}}{2\Delta t} + \frac{1}{\Delta x}\left[\frac{1}{h^{n+1}_{I+1/2,j+1/2}} \left(\frac{M^{n}_{I+1,j+1/2} + M^{n}_{I,j+1/2}}{2}\right)^2 - \frac{1}{h^{n+1}_{I-1/2,j+1/2}} \left(\frac{M^{n}_{I,j+1/2} + M^{n}_{I-1,j+1/2}}{2}\right)^2 \right]$$

$$+ \frac{1}{\Delta y}\left[\frac{(M^{n}_{I,j+1/2} + M^{n}_{I,j+3/2})(N^{n}_{I+1/2,j+1} + N^{n}_{I-1/2,j})}{h^{n+1}_{I-1/2,j+1/2} + h^{n+1}_{I+1/2,j+1/2} + h^{n+1}_{I+1/2,j+3/2} + h^{n+1}_{I-1/2,j+3/2}} - \frac{(M^{n}_{I,j+1/2} + M^{n}_{I,j-1/2})(N^{n}_{I+1/2,j} + N^{n}_{I-1/2,j})}{h^{n+1}_{I-1/2,j+1/2} + h^{n+1}_{I+1/2,j-1/2} + h^{n+1}_{I+1/2,j+1/2} + h^{n+1}_{I-1/2,j+1/2}} \right]$$

$$- g \frac{(h^{n+1}_{I+1/2,j+1/2} + h^{n+1}_{I-1/2,j+1/2})(H^{n+1}_{I+1/2,j+1/2} - H^{n+1}_{I-1/2,j+1/2})}{2\Delta x}$$

$$- g n^2_{I,j+1/2} \frac{u_{I,j+1/2}\sqrt{[(u_{I,j+1/2})^2 + (v_{I,j+1/2})^2]}}{[(h^{n+1}_{I+1/2,j+1/2} + h^{n+1}_{I-1/2,j+1/2})/2]^{1/3}} \quad \ldots\ldots\ldots\ldots (6)$$

Where, $u_{I,j+1/2} = (M^{n+2}_{I,j+1/2} + M^{n}_{I,j+1/2})/(h^{n+1}_{I+1/2,j+1/2} + h^{n+1}_{I-1/2,j+1/2})$

$v_{I+1/2,j} = (N^{n+2}_{I+1/2,j} + N^{n}_{I+1/2,j})/(h^{n+1}_{I+1/2,j+1/2} + h^{n+1}_{I+1/2,j-1/2})$

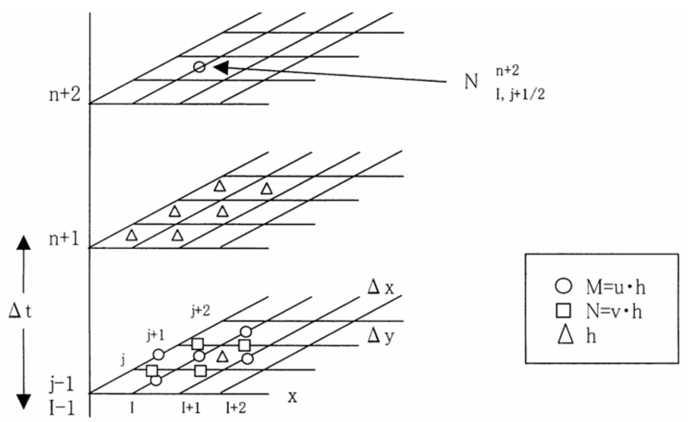


Figure 5.2-31 Finite Difference Grid in X-direction Momentum Formula

Y direction momentum formula

$$\frac{N^{n+2}_{I,j+1/2}-N^{n}_{I,j+1/2}}{2\Delta t}+\frac{1}{\Delta x}\left[\frac{(M^{n}_{I+1,j+1/2}+M^{n}_{I+1/2,j-1/2})(N^{n}_{I+1/2,j}+N^{n}_{I+3/2,j})}{h^{n+1}_{I+1/2,j+1/2}+h^{n+1}_{I+1/2,j-1/2}+h^{n+1}_{I+3/2,j-1/2}+h^{n+1}_{I+3/2,j+1/2}}\right.$$

$$\left.-\frac{(M^{n}_{I,j+1/2}+M^{n}_{I,j-1/2})(N^{n}_{I-1/2,j}+N^{n}_{I+1/2,j})}{h^{n+1}_{I-1/2,j+1/2}+h^{n+1}_{I-1/2,j-1/2}+h^{n+1}_{I+1/2,j}+h^{n+1}_{I+1/2,j+1/2}}\right]$$

$$+\frac{1}{\Delta y}\left[\frac{1}{h^{n+1}_{I+1/2,j+1/2}}\left(\frac{N^{n}_{I,j+1/2}+N^{n}_{I+1/2,j+1/2}}{2}\right)^{2}-\frac{1}{h^{n+1}_{I+1/2,j+1/2}}\left(\frac{N^{n}_{I+1/2,j-1}+N^{n}_{I+1/2,j}}{2}\right)^{2}\right]$$

$$-g\frac{(h^{n+1}_{I+1/2,j+1/2}+h^{n+1}_{I+1/2,j-1/2})(H^{n+1}_{I+1/2,j+1/2}-H^{n+1}_{I+1/2,j-1/2})}{2\Delta y}$$

$$-gn^{2}_{j+1/2,j}\frac{v_{I+1/2,j}\sqrt{[(u_{I,j+1/2})^{2}+(v_{I,j+1/2})^{2}]}}{[(h^{n+1}_{I+1/2,j+1/2}+h^{n+1}_{I+1/2,j-1/2})/2]^{1/3}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (7)$$

Where, $u_{I,j+1/2}=(M^{n+2}_{I,j+1/2}+M^{n}_{I,j+1/2})/(h^{n+1}_{I+1/2,j+1/2}+h^{n+1}_{I-1/2,j+1/2})$

$v_{I+1/2,j}=(N^{n+2}_{I+1/2,j}+N^{n}_{I+1/2,j})/(h^{n+1}_{I+1/2,j+1/2}+h^{n+1}_{I+1/2,j-1/2})$

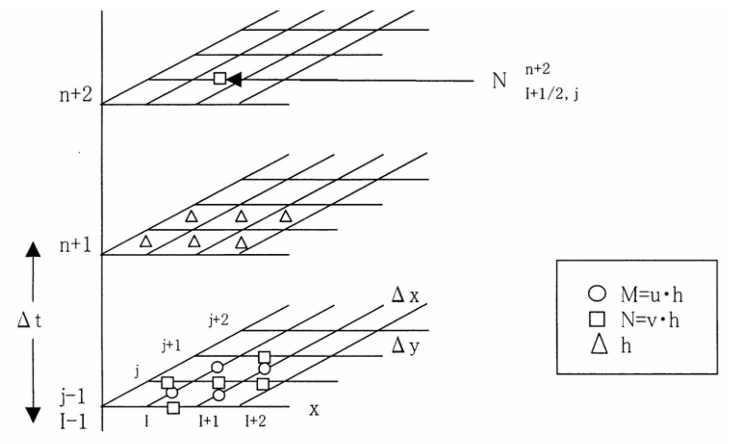


Figure 5.2-32 Finite Difference Grid in Y-direction Momentum Formula

Difference in level of inundation flow is handled as shown below:

1. Drop
In case that ground elevation is remarkably different, water surface profile becomes discontinuous. In this case, flow flux is obtained by drop flow by the equation below.

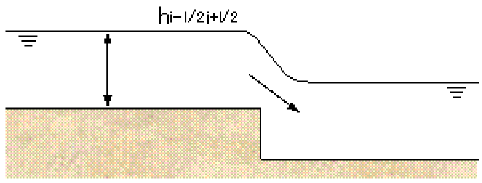


Figure 5.2-33 Drop Flow

$$\left|N_{i+1/2,j}\right| \quad or \quad \left|M_{i,j+1/2}\right| = \alpha \cdot h_{i-1/2,j+1/2}\sqrt{g \cdot h_{i-1/2,j+1/2}}$$
$$= \alpha \cdot g^{1/2} \cdot h^{3/2}_{i-1/2,j+1/2} \qquad (\alpha: \ Coefficient, \quad generally\ 0.35)$$

2. Step up
In case that water in low level ground is inundated and the level becomes higher than the higher ground level, which is the step up condition.

The flow flux is calculated from water depth slope between grids, using water depth from higher ground level.

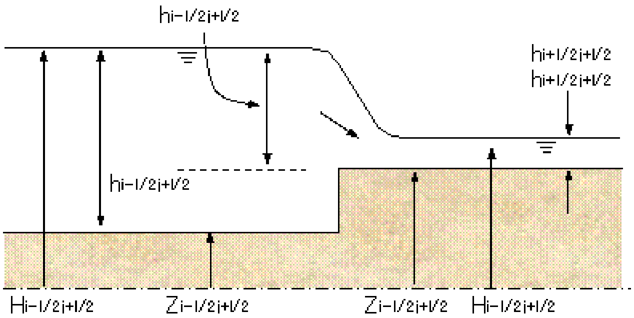


Figure 5.2-34 Set-up Flow

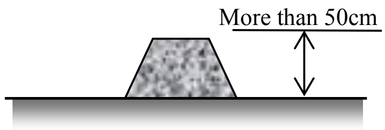
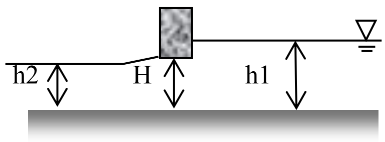
$$M_{i,j+1/2} = \frac{\left(h_{i-1/2,j+1/2} + h_{i+1/2,j+1/2}\right)^{5/3} \cdot \sqrt{\left(H_{i-1/2,j+1/2} - H_{i+1/2,j+1/2}\right)/\Delta\chi}}{2^{5/3} \cdot n}$$

$$Here, \quad h_{i-1/2,j+1/2} = H_{i+1/2,j+1/2} - \left|Z_{i-1/2,j+1/2} - Z_{i+1/2,j+1/2}\right|$$

b) Layout of Each Structure

Structures which may affect the inundation phenomena are built in to the Inundation analysis model.

Table 5.2-7 Structures Build into Inundation Model

Structure	Build in the Method	In Case of Nadi River
Embankment	・Modeling of embankment Embankments with different elevation (dikes, railway, others) of over 50cm are built into the Model as well as main roads  ・Modeling method Embankments are arranged boundary of calculation grid on which embankments cross so that they are arranged step like in inundation field. ・Facilities which cross embankment is modeled as culvert. Culvert is modeled in the same way as gate, sluice.	The main facilities considered are ・ Queens Road ・ Runway of International Airport ・ Back Road
Water Channel	・Main channel and rivers in the inundation area are modeled. Channels are laid on the grid border.	7 tributaries are considered Nadi River: 3 branches Nawaka River: 1 branch Makalua River: 1 branch Denarau Port: 2 rivers
Sluice	 H: height of gate, B: width of gate and the highest water level which is measured from foundation is h1, and the lowest is h2. ・Submerged flow：$h_2 \geqq H$ $Q = C B H \sqrt{2g(h_1 - h_2)}$ 、 $C = 0.75$ ・Intermediate flow：$h_2 < H$ and $h_1 \geqq 3/2H$ $Q = C B H \sqrt{2gh_1}$ 、 $C = 0.51$ ・Free flow：$h_2 < H$ and $h_1 < 3/2H$ $Q = C B h_2 \sqrt{2g(h_1 - h_2)}$ $C = 0.79$ Note, in case of $h_1/h_2 \geqq 3/2$ at free flow, $h_2 = 2/3h_1$	No gates in the Nadi River Basin
Pump station	Operation rules are applied.	No pumps in the Nadi River Basin

ｉ) Water Channel Model

Water channels are modeled in the procedures shown below:

*** Target Channels of Modeling**

Tributaries of the main river are targeted.

*** Layout and Shape**

Layout and shape (Width, height of channel, foundation height) of selected channels are determined based on survey drawing and site survey.

*** Build up Modeling**

Selected channels are arranged as shown in Figure 5.2-35 on the border of grid.

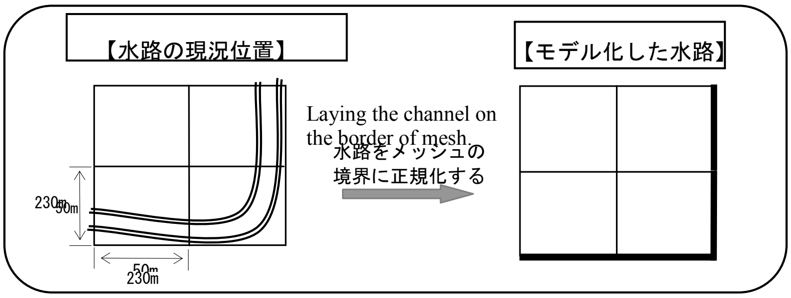


Figure 5.2-35 Modeling of Channels

The calculation of channel model has carried out the following unsteady flow in which advection term is ignored and acceleration term in the field is considered based on "Inundation Simulation Manual (draft)".

【The basic equation for channel calculation】

$$\frac{1}{g}\cdot\frac{\Delta Vd}{2\Delta t}=-\frac{\Delta Hd}{\Delta I}-\frac{n_d{}^2 Vd|Vd|}{h_{dm}{}^{4/3}}$$

h_{dm} : Average channel depth of adjacent grid(m)

X direction velocity formula

$$h_{dmx}(I,j)=(hs(I,j)+hs(I+1,j))/2$$

hs : water depth in Channel(m)

$$Vx(t)_{I,j}=\{Vx(t-1)_{I,j}/g2\Delta t+(Hs(I,j)-Hs(I+1,j))/dx\}$$
$$/\{1/g2\Delta t+nx_{i,j}{}^2|Vx(t-1)_{i,j}|/h_{dmx}(I,j)^{4/3}\}$$

$$Fx(t)_{I,j}=h_{dmx}(I,j)\cdot Vx(t)_{I,j}$$

Y direction velocity formula

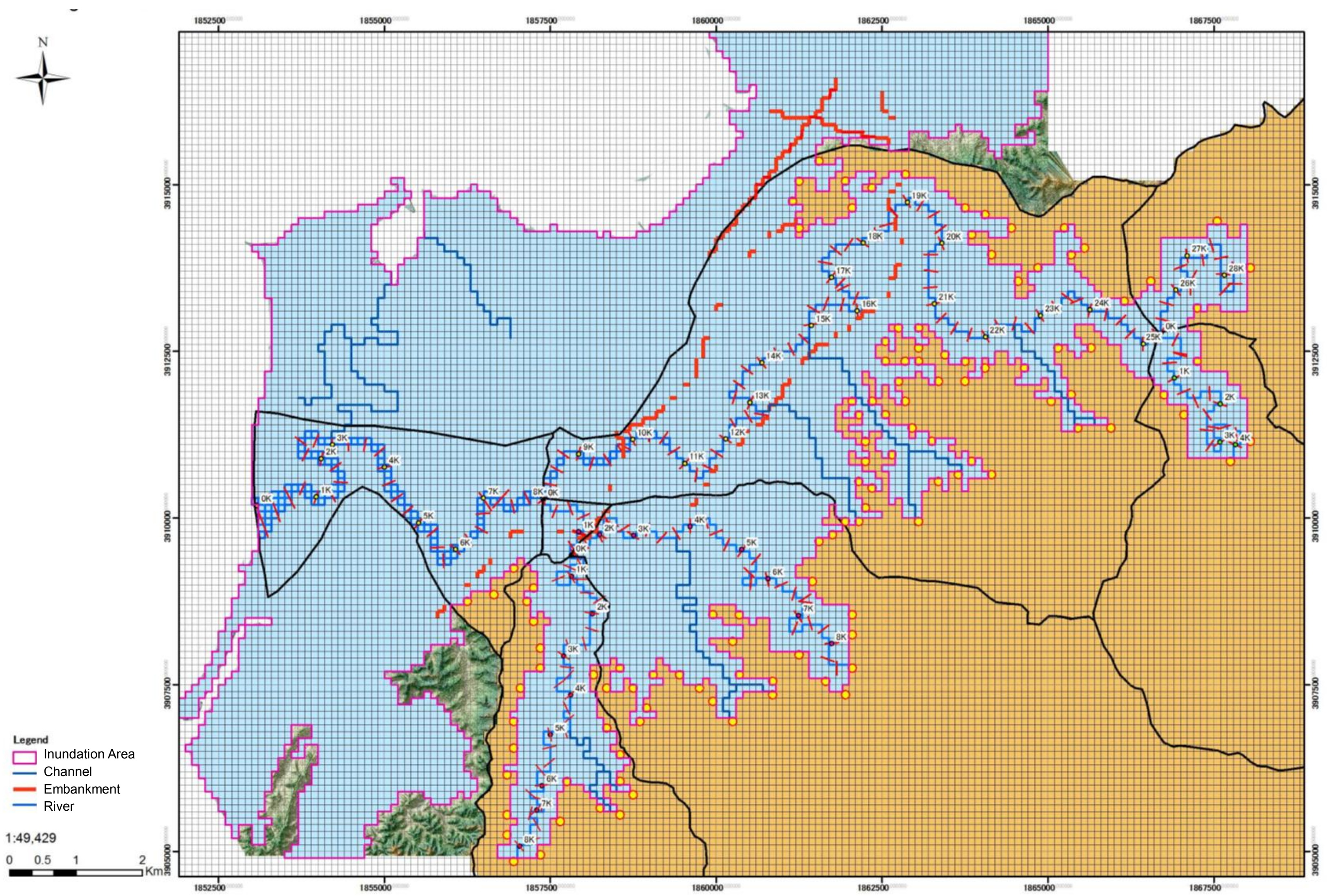
$$h_{dmy}(I,j) = (hs(I,j) + hs(I,j+1))/2$$

$$Vy(t)_{I,j} = \left\{ Vy(t-1)_{I,j} / g2\Delta t + (Hs(I,j) - Hs(I,j+1))/dY \right\} / \left\{ 1/g2\Delta t + ny_{I,j}{}^{2} \left| Vy(t-1)_{I,j} \right| / h_{dmy}(I,j)^{4/3} \right\}$$

$$Fy(t)_{I,j} = h_{dmy}(I,j) \cdot Vy(t)_{I,j}$$

c) Inundation analysis model

The inundation model is shown in Figure 5.2-36.



Source : JICA Study Team

Figure 5.2-36 Inundation Area Model

Conditions of inundation analysis are shown in Table 5.2-8.

Table 5.2-8 Conditions of Inundation Analysis

<table>
<tr><th colspan="2">Item</th><th colspan="3">Condition</th></tr>
<tr><td colspan="2">Calculation Method</td><td colspan="3">River Course: One dimensional unsteady flow (Dynamic Wave)
Inundation Area: Two dimensional unsteady flow (Dynamic Wave)</td></tr>
<tr><td rowspan="10">River Conditions</td><td>Target Area</td><td colspan="3">Nadi River (0.0k - 28.0k)
Namosi River (0.0k - 4.0k)
Nawaka River (0.0k - 8.5k)
Malakua River (0.0k - 8.0k)</td></tr>
<tr><td>Section intervals</td><td colspan="3">Approx. 250m</td></tr>
<tr><td>Sections</td><td colspan="3">Sections seurveyed in 2014
Data interpolation by LiDAR for unsurveyed sections</td></tr>
<tr><td>Boundary Conditions</td><td colspan="3">Nadi Bay: Actual Tide (Lautoka)</td></tr>
<tr><td rowspan="5">Roughness Coefficient</td><td>River Sections</td><td>low-water channel</td><td>high-water channel</td></tr>
<tr><td>Nadi River
0.0k - 4.0k
4.0k - 25.25k
25.25k -</td><td>0.035
0.043
0.047</td><td>Dead Water Zone
0.060
0.060</td></tr>
<tr><td>Namosi River
0.0k - 4.0k</td><td>0.042</td><td>0.060</td></tr>
<tr><td>Nawaka River
0.0k - 8.5k</td><td>0.046</td><td>0.060</td></tr>
<tr><td>Malakua River
0.0k- 8.0k</td><td>0.047</td><td>0.060</td></tr>
<tr><td rowspan="4">Inundation Area Condition</td><td>Type of Inundation</td><td colspan="3">Upstream of Nadi River10K: flow along the river
Downstream of Nadi River 10K: Distribution</td></tr>
<tr><td>Elevation</td><td colspan="3">Mean elevation of 100m Grid (data from LiDAR)</td></tr>
<tr><td>Roughness Coefficient</td><td colspan="3">Determined by land surface roughness and building occupancy
land surface roughness coefficient:
Agriculture Field: 0.060, Other: 0.050, Road: 0.047</td></tr>
<tr><td>Over Flow Condition</td><td colspan="3">Higher elevation of embankment or land surface of inner side of the embankment</td></tr>
</table>

5.2.3 Reproduction of Existing Flood

(1) Target Flood

The target flood for reproduction was selected from the floods shown below, which have hourly rainfall and water level data and actual records of inundation.

Calibration of the model was conducted by using the March, 2012 flood inundation data shown in Figure 5.2-38.

Calibration: by the flood in March, 2012

Verification: by the flood in January, 2009

Table 5.2-9 Target Flood for Reproduction

Occurrence Date	Max water level at Votualevu (m)	Max water level at Nadi town Bridge(m)	Ave. rainfall in Nadi town Bridge Basin (mm/2day)	Actual result of inundation record	Adaptation for	Remarks
January, 2009 Flood 2009/1/8-12	More than 12.2*	No data	442.0 (Generally 1/30)	○	Verification	Water level was recorded at only Votualevu
March, 2012 Flood 2012/3/28-4/2	More than 11.87	7.62	483.1 (Generally 1/50)	○	Calibration	Peak water level was not recorded at Votualevu

Notes ; ＊ : PACIFIC HYCOS MISSION FLOOD RESPONSE NADI/BA JANUARY-FEBRUARY2009 (SOPAC)

Recorded value ( ): probability scale

Source: JICA Study Team

Actual rainfall, recorded water level and inundation map of March 2012 flood and January 2009 flood are shown in Figure 5.2-37 ~ Figure 5.2-40.

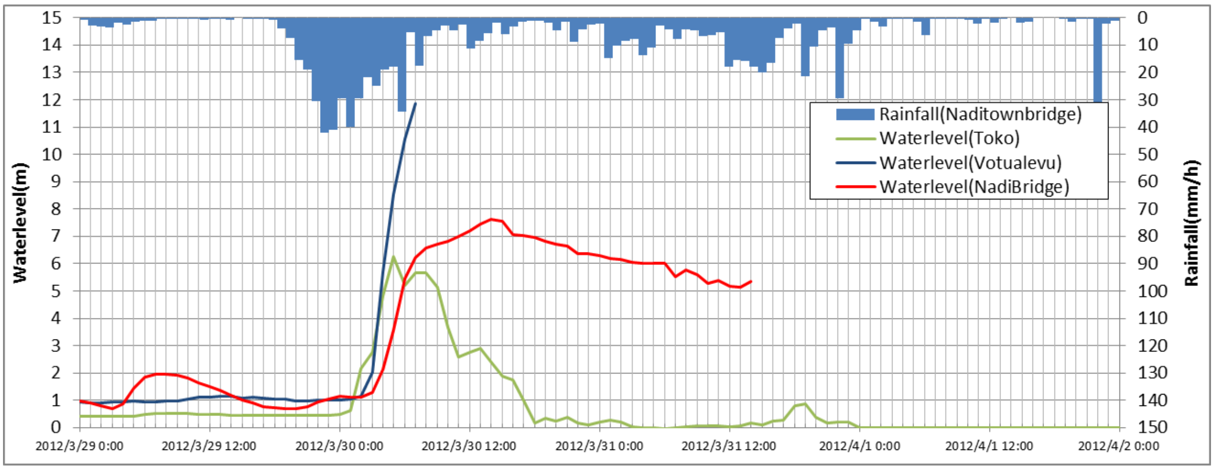
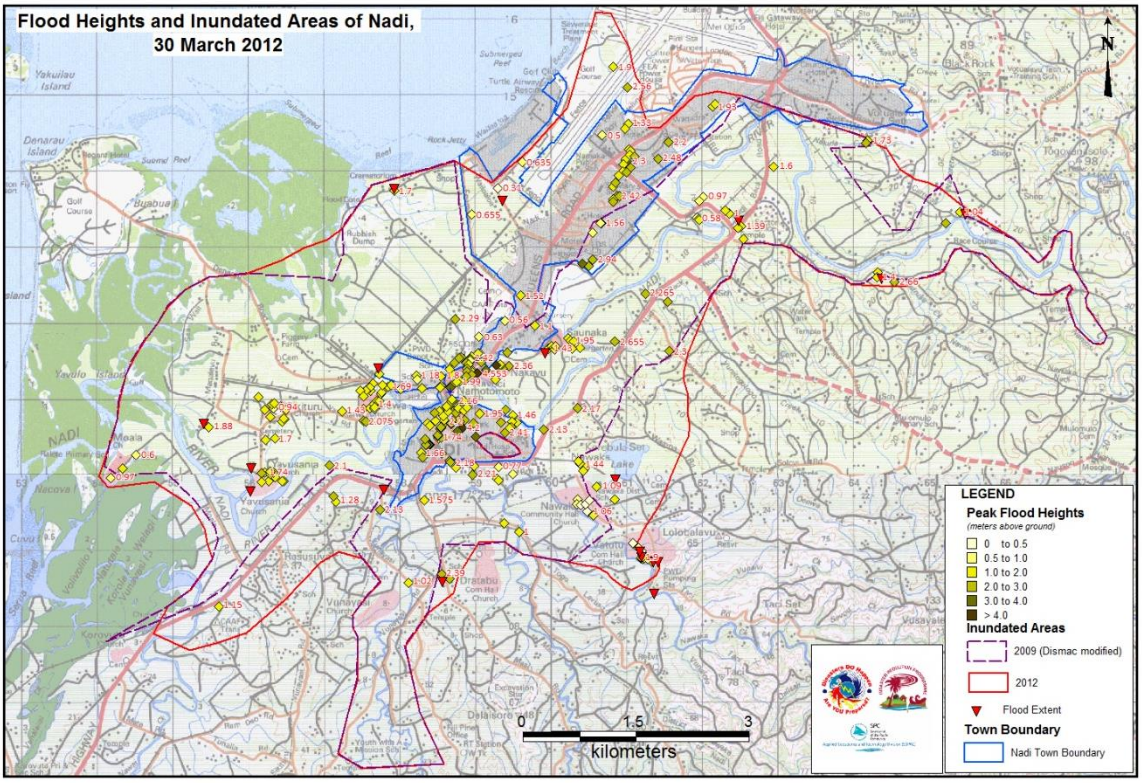


Figure 5.2-37 Actual Hydrograph of Flood in March 2012



Source: SPC/SOPAC

Figure 5.2-38 Actual Inundation Area of Flood in March 2012

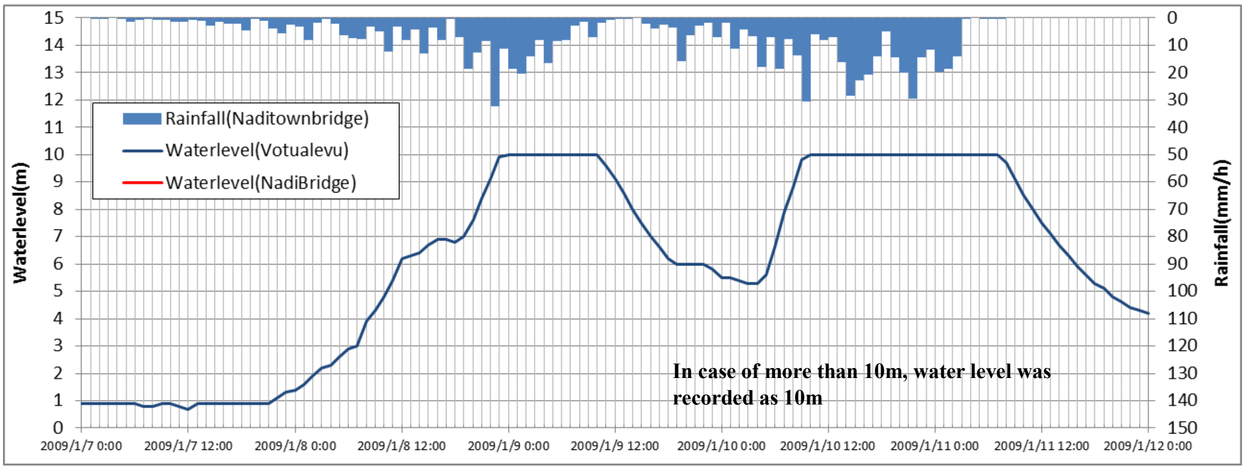
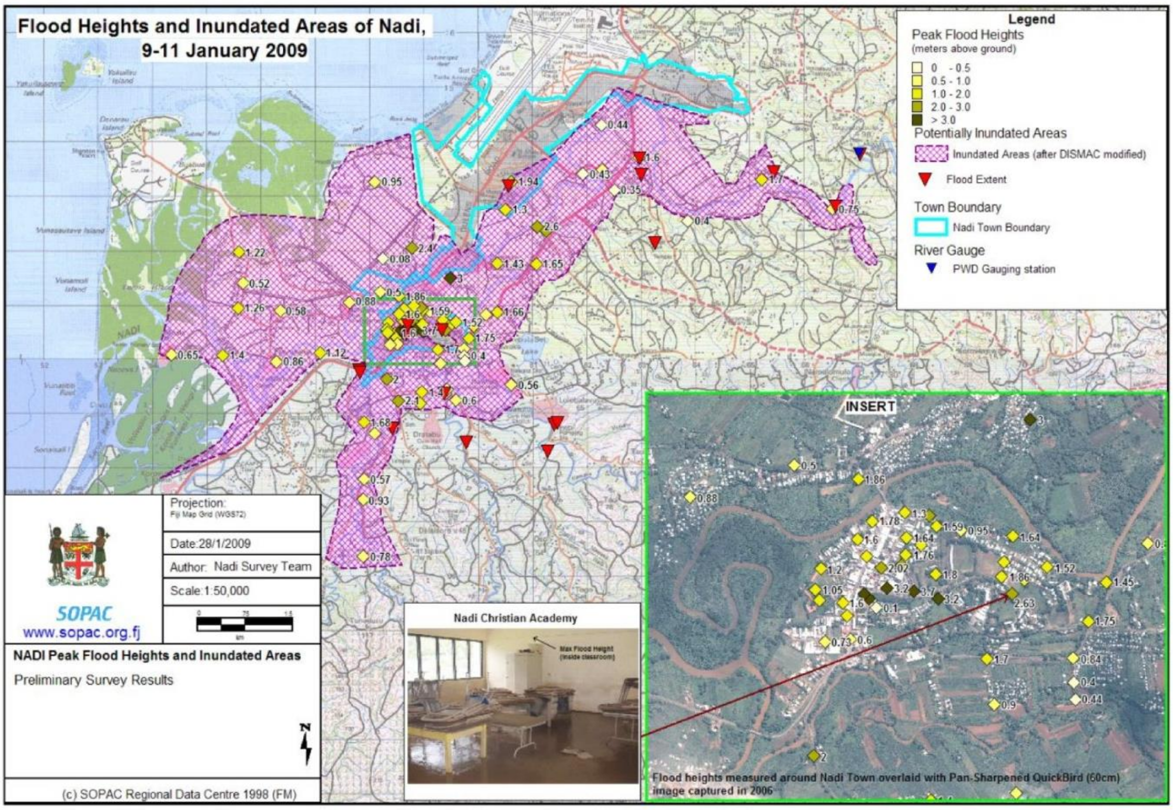


Figure 5.2-39 Actual Hydrograph of Flood on 9 January, 2009



Source：SPC/SOPAC

Figure 5.2-40 Actual Inundation Area of Flood on 9 January, 2009

Based on the actual inundation record by the SPC/SOPAC, 100m grid actual inundation map was developed. From the inundation map, inundation area, inundation volume and average inundation depth were summarized (refer to Figure 5.2-41 and Figure 5.2-42, Table 5.2-10 and Table 5.2-11).

The differences between actual inundation record (Figure 5.2-38) and reproduced inundation map (Figure 5.2-41) have appeared in the south side runway of the airport.

The detailed examination was conducted to check the potential inundation of the airport. The maximum inundation is considered as 1/4 of the south side runway. Also, it was confirmed that the inundation area of reproduced inundation map is valid (refer to Figure 5.2-43).

Table 5.2-10 Reproduced Inundation Area, Volume and Depth of the March, 2012 Flood

NO.	Block	Name	Inundation Area (ha)	Inundation Volume (1000m3)	Average Inundation Depth (m)	No of Flood Marks (points)
1	NAD-LD	Nadi, Left, Down stream	257	5,461	2.12	7
2	NAD-LM	Nadi, Left, Mid stream	614	15,990	2.60	76
3	NAD-LU	Nadi, Left, Up stream	74	3,107	2.90	3
4	NAD-RD	Nadi, Right, Down	990	16,565	1.67	58
5	NAD-RM	Nadi, Right, Mid stream	468	9,729	2.08	83
6	NAD-RU	Nadi, Right, Up stream	204	4,986	2.44	4
7	MAL-L	Malakua, Left	53	926	1.76	2
8	MAL-R	Malakua, Right	11	73	0.67	0
9	NAW-L	Nawaka, Left	191	3,782	1.98	7
10	NAW-R	Nawaka, Right	229	5,270	2.30	31
11	NAM-L	Namosi, Left	1	24	1.76	0
12	NAM-R	Namosi, Right	7	122	1.66	0
	Total		3,100	66,035	2.13	271

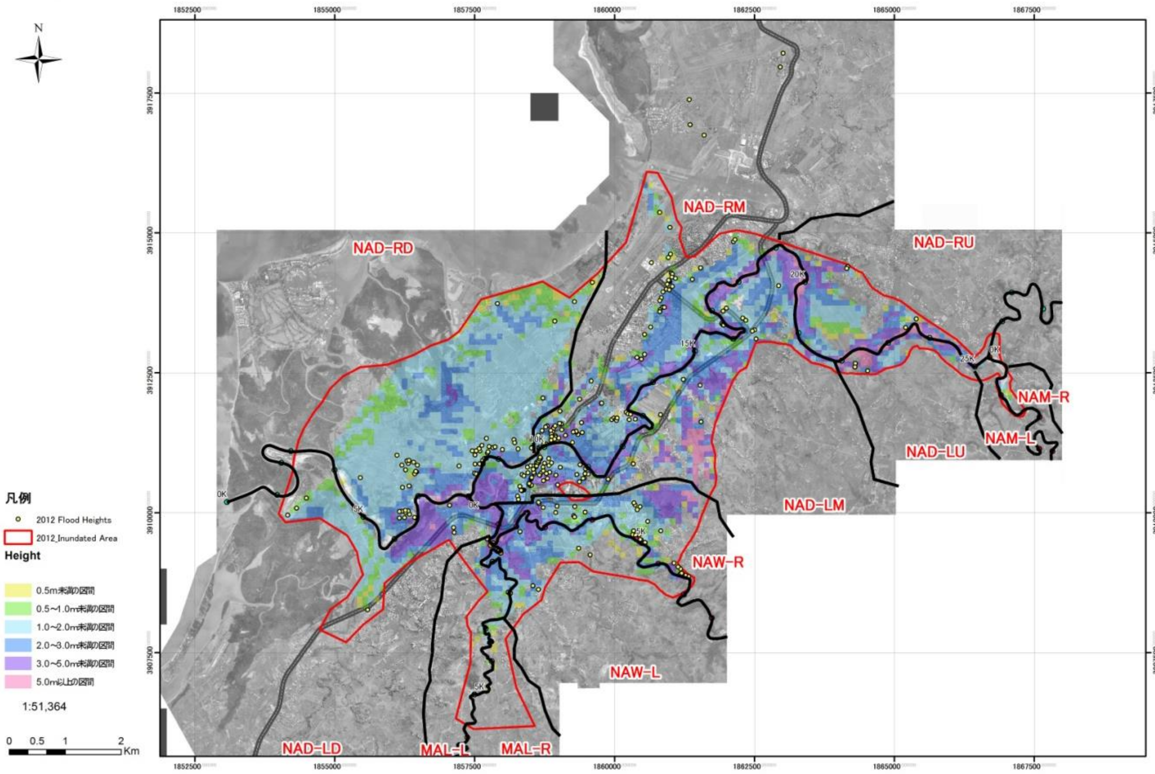


Figure 5.2-41 Actual Flood Marks and Reproduced Inundation Depth of the March, 2012 Flood

Table 5.2-11 Reproduced Inundation Area, Volume and Depth of Inundation in the January 2009 flood

NO.	Block	Name	Inundation Area (ha)	Inundation Volume (1000m3)	Average Inundation Depth (m)	No of Flood Marks (points)
1	NAD-LD	Nadi, Left, Down stream	175	2,635	1.50	3
2	NAD-LM	Nadi, Left, Mid stream	561	13,370	2.38	43
3	NAD-LU	Nadi, Left, Up stream	59	1,730	2.51	0
4	NAD-RD	Nadi, Right, Down	939	10,512	1.12	11
5	NAD-RM	Nadi, Right, Mid stream	320	6,923	2.16	6
6	NAD-RU	Nadi, Right, Up stream	206	6,318	3.07	2
7	MAL-L	Malakua, Left	74	1,295	1.75	2
8	MAL-R	Malakua, Right	38	363	0.96	3
9	NAW-L	Nawaka, Left	172	3,236	1.89	7
10	NAW-R	Nawaka, Right	167	2,438	1.46	7
11	NAM-L	Namosi, Left	2	17	0.82	0
12	NAM-R	Namosi, Right	6	136	2.11	0
	Total		2,719	48,973	1.80	84

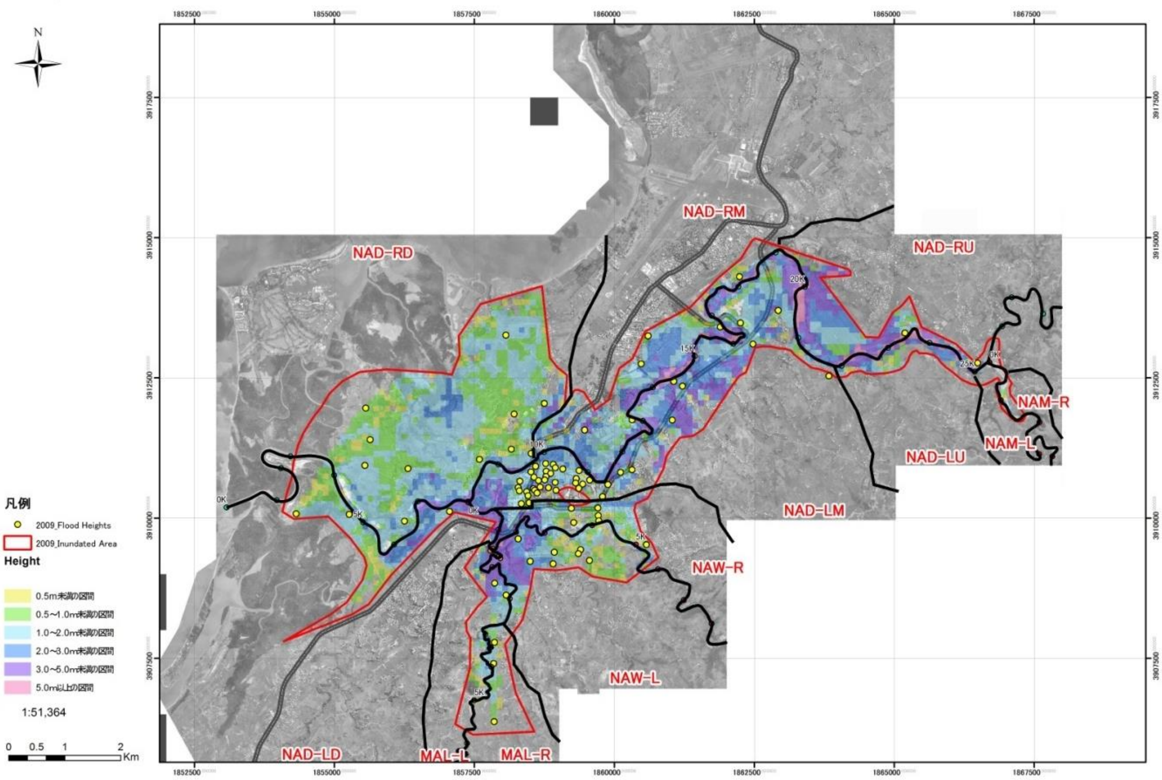


Figure 5.2-42 Actual Flood Marks and Reproduced Inundation depth of the January 2009 flood

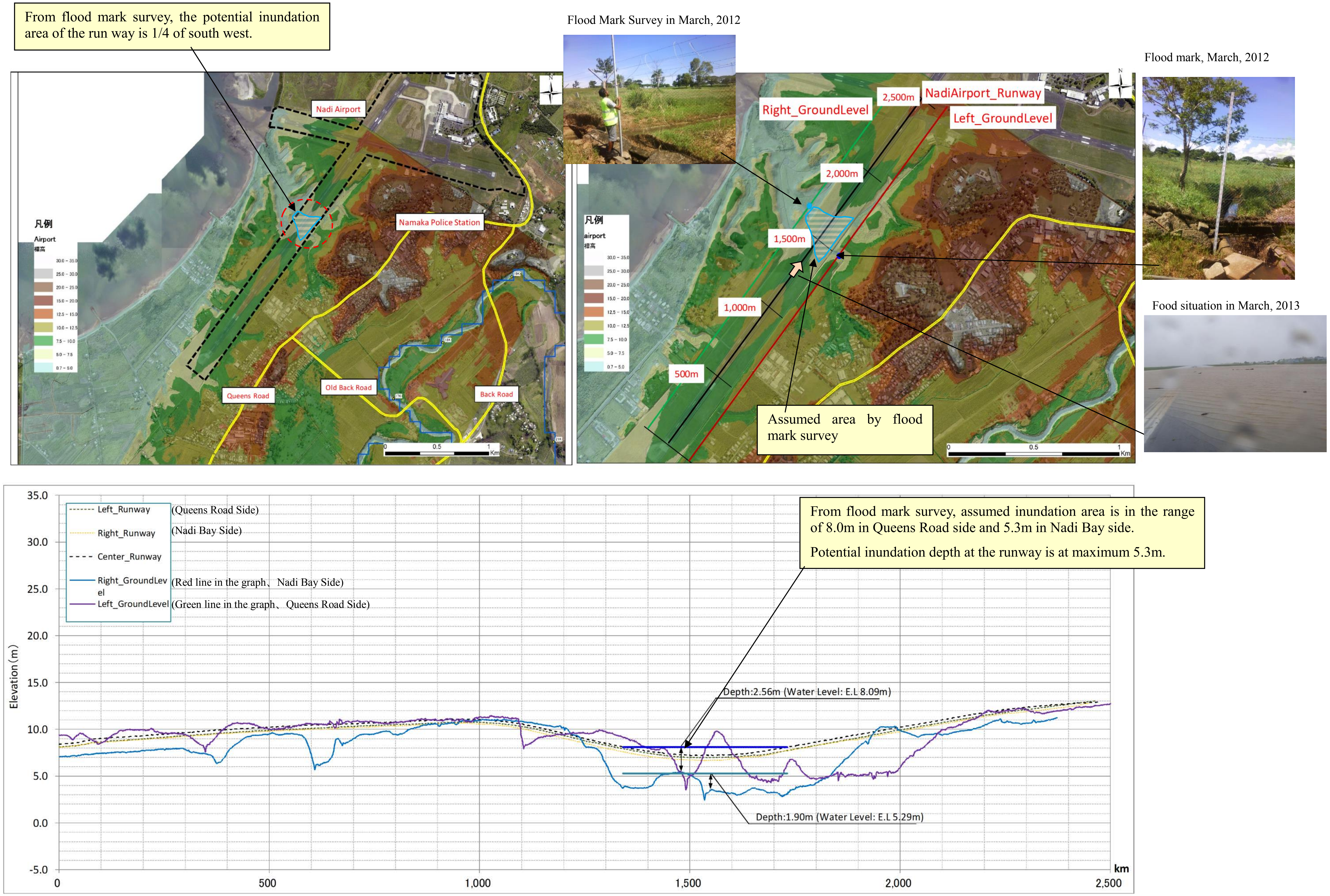


Figure 5.2-43 Relationship between Ground Elevation and Actual Inundation near Airport

(2) Reproduction

1) Methodology of Calibration of the Model

For the calibration of the model, boundary condition of inundation model is given by the discharge from the run-off model (without inundation). The calibration was implemented to compare the reproduced water level and channel discharge and inundation area with the actual records.

Run-off Area Model

Based on the initial parameters determined in Table 5.2-8, the parameters which fit the actual run off during flood.

The target of this examination is reproduction of the situation during the flood. Therefore, roughness coefficient which is the parameter of surface land use, and Rsa which is the parameter of wet condition, is changed.

Inundation Area Model

The water level and discharge at the Nadi Town Bridge Point change in accordance with the inundation volume of upstream. Therefore, roughness coefficient is to be adjusted based on the initial roughness coefficient in the river channel.

2) Result of reproduction calculation

Flood in March, 2012

a) Run-off model

Roughness coefficient and wetness condition of the basin were adjusted by the comparison of the discharge of HQ equation which is converted form actual water level at Votualevu water level station and calculated discharge in the model. The result of calibration shows that the equivalent roughness is the same as the initial value. Regarding Rsa, the value is set to be 70 for the following reasons. Rsa is adjusted, considering for the forest area, farmland and grassland which are large in the upstream of Namosi (refer to Figure 5.2-44).

1) The average value of the initial discharge area is 240. (Table 5.2-12)

2) Precipitation before 3weeks of the flood in March, 2012. (Approx. 150mm)

3) Calculation results of the records at Votualevu water level station are well reproduced.

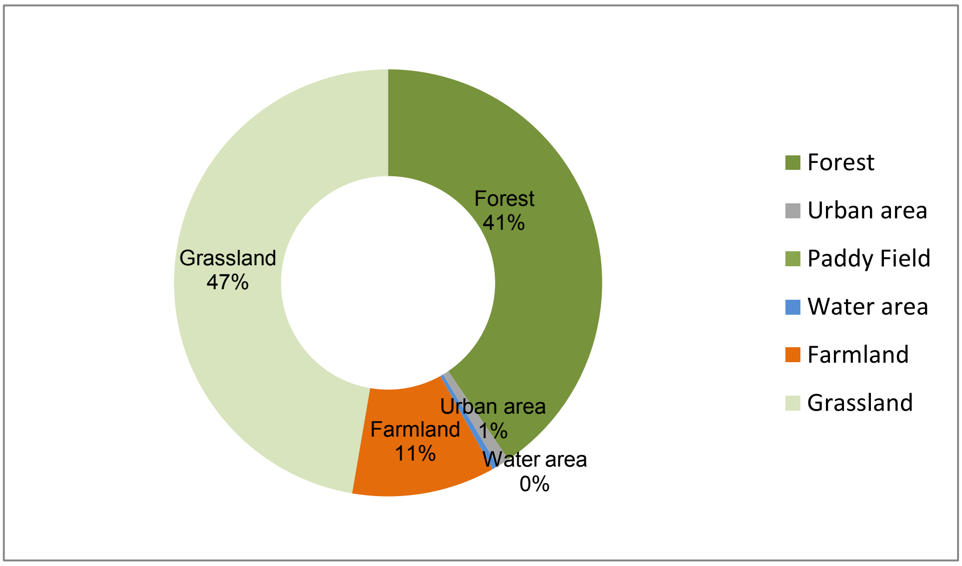


Figure 5.2-44 Ratio of Land Use in Run-off Area

Table 5.2-12 Average Rsa in Run-off Area (initial value)

Run-off Area Model			
	Area (km^2)	Ratio	Rsa
Forest	188.0	59.8	150
Urban area	4.3	1.4	55
Paddy Field	0.0	0.0	50
Water area	2.1	0.7	0
Farmland	50.1	15.9	300
Grassland	219.5	69.9	300
		Basin Ave. Rsa	236

The output is the discharge before the inundation because the area is run-off area.

The result of calculation is shown in Figure 5.2-45 based on the determined coefficients.

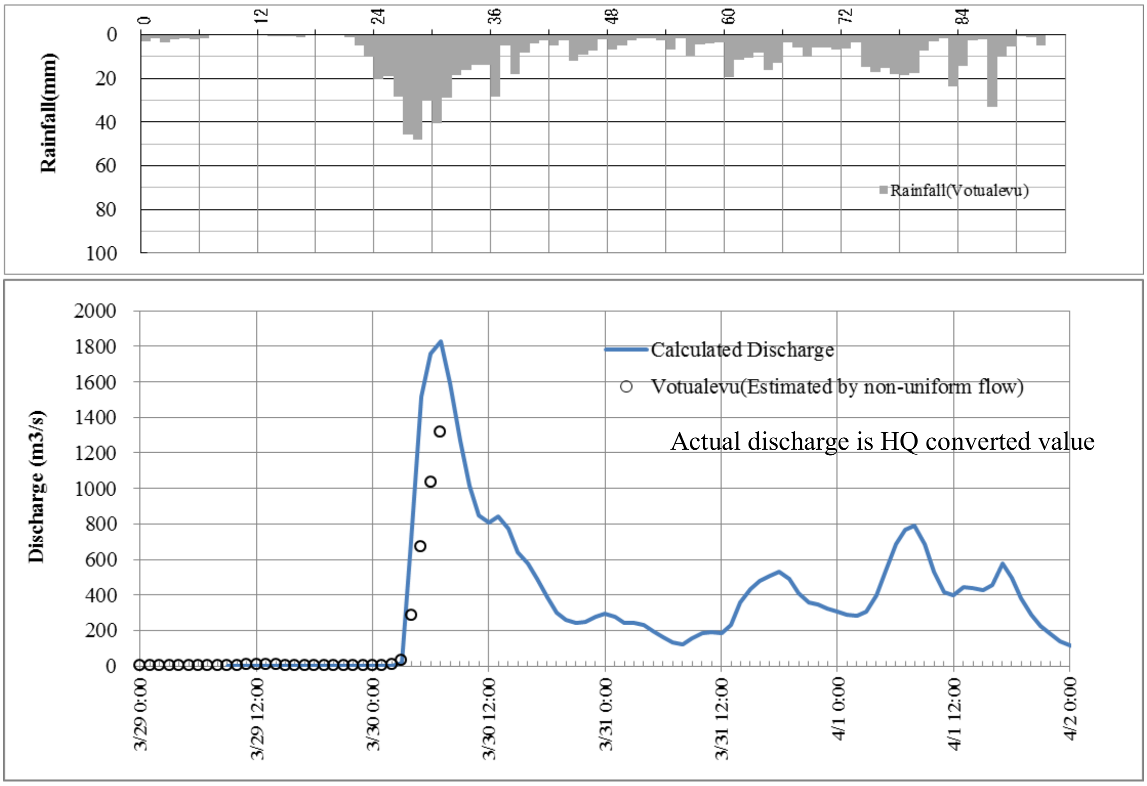


Figure 5.2-45 Actual and Calculated Hydrograph at Votualevu Station of 2012 Flood

b) Inundation Model

- **Water level in the river Channel**

At the Nadi Town Bridge where the peak water level of flood is observed, roughness coefficient is adjusted by using the actual water level and the calculated value. The value is adjusted mainly to fit the initial rise of the flood. The comparison of the actual water level and the calculated value is shown in Figure 5.2-46.

✓ Calculation result is RL.8.11 (SG8.00m) and actual peak water level is RL.7.73m (SG7.62m) at Nadi Town Bridge (NTB) so this difference is about 38cm and with calculation error of 5%.

✓ Calculation could not reflect part of inundation influence in upstream so that arrival of flood peak was earlier than actual result.

✓ The start of flood wave was generally consistent.

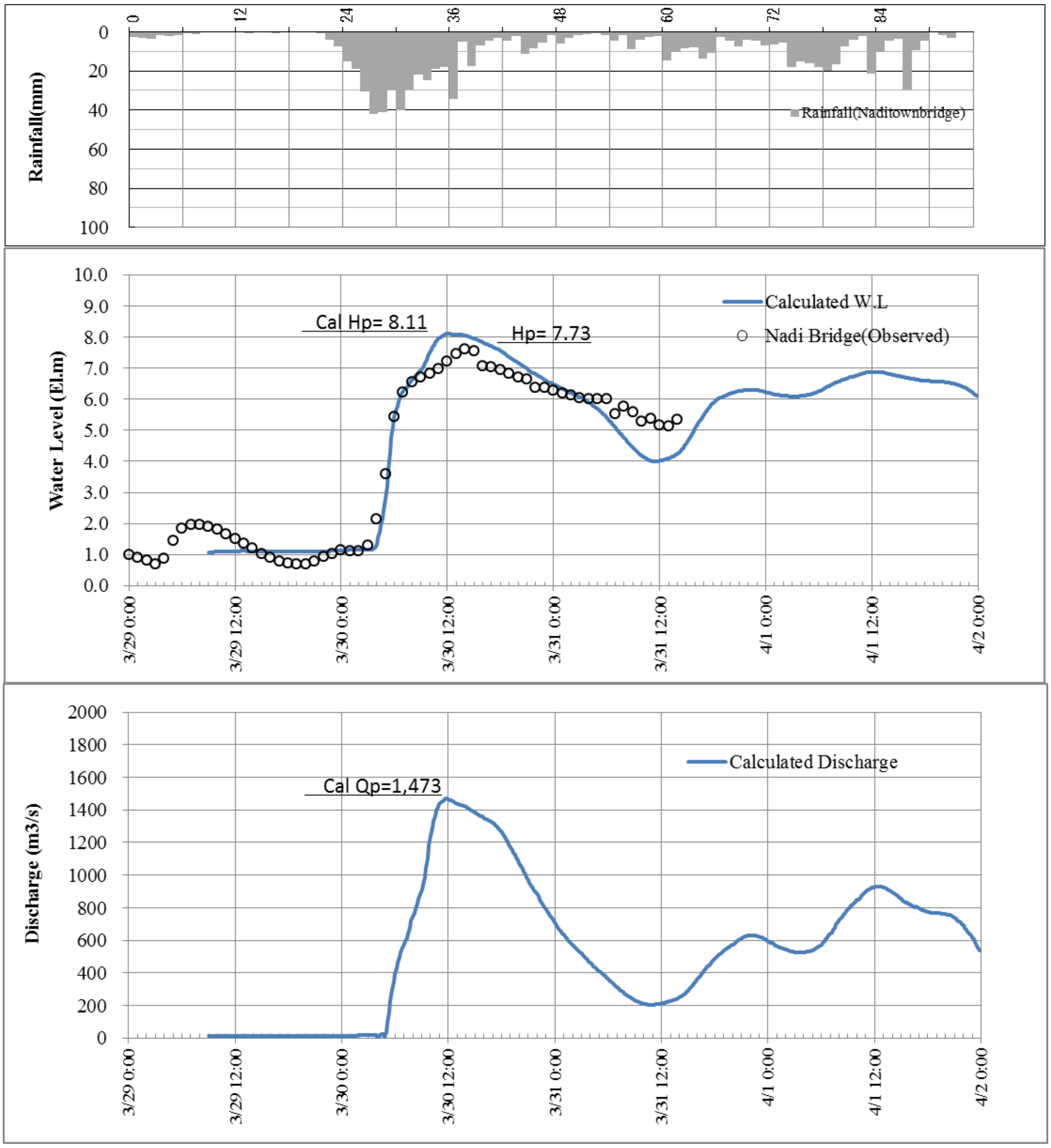
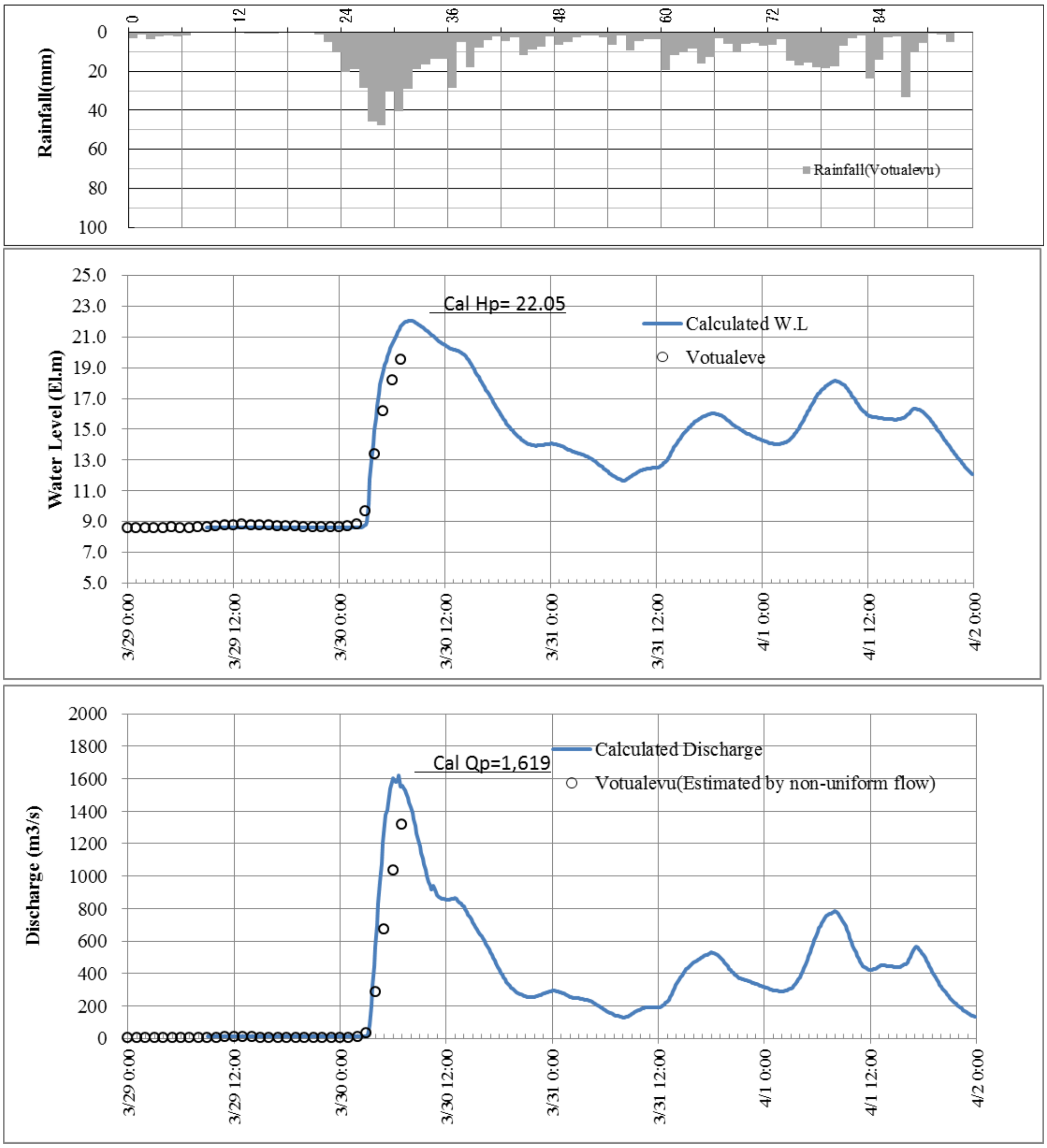


Figure 5.2-46 Actual and Calculated Hydrograph of 2012 Flood at the Nadi Town Bridge Station

Regarding the Votualevu water level station, calculated initial rise of flood is faster than actual. This result shows the inundation in the upstream is not included.



Actual discharge is HQ converted value. HQ curve is generated by one-dimensional steady flow model.

Figure 5.2-47 Actual and Calculated Hydrograph of the 2012 Flood at Votualevu Station

- **Maximum inundation**

The maximum inundation depth distribution map is shown in Figure 5.2-49. Table 5.2-13 and Figure 5.2-48 show the result of block by block comparison of inundation area, volume and depth.

The comparison between actual and calculated value in NAD-LM (Nadi River Left bank, Midstream) which has many flood mark records is shown below.

- ✓ The actual and calculated inundation areas are 614ha and 620 ha, respectively. The gap is +7ha (approx. -1%).
- ✓ The actual and calculated inundation volumes are 15,990,000m^3 and 15,820,000m^3, respectively. The gap is +17,000m^3 (approx. 1%).
- ✓ The average of the actual and calculated inundation depths are 2.60m and 2.55m, respectively. The gap is -0.05m (approx. -2%).

Table 5.2-13 Comparison of Reproduced and Actual Inundation by Block (March, 2012 flood)

NO.	Block	Name	(a) Reproduction			(b) Actual Records			(a) / (b)			No of Flood Marks (points)
			Inundation Area (ha)	Inundation Volume (1000m3)	Average Inundation Depth (m)	Inundation Area (ha)	Inundation Volume (1000m3)	Average Inundation Depth (m)	Inundation Area (ha)	Inundation Volume (1000m3)	Average Inundation Depth (m)	
1	NAD-LD	Nadi, Left, Down stream	311	4,046	1.30	257	5,461	2.12	1.21	0.74	0.61	7
2	NAD-LM	Nadi, Left, Mid stream	620	15,823	2.55	614	15,990	2.60	1.01	0.99	0.98	76
3	NAD-LU	Nadi, Left, Up stream	72	2,438	2.58	74	3,107	2.90	0.98	0.78	0.89	3
4	NAD-RD	Nadi, Right, Downstream	997	12,365	1.24	990	16,565	1.67	1.01	0.75	0.74	58
5	NAD-RM	Nadi, Right, Mid stream	513	10,935	2.13	468	9,729	2.08	1.10	1.12	1.03	83
6	NAD-RU	Nadi, Right, Up stream	230	6,392	2.78	204	4,986	2.44	1.13	1.28	1.14	4
7	MAL-L	Malakua, Left	84	1,843	2.19	53	926	1.76	1.59	1.99	1.25	2
8	MAL-R	Malakua, Right	57	822	1.44	11	73	0.67	5.18	11.19	2.16	0
9	NAW-L	Nawaka, Left	208	4,927	2.37	191	3,782	1.98	1.09	1.30	1.20	7
10	NAW-R	Nawaka, Right	229	4,554	1.99	229	5,270	2.30	1.00	0.86	0.86	31
11	NAM-L	Namosi, Left	10	413	4.13	1	24	1.76	7.24	16.99	2.34	0
12	NAM-R	Namosi, Right	17	755	4.44	7	122	1.66	2.32	6.19	2.67	0
	Total		3,348	65,314	1.95	3,100	66,035	2.13	1.08	0.99	0.92	271

- **Time-series Inundation depth map**

Time-series inundation depth maps are shown in Figure 5.2-50. 12 hour time-series inundation depth maps from 30 March, 2012 are shown in Figure 5.2-51 and Figure 5.2-52. Also, longitudinal sections of water level graphs of the same time are shown in Figure 5.2-53

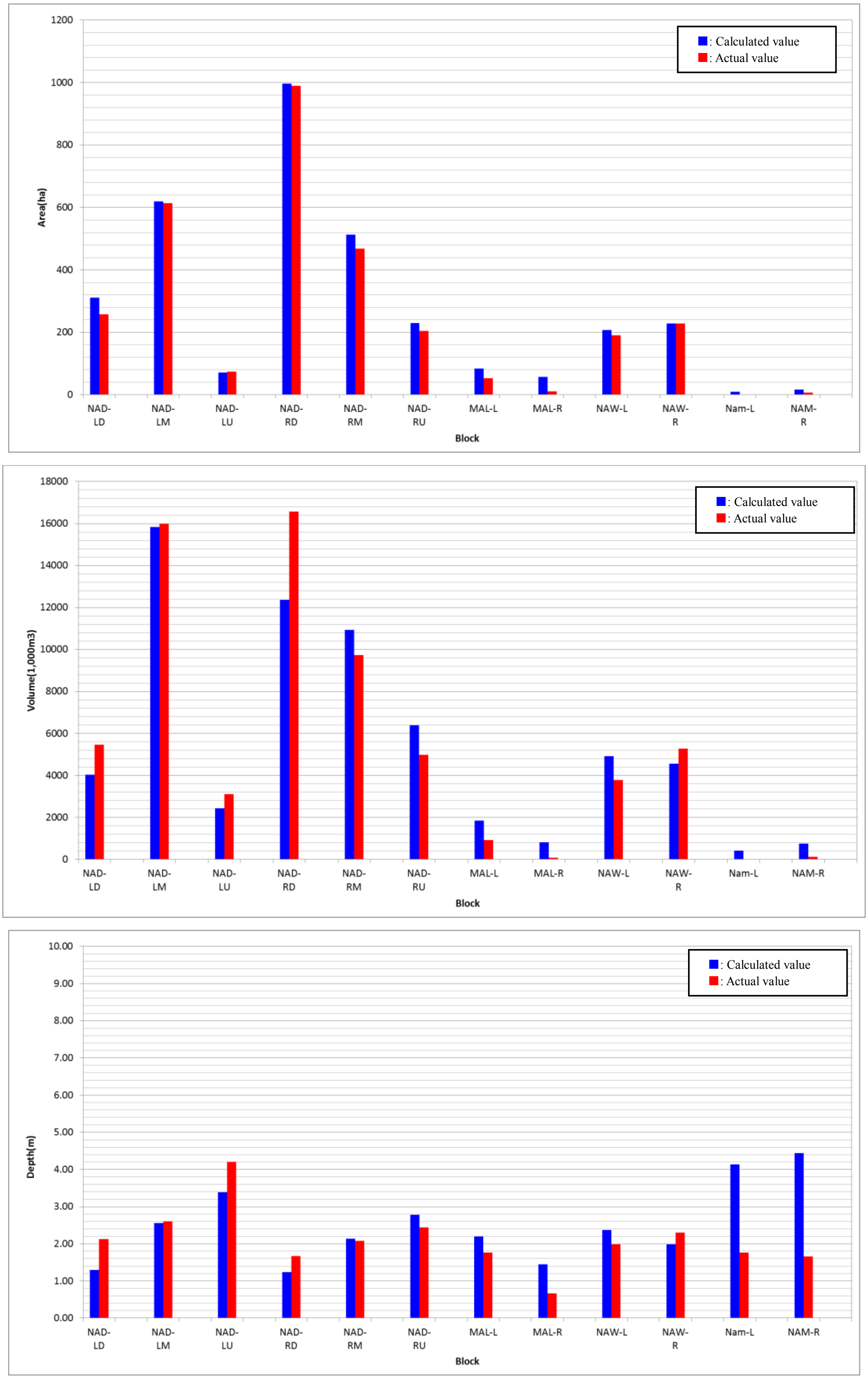


Figure 5.2-48 Comparison of Calculated and Actual Inundations by Block (March, 2012 flood)

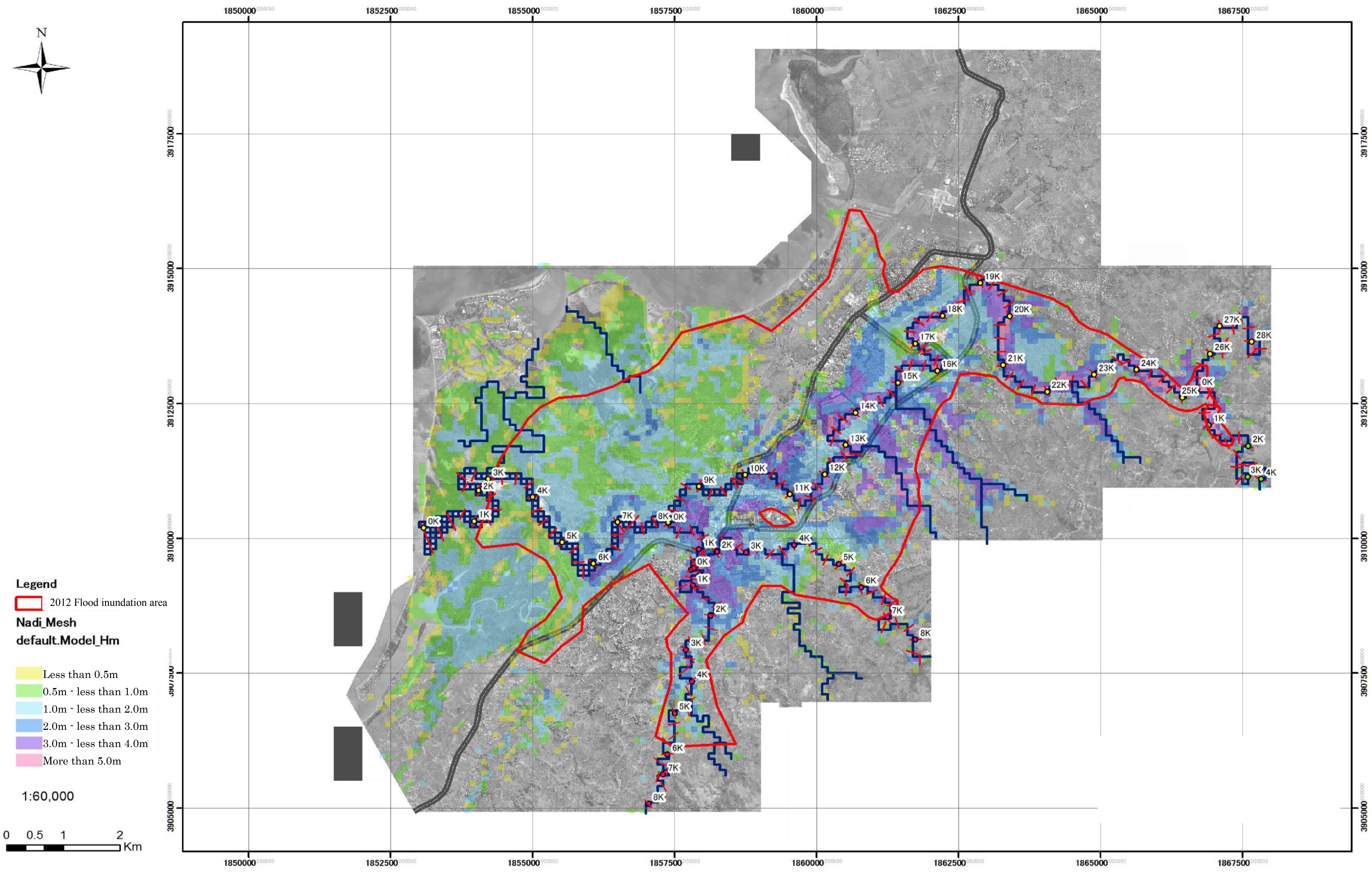


Figure 5.2-49 Result of Inundation Simulation (maximum inundation distribution of the March 2012 flood)

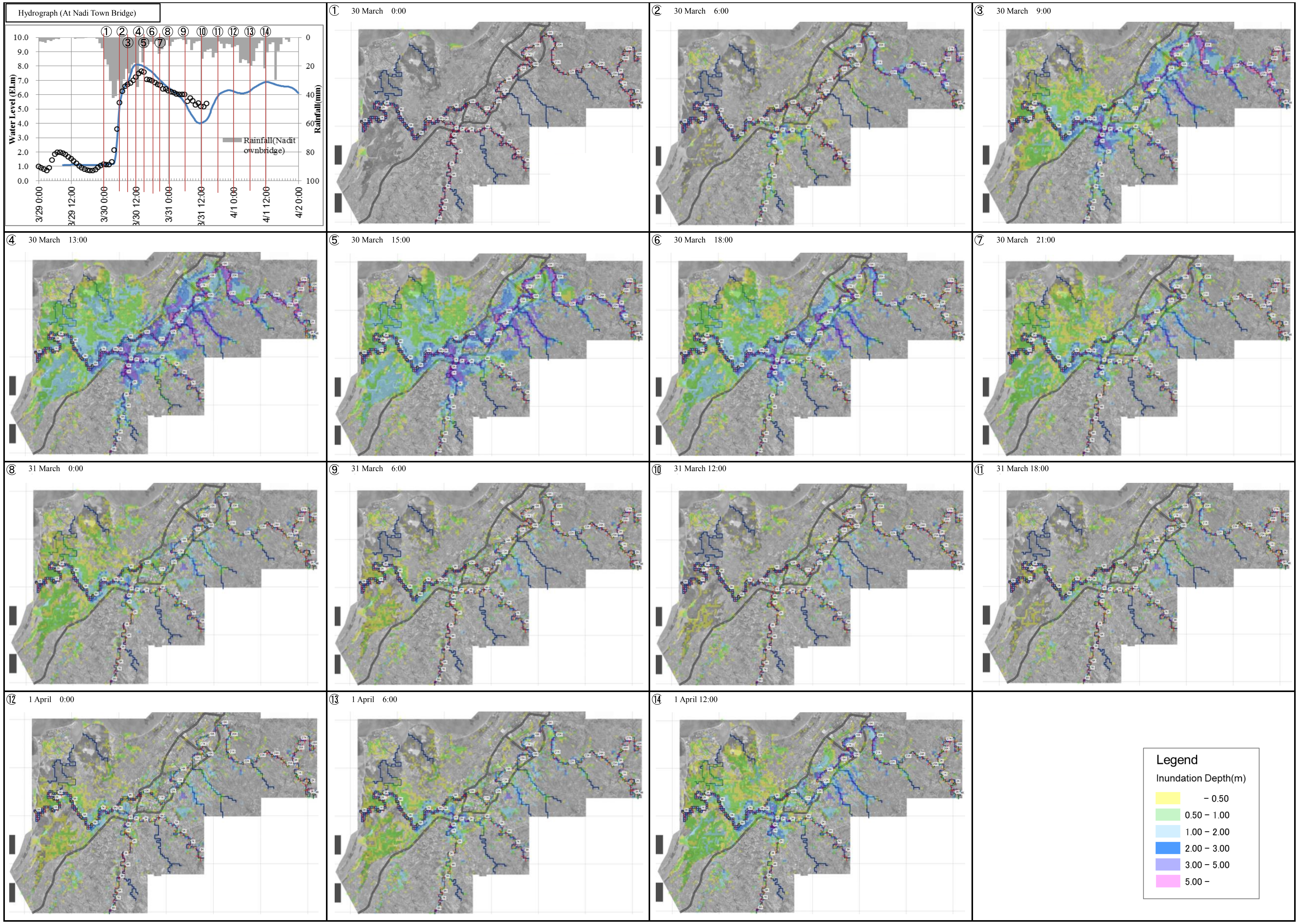


Figure 5.2-50 Result of Inundation Simulation (time-series inundation distribution of the March 2012 flood)

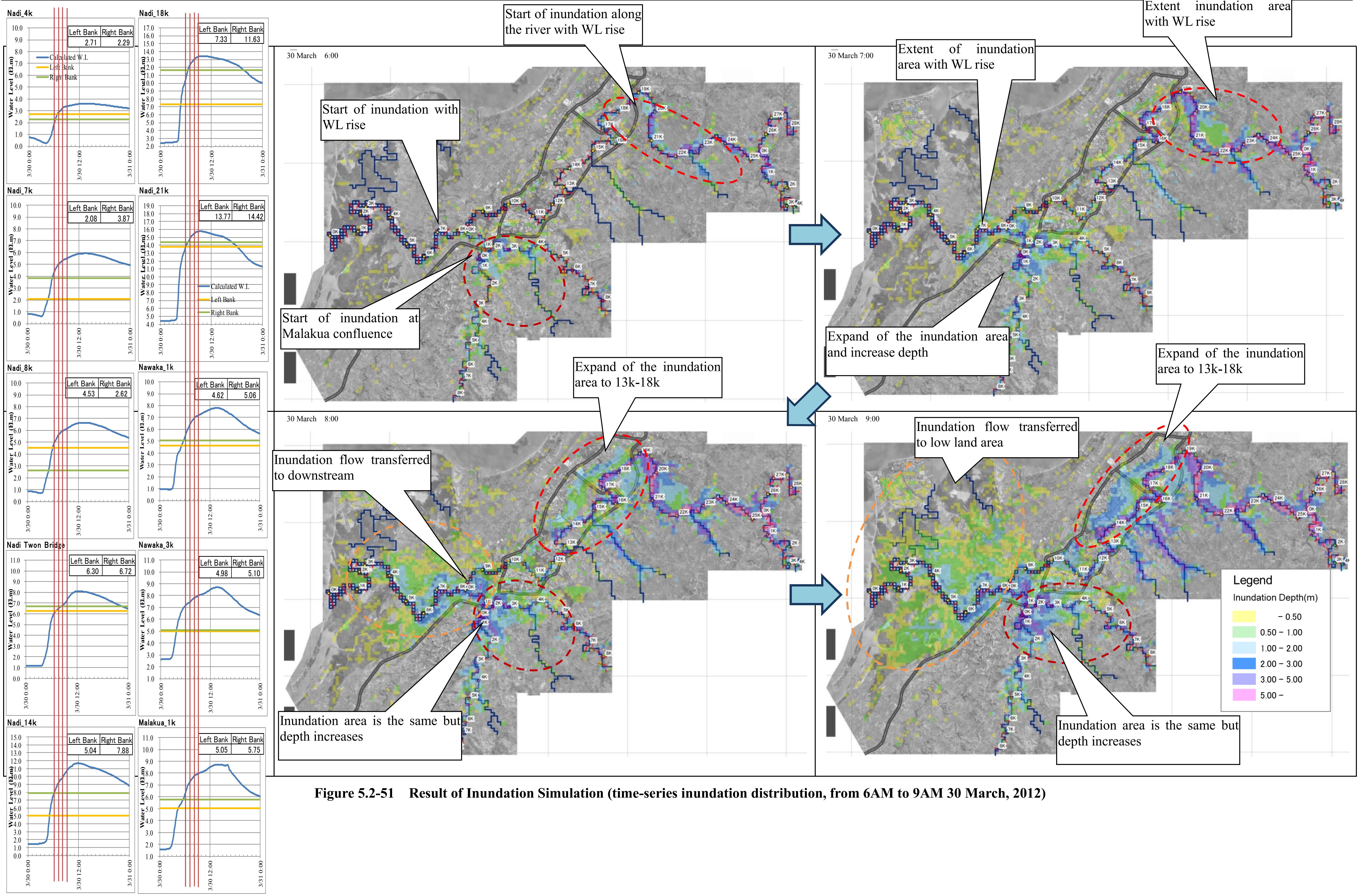


Figure 5.2-51 Result of Inundation Simulation (time-series inundation distribution, from 6AM to 9AM 30 March, 2012)

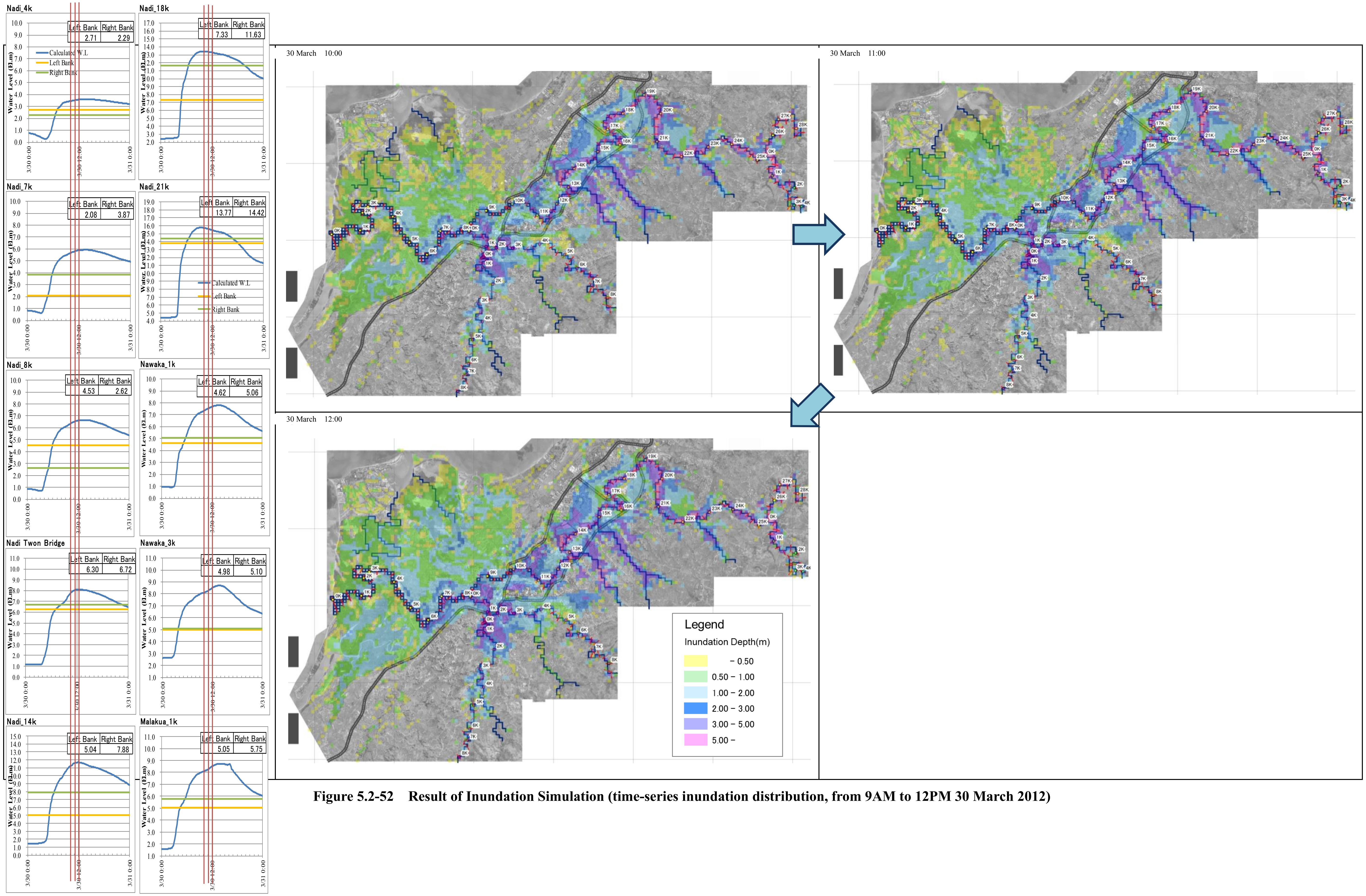
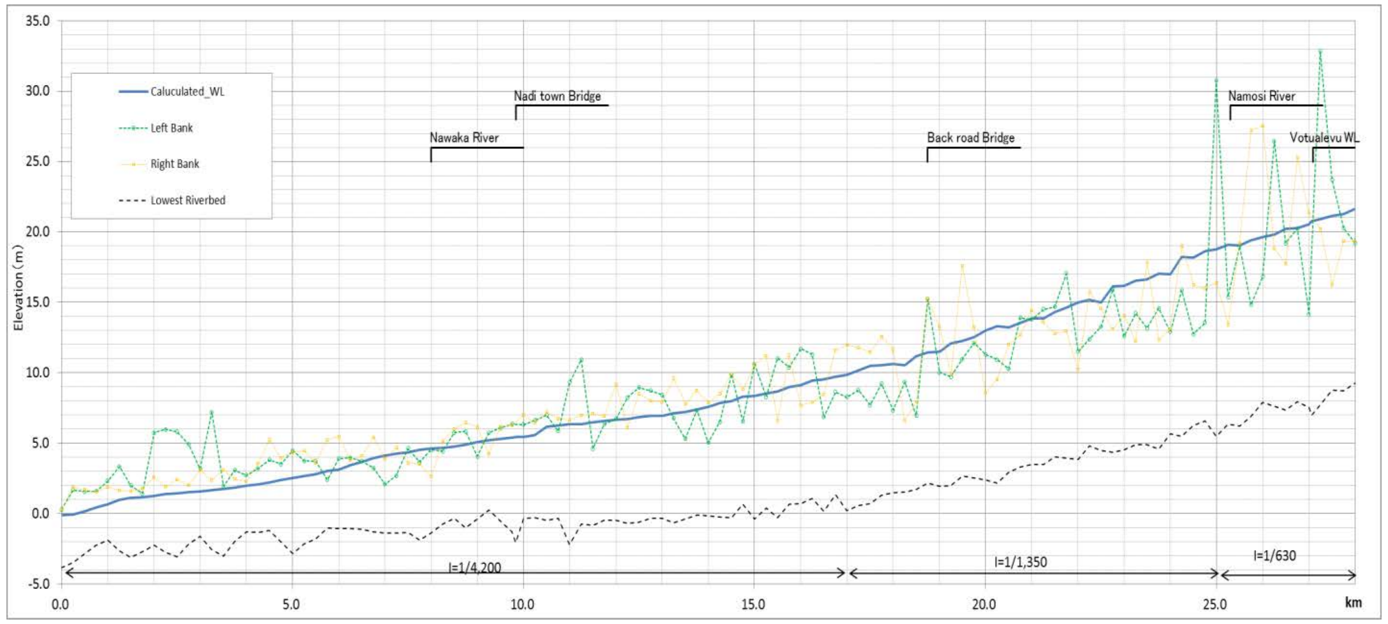


Figure 5.2-52 Result of Inundation Simulation (time-series inundation distribution, from 9AM to 12PM 30 March 2012)

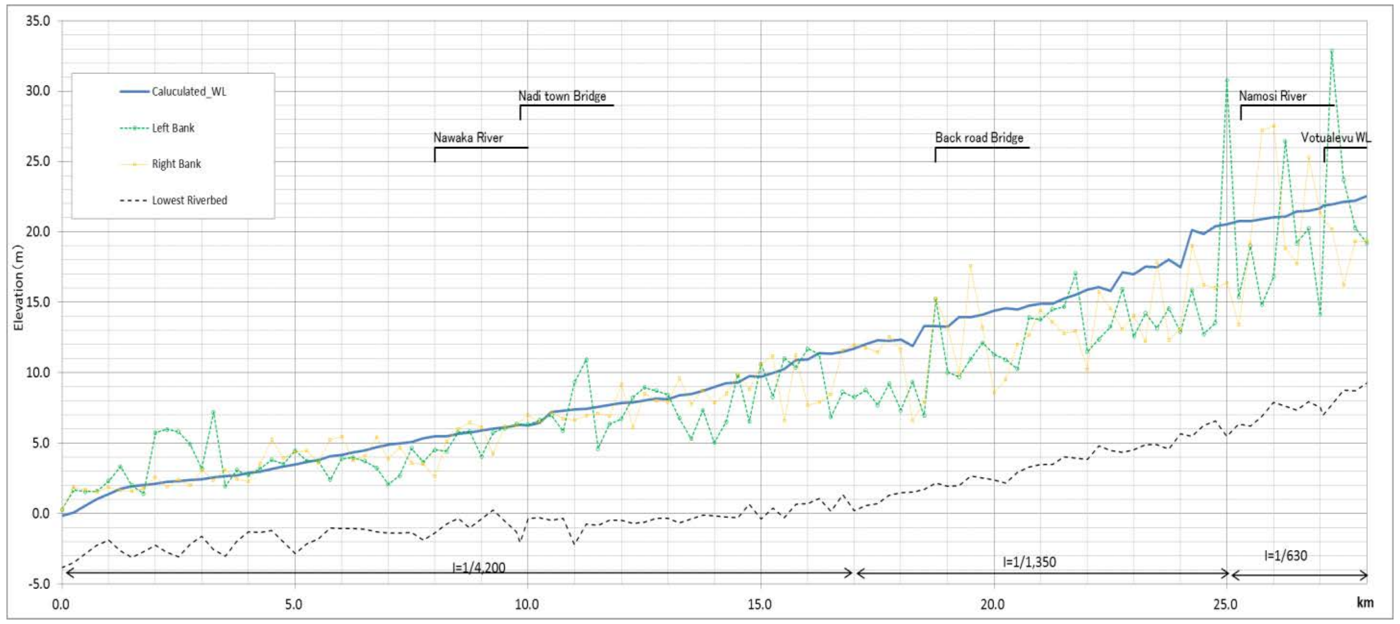
30th 6:00

Nadi River

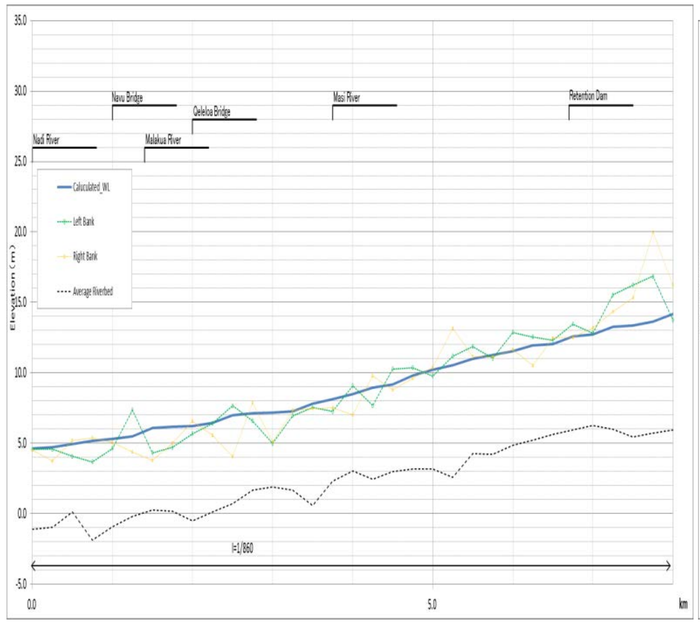


30th 7:00

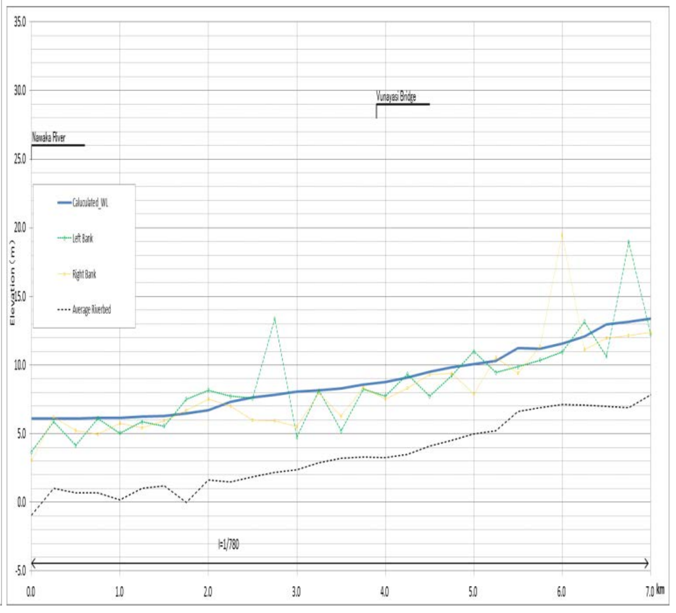
Nadi River



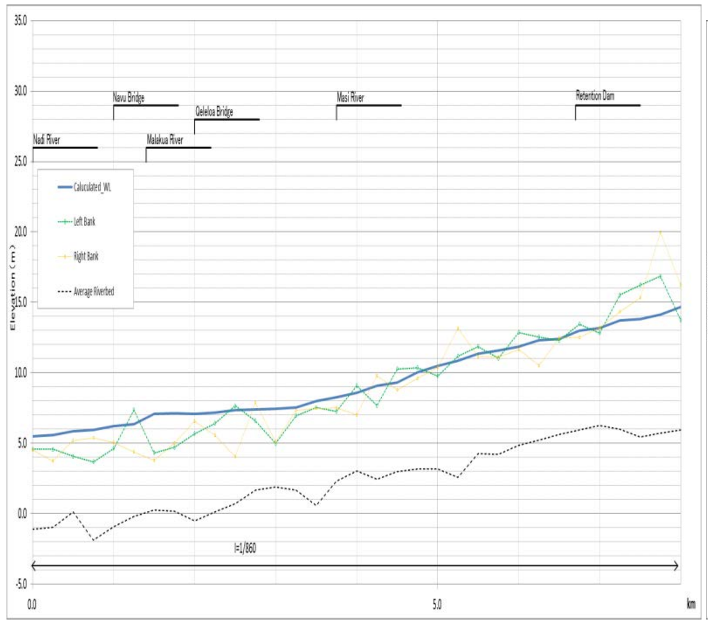
Nawaka River



Malakua



Nawaka River



Malakua

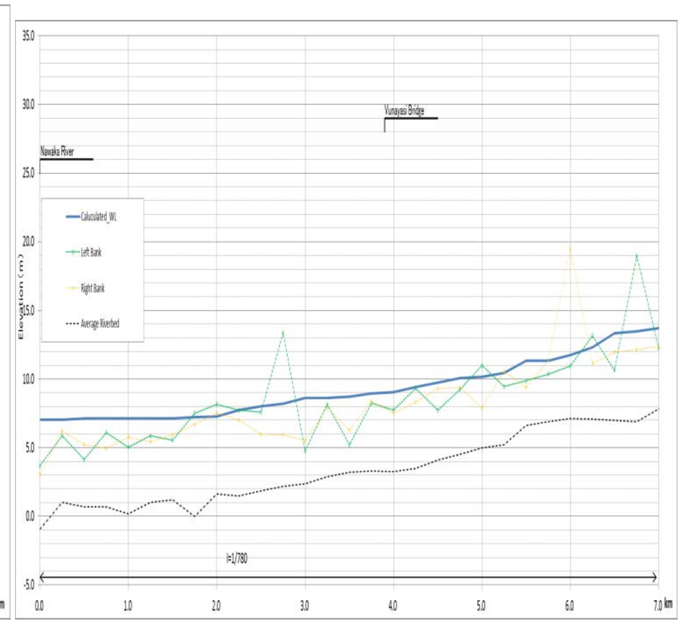
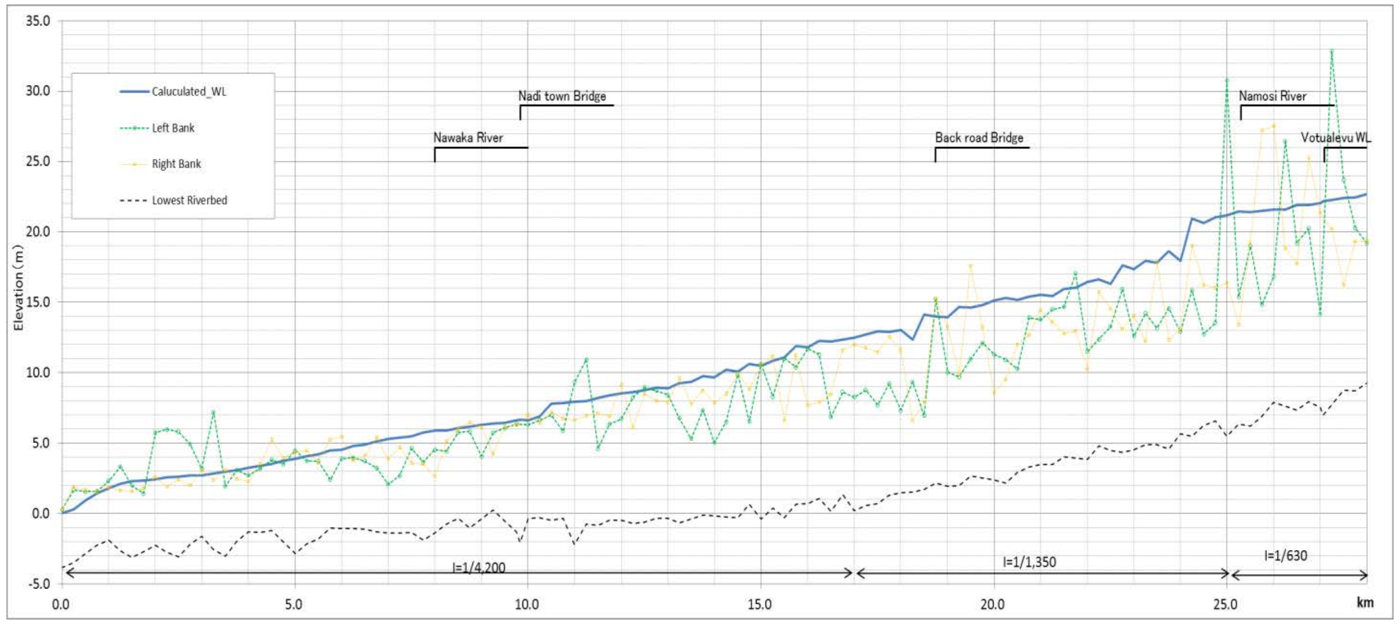


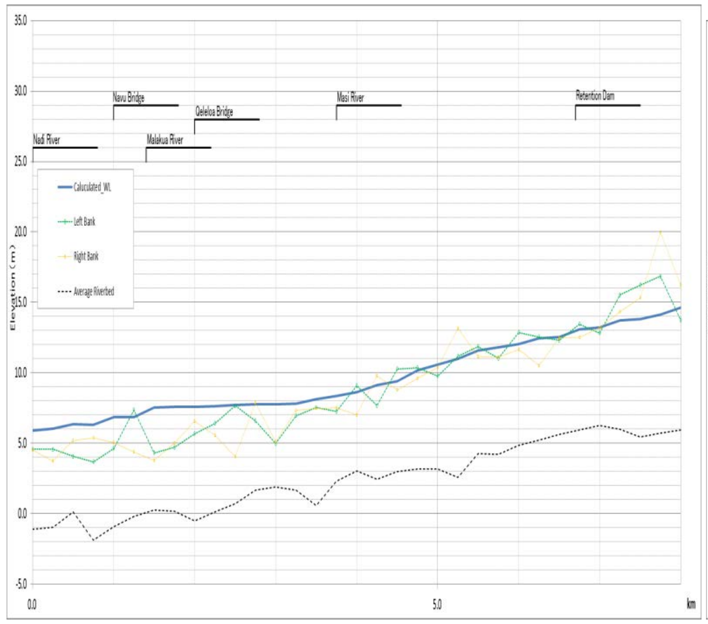
Figure 5.2-53 (1) Result of Inundation Simulation (longitudinal sections of water level of the March 2012 flood)

30th 8:00

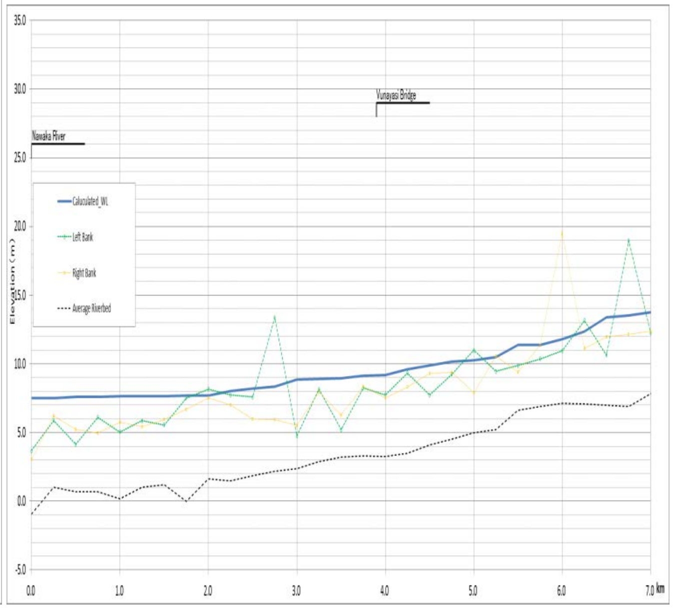
Nadi River



Nawaka River

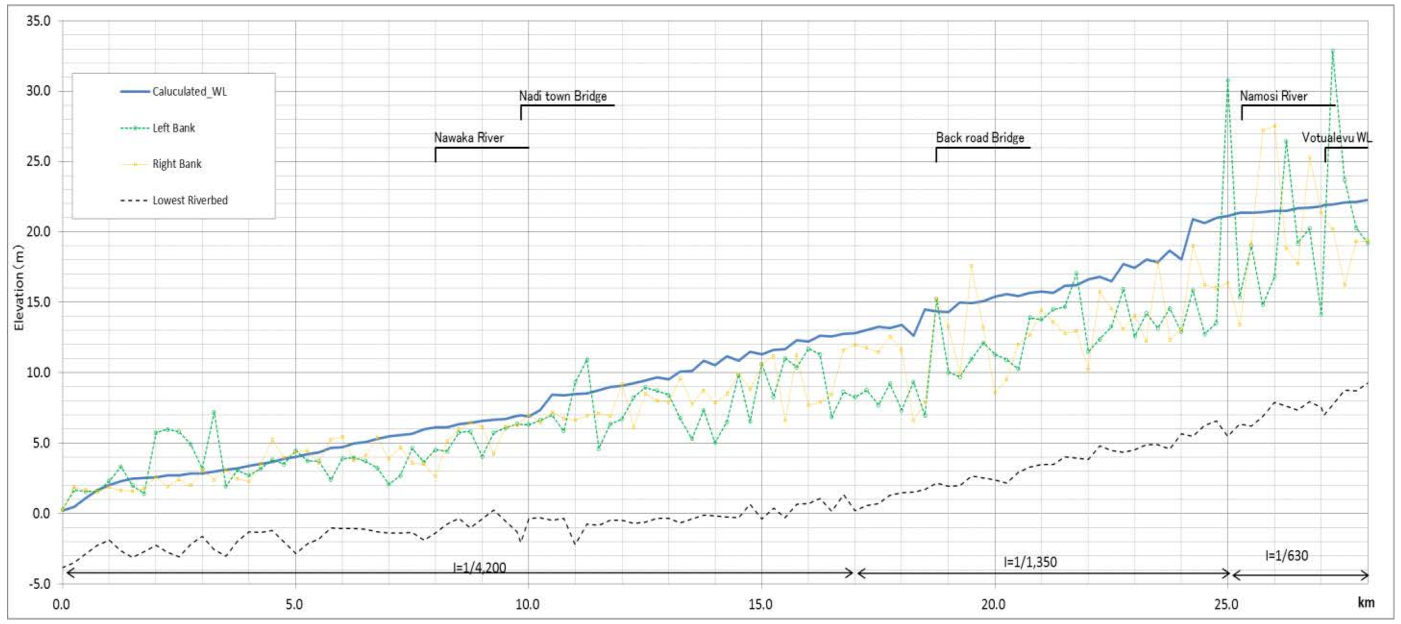


Malakua

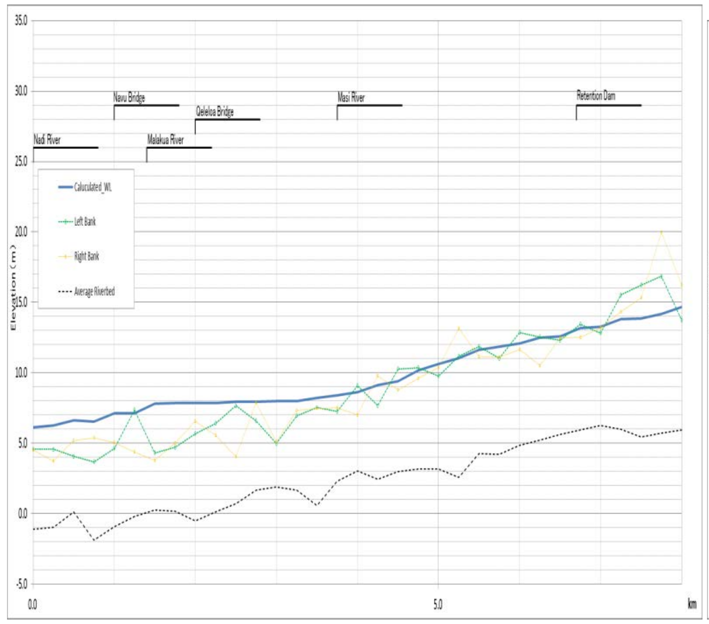


30th 9:00

Nadi River



Nawaka River



Malakua

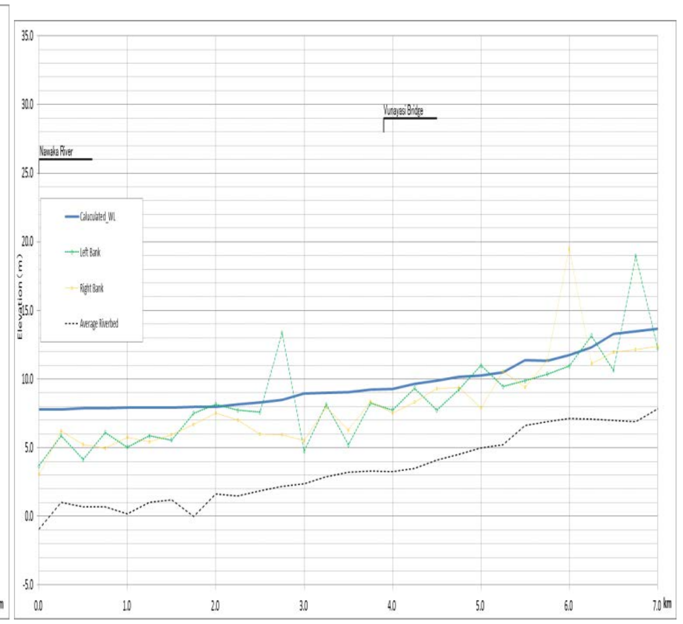
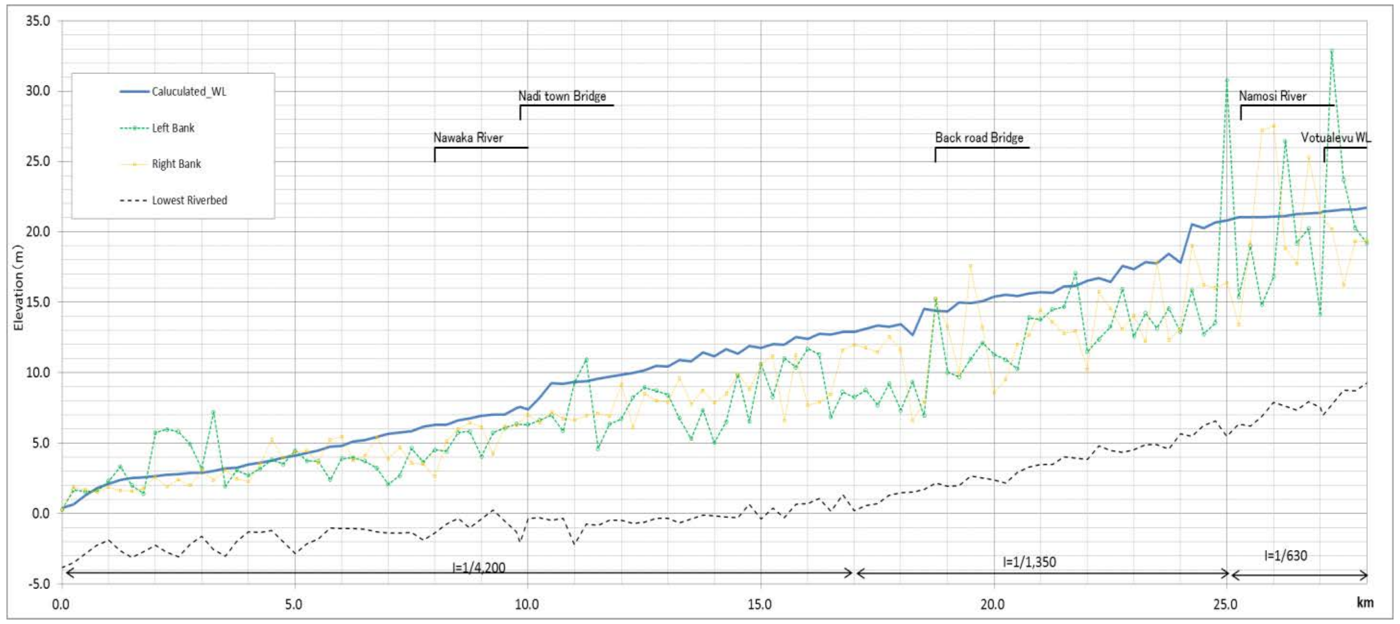


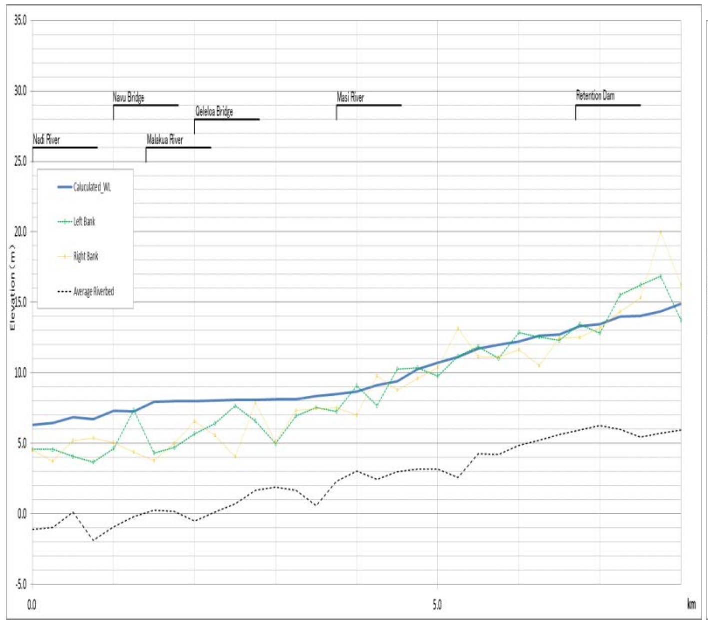
Figure 5.2-53 (2) Result of Inundation Simulation (longitudinal sections of water level of the March 2012 flood)

30th 10:00

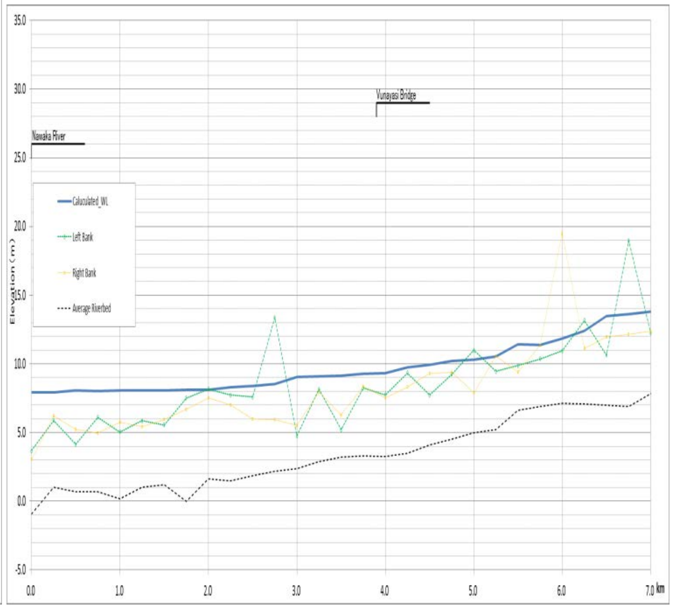
Nadi River



Nawaka River

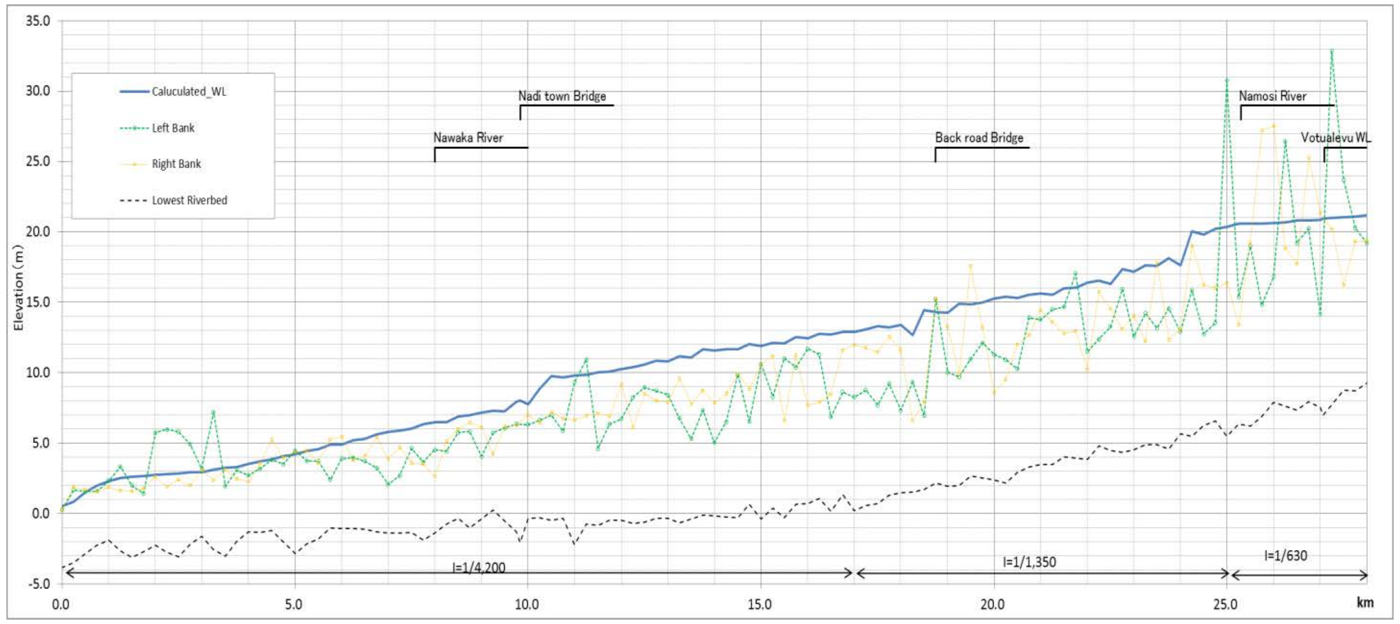


Malakua

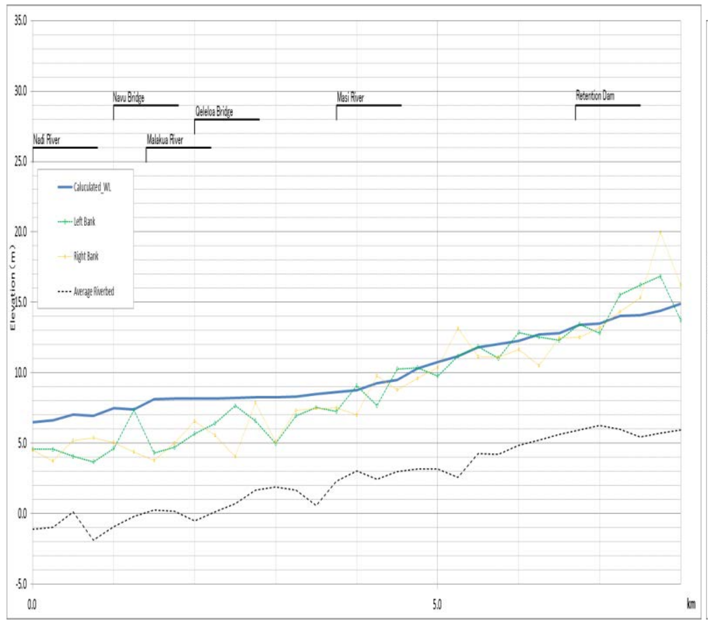


30th 11:00

Nadi River



Nawaka River



Malakua

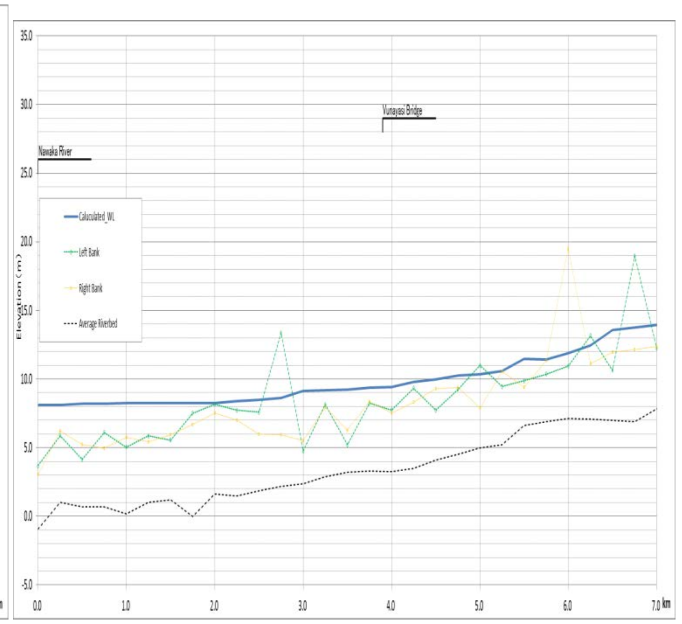
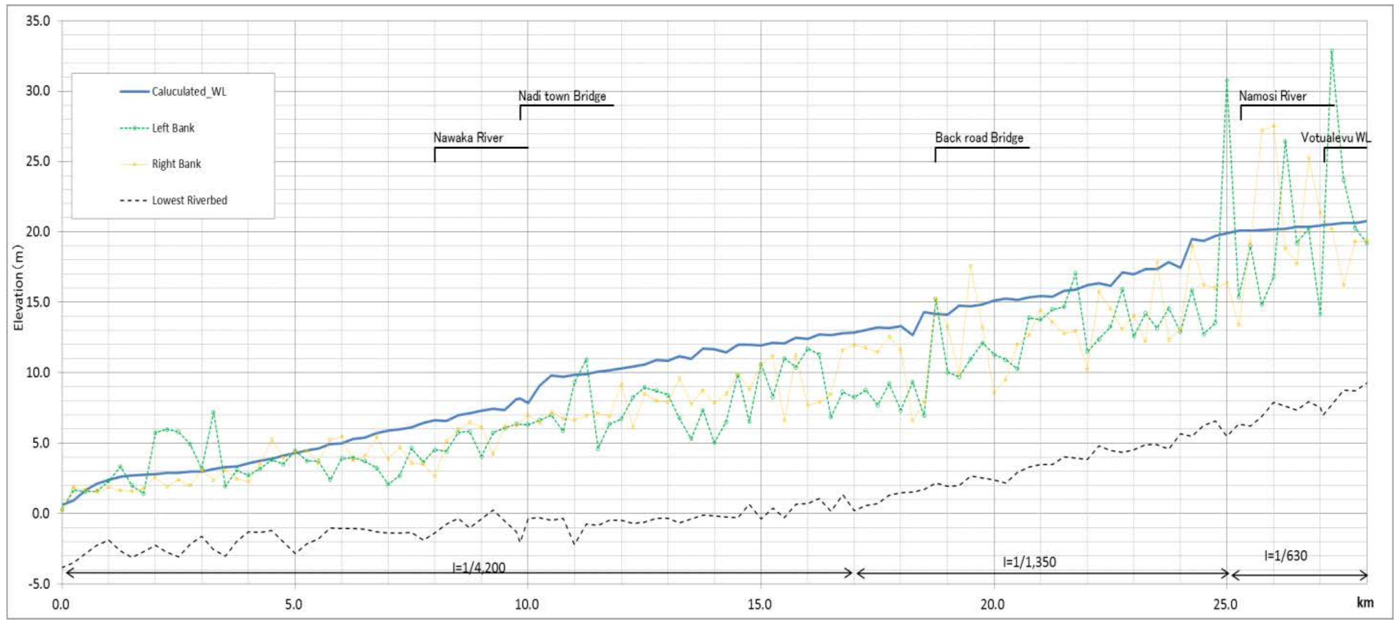


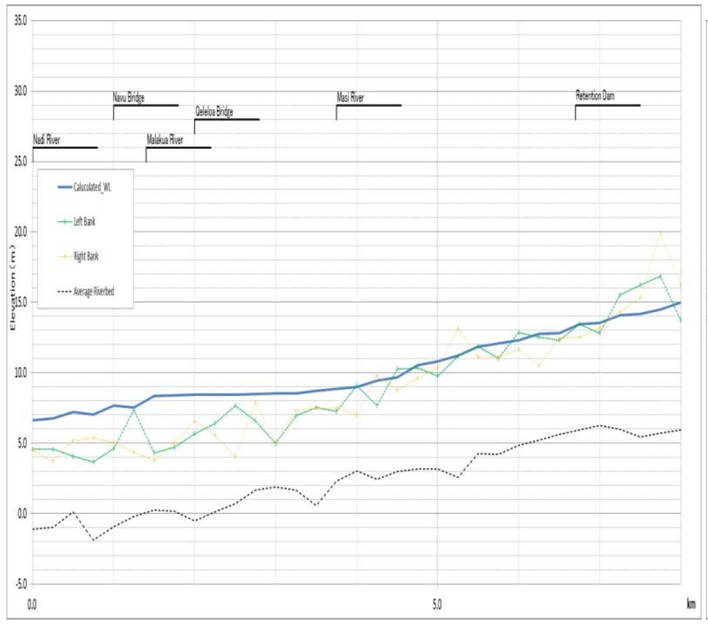
Figure 5.2-53 (3) Result of Inundation Simulation (longitudinal sections of water level of the March 2012 flood)

30th 12:00

Nadi River



Nawaka River



Malakua

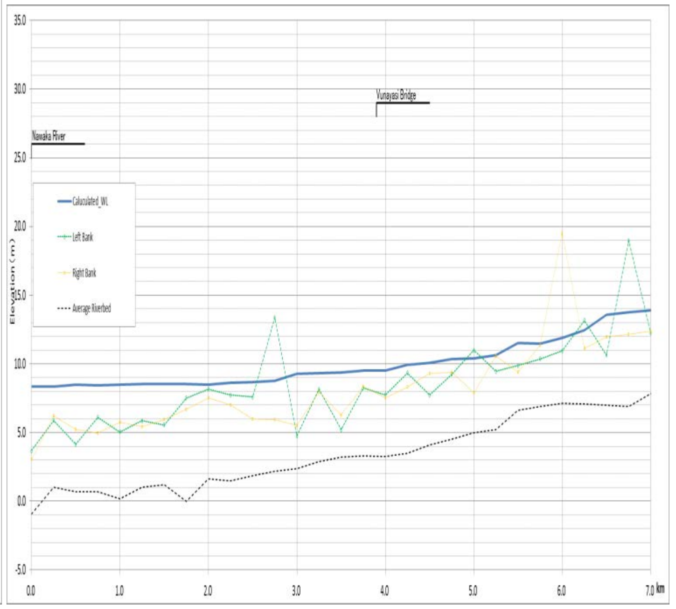


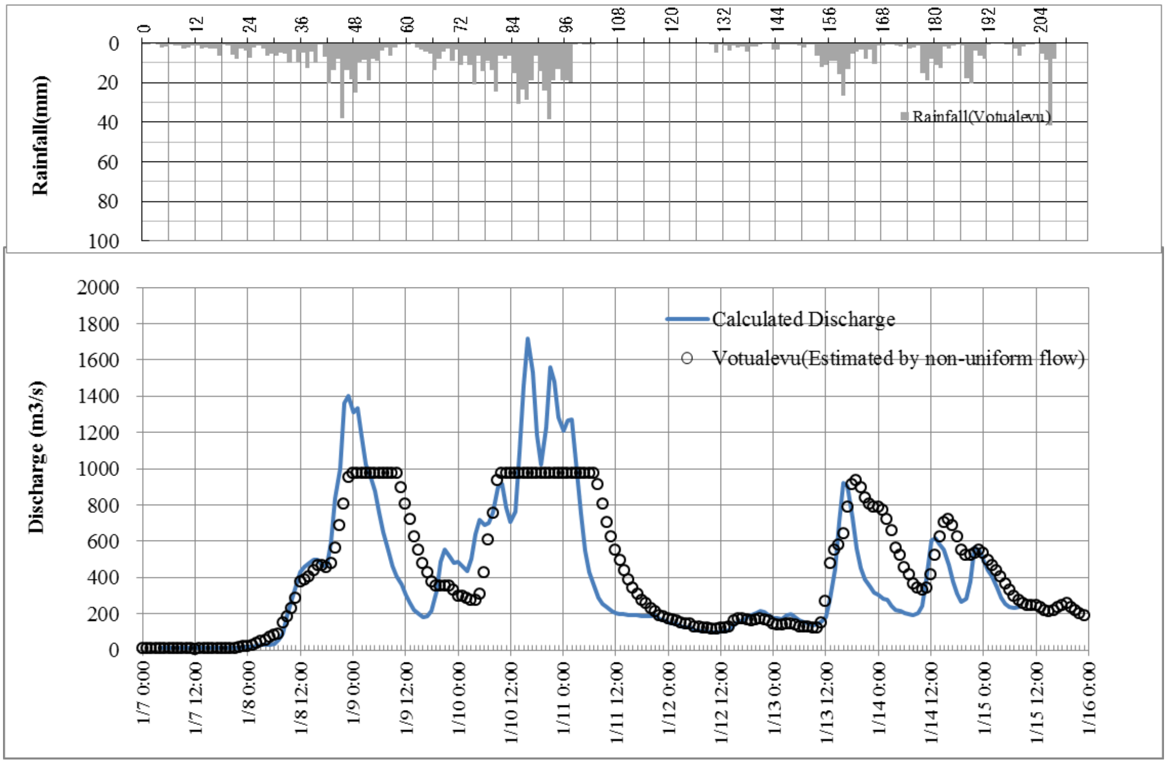
Figure 5.2-53 (4) Result of Inundation Simulation (longitudinal sections of water level of the March 2012 flood)

Flood in 9th January, 2009

By using the coefficients calibrated for the flood in March, 2012, the flood on 9 January, 2009 is calculated. The initial calculation result shows that the volume at the Votualevu station is not enough. Therefore, the data of precipitation at Waidumu station located upstream of Votualevu, is utilized as the precipitation of Navilawa for calibration.

c) Discharge model

The discharge at the Votualevu station is shown below.



Actual discharge is HQ converted value. HQ curve is generated by one-dimensional steady flow

Figure 5.2-54 Actual and Calculated Hydrograph of the 9 Jan, 2009 Flood at Votualevu Station

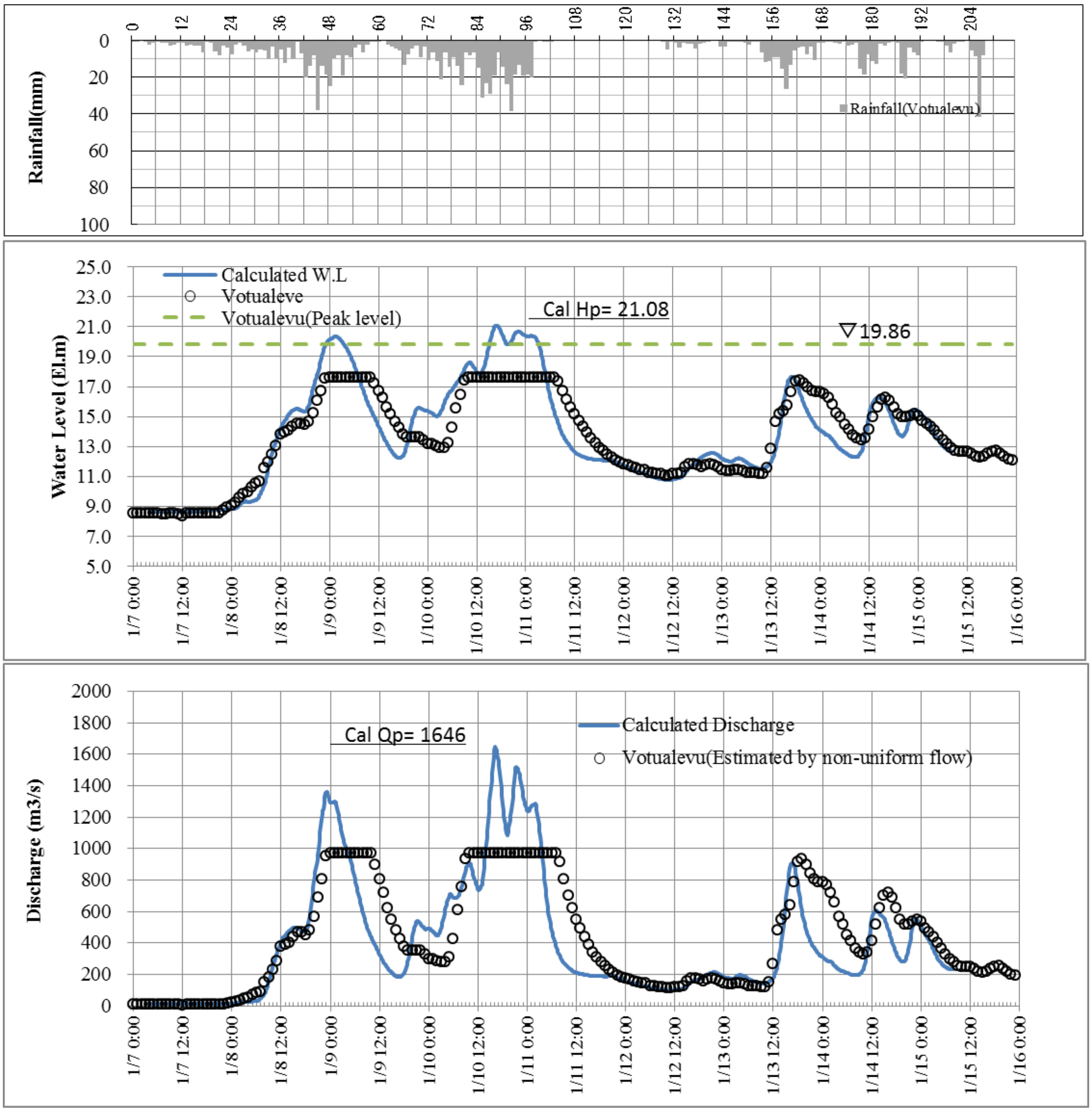
d) Inundation Model

- **Water level in the river channel**

The comparison of calculated water level and actual value recorded at Votualevu water level observatory during January 2009 flood is shown using identified roughness coefficients in Figure 5.2-55, and the maximum water depth map is also shown in Figure 5.2-58.

✓ The calculation result of water level is EL. 21.06m and actual peak water level was EL. 19.86m (SG12.215m) at Votualevu so that the difference is about 1.22m.

✓ The start of flood wave generally consistent but the drop timing was earlier because a part of inundation upstream area was not reflected.



Actual discharge is HQ converted value. HQ curve is generated by one-dimensional steady flow

Figure 5.2-55 Actual and Calculated Hydrograph of the 9 Jan, 2009 Flood at Votualevu Station

The water level in Nadi Town Bridge is shown below. The peak water level is EL.7.76m, and the discharge in the channel is 1,400m^3/s.

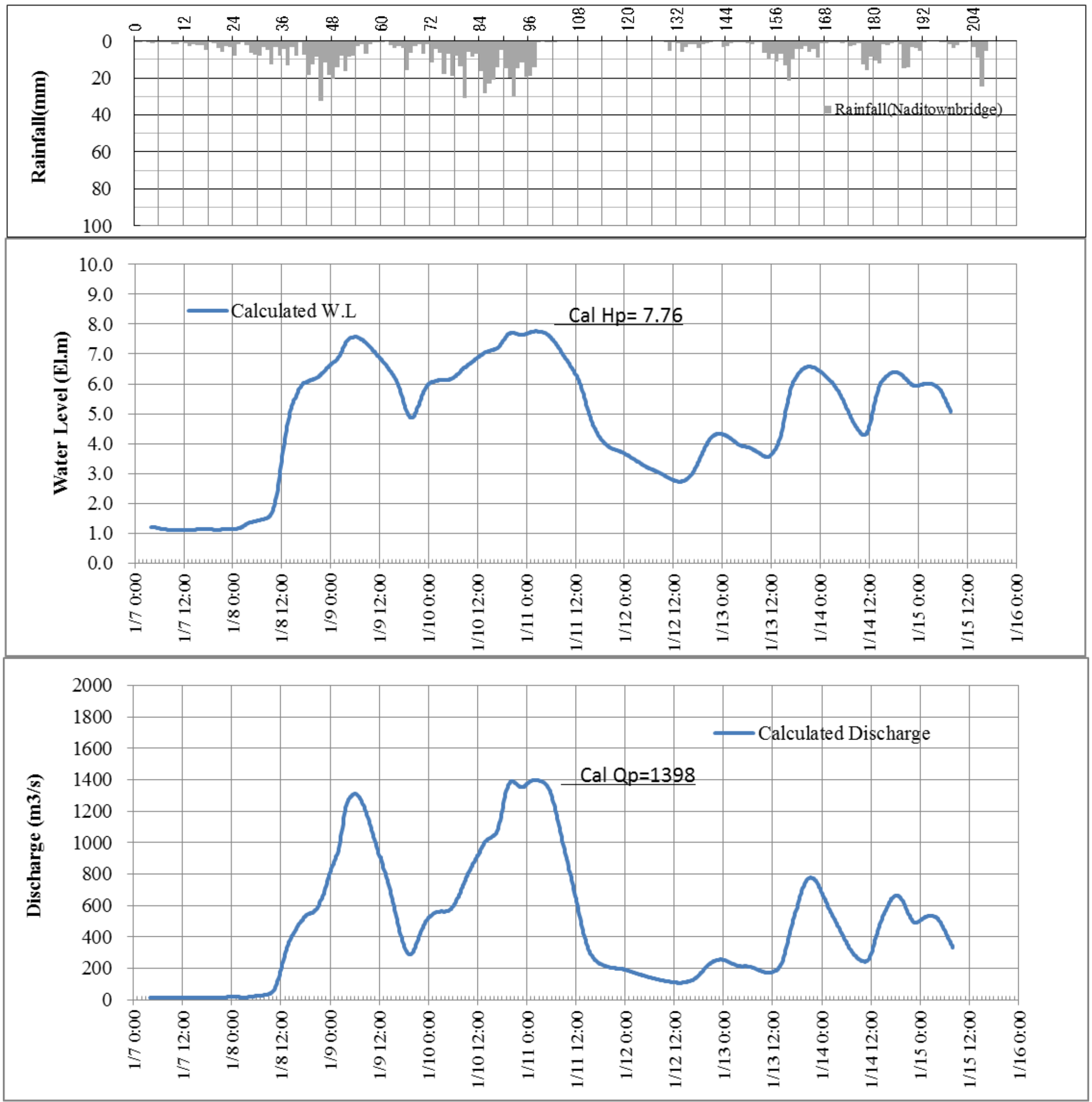


Figure 5.2-56 Actual and Calculated Hydrograph of the 9 Jan, 2009 Flood at Votualevu Station

- **Maximum inundation**

The maximum inundation depth distribution map is shown in Figure 5.2-58. Table 5.2-14 shows the result of block by block comparison of inundation area, volume and depth.

The comparison between actual and calculation in NAD-LM (Nadi River Left bank, Midstream) which has many flood mark records is as follows:

✓ The actual and calculated Inundation areas are 292ha and 283 ha, respectively. The gap is -9ha (approx. -3%).

The actual and calculated Inundation volumes are 6,910,000m^3 and 6,360,000m^3, respectively. The gap is -55,000m^3 (approx. -8%).

✓ The average of the actual and calculated inundation depths are 2.36m and 2.25m, respectively. The gap is -0.11m (approx. -5%).

Table 5.2-14 Comparison of Reproduced and Actual Values by Block (9 Jan, 2009 flood)

NO.	Block	Name	(a) Reproduction			(b) Actual Records			(a) / (b)			No of Flood Marks (points)
			Inundation Area (ha)	Inundation Volume (1000m3)	Average Inundation Depth (m)	Inundation Area (ha)	Inundation Volume (1000m3)	Average Inundation Depth (m)	Inundation Area (ha)	Inundation Volume (1000m3)	Average Inundation Depth (m)	
1	NAD-LD	Nadi, Left, Down stream	201	2,523	1.26	175	2,635	1.50	1.15	0.96	0.83	3
2	NAD-LM	Nadi, Left, Mid stream	538	11,497	2.14	561	13,370	2.38	0.96	0.86	0.90	43
3	NAD-LU	Nadi, Left, Up stream	56	1,752	2.21	59	1,730	2.51	0.95	1.01	0.88	0
4	NAD-RD	Nadi, Right, down stream	978	8,820	0.90	939	10,512	1.12	1.04	0.84	0.81	11
5	NAD-RM	Nadi, Right, Mid stream	346	7,426	2.15	320	6,923	2.16	1.08	1.07	0.99	6
6	NAD-RU	Nadi, Right, Up stream	202	4,998	2.47	206	6,318	3.07	0.98	0.79	0.81	2
7	MAL-L	Malakua, Left	76	1,045	1.37	74	1,295	1.75	1.03	0.81	0.78	2
8	MAL-R	Malakua, Right	48	448	0.93	38	363	0.96	1.26	1.23	0.98	3
9	NAW-L	Nawaka, Left	156	2,423	1.55	172	3,236	1.89	0.91	0.75	0.82	7
10	NAW-R	Nawaka, Right	102	1,415	1.39	167	2,438	1.46	0.61	0.58	0.95	7
11	NAM-L	Namosi, Left	9	302	3.35	2	17	0.82	4.41	18.02	4.09	0
12	NAM-R	Namosi, Right	16	540	3.38	6	136	2.11	2.48	3.97	1.60	0
	Total		2,728	43,187	1.58	2,719	48,973	1.80	1.00	0.88	0.88	84

- **Time-series Inundation depth map**

Time-series inundation depth maps are shown in Figure 5.2-59.

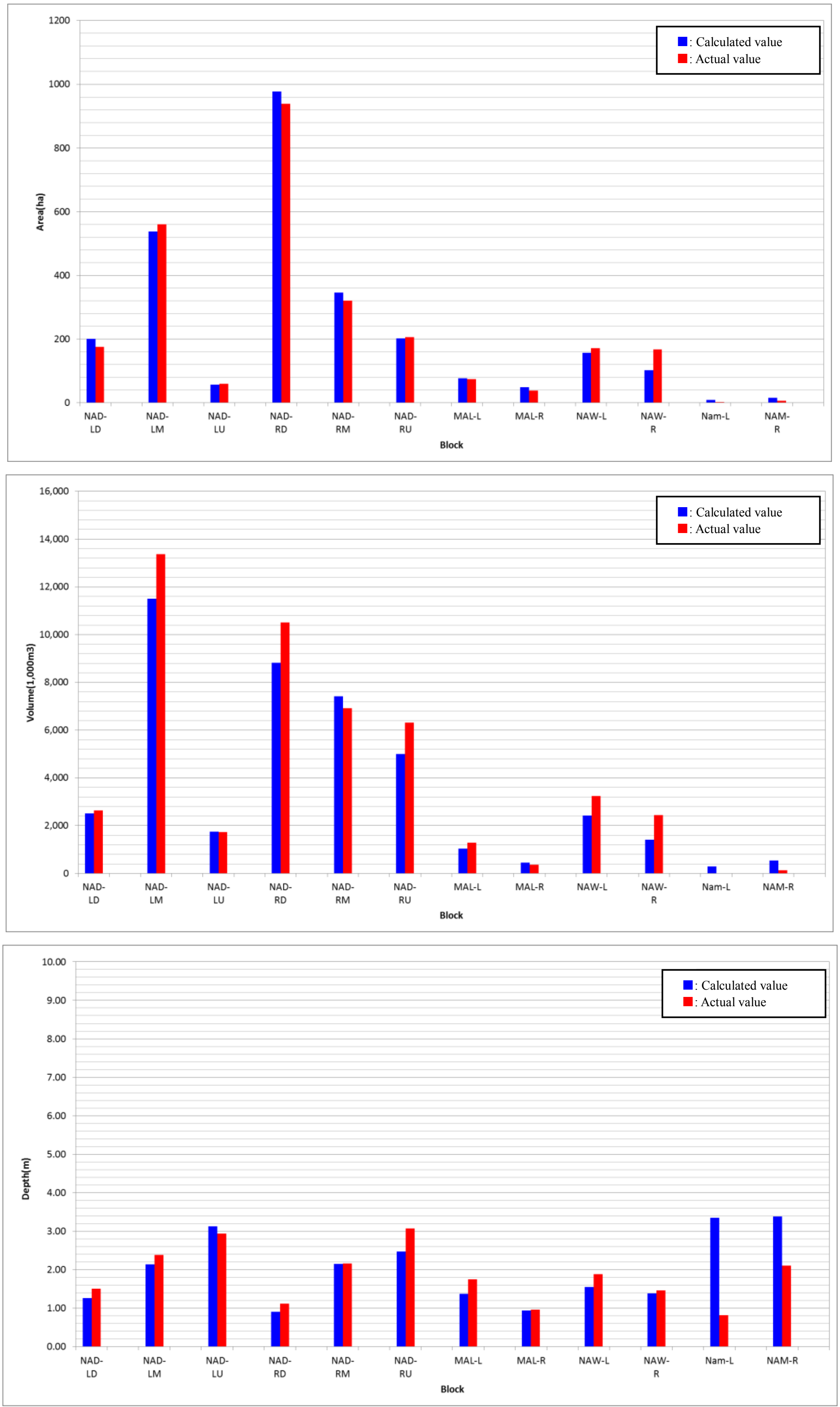


Figure 5.2-57 Comparison of Calculated and Actual Inundations by Block (9 Jan, 2009 flood)

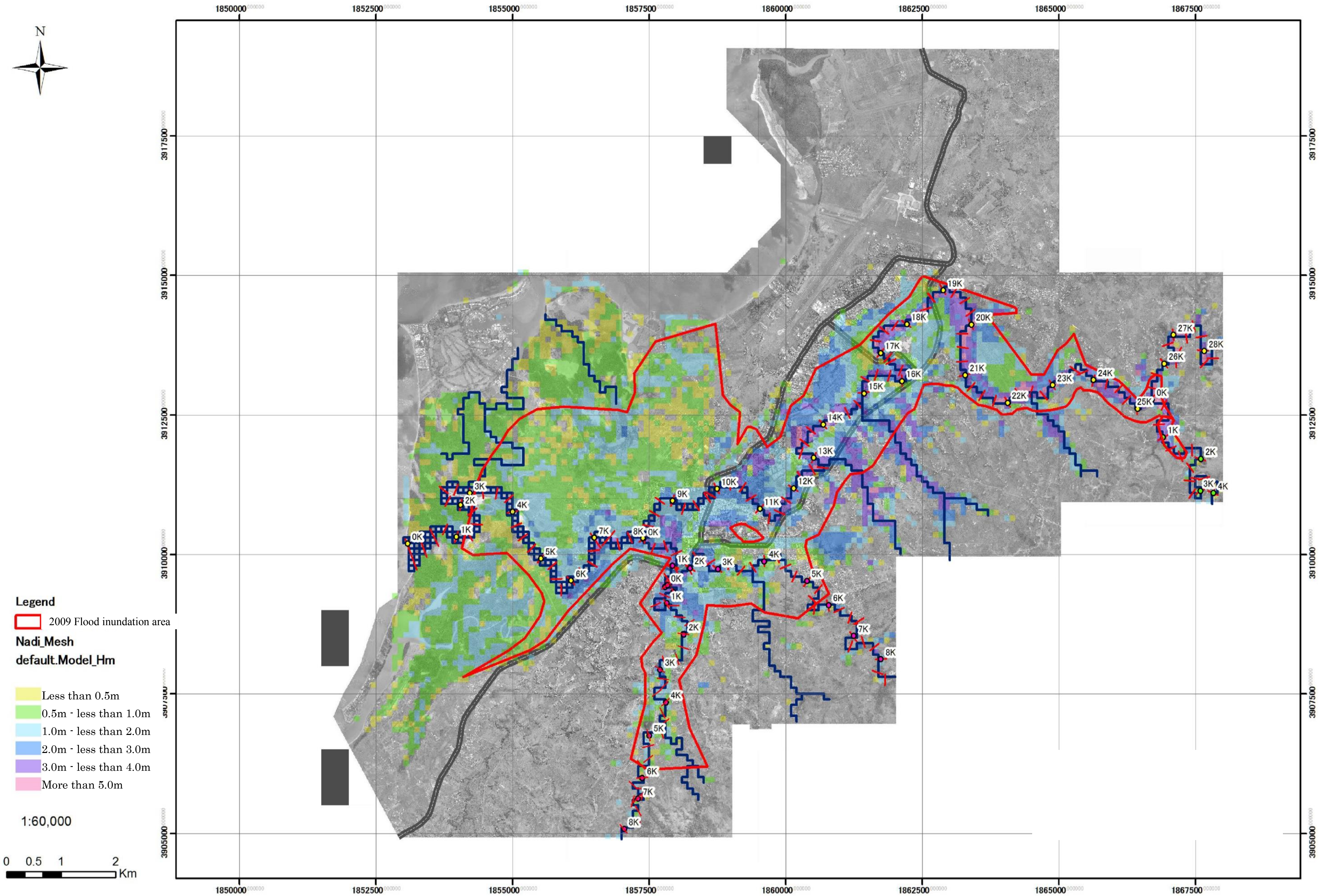


Figure 5.2-58 Result of Inundation Simulation (maximum inundation distribution of the 9 Jan, 2009 flood)

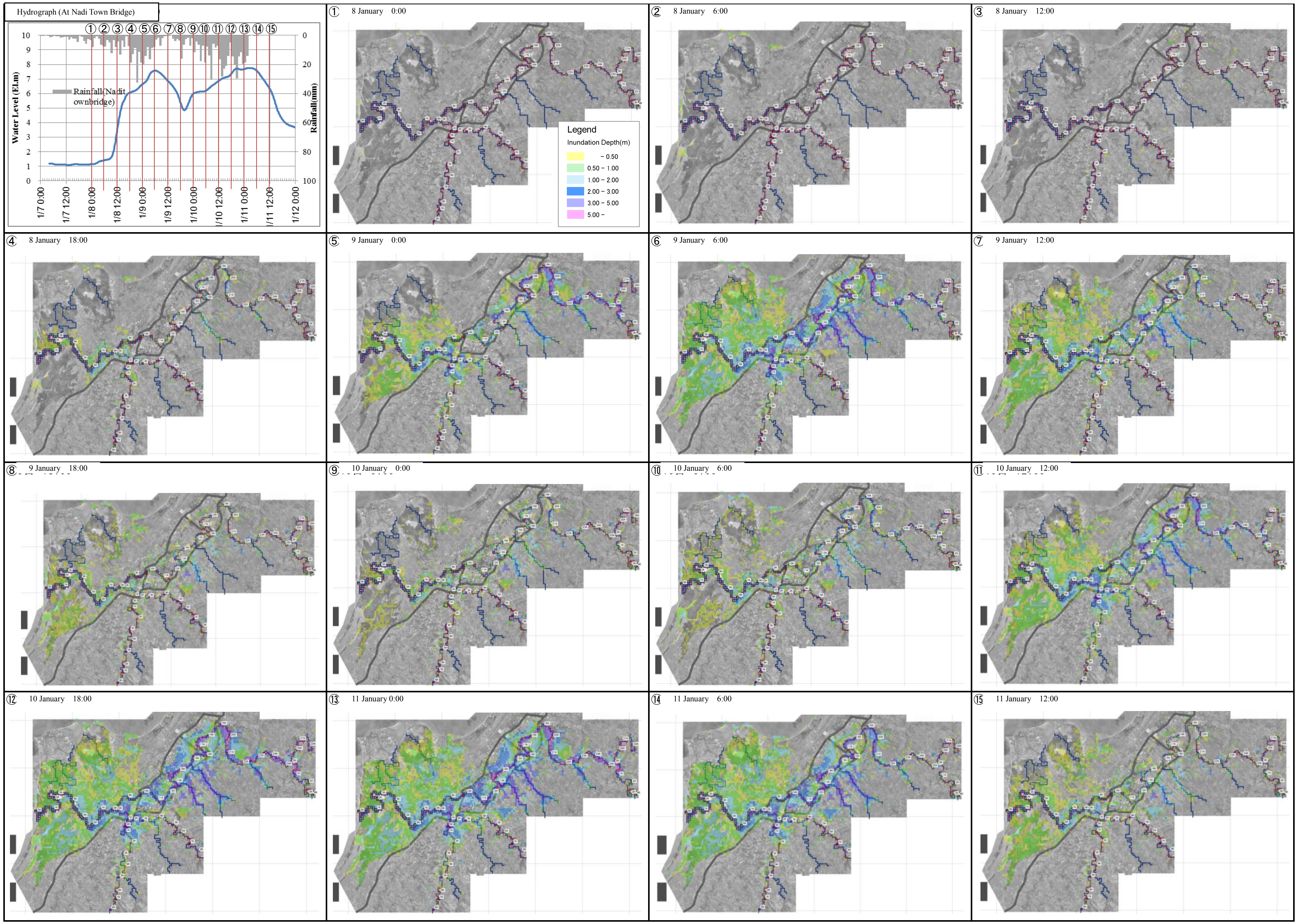


Figure 5.2-59 Result of Inundation Simulation (time-series inundation distribution of the 9 Jan, 2009 flood)

(3) Evaluation of the simulation result

Calculation results of the run off analysis are used as the boundary conditions of inundation model. Even though the calculation result does not agree with the actual hydrograph, it is possible since run off is calculated without overflow from the river and the loss of discharge to inundation area does not contribute to the calculated hydrograph.

Even though the calculated inundation volume does not agree with the actual inundation volume in 2009 and March 2012, calculated inundation area and the inundation depth relatively agree with the actual situation (refer to Figure 5.2-48 and Figure 5.2-57). Moreover, the calculated hydrograph agrees with actual hydrograph in the timing of the flood peak (refer to Figure 5.2-45 to Figure 5.2-47 and Figure 5.2-55). Therefore, the hydraulic analysis model is considered as appropriate.

Conditions used in the hydraulic analysis model are shown in Table 5.2-15. The results are used for examination of basic flood discharge and design flood discharge.

Table 5.2-15 Conditions of Hydraulic Analysis Model

<table>
<tr><th colspan="2">Item</th><th>Condition</th></tr>
<tr><td rowspan="3">Method</td><td>Run off Area</td><td>Distributed Runoff Analysis Model (Kinematic Wave)</td></tr>
<tr><td>Inundation Area</td><td>Two dimension unsteady flow (Dynamic Wave)</td></tr>
<tr><td>River Channel</td><td>One dimension unsteady flow (Dynamic Wave)</td></tr>
<tr><td rowspan="4">Run off Area</td><td>Elevation</td><td>Average elevation of each 100m grid (based on contour map [1/50,000])</td></tr>
<tr><td>Equivalent roughness coefficient: N</td><td rowspan="2"><table>
<tr><th>Landuse Classification</th><th>f1</th><th>Rsa</th><th>fsa</th><th>N</th></tr>
<tr><td>Grassland</td><td>0.15</td><td>70</td><td>1</td><td>0.30</td></tr>
<tr><td>Farmland</td><td>0.15</td><td>70</td><td>1</td><td>0.30</td></tr>
<tr><td>Water area</td><td>1.00</td><td>0</td><td>1</td><td>0.00</td></tr>
<tr><td>Paddy field</td><td>0.00</td><td>50</td><td>1</td><td>2.00</td></tr>
<tr><td>Urban area</td><td>0.70</td><td>55</td><td>1</td><td>0.03</td></tr>
<tr><td>Forest</td><td>0.25</td><td>70</td><td>1</td><td>0.70</td></tr>
<tr><td>Golf course</td><td>0.15</td><td>300</td><td>1</td><td>0.30</td></tr>
</table></td></tr>
<tr><td>Effective Rainfall: f1,Rsa,fsa</td></tr>
<tr><td>Rainfall Pattern</td><td>According to the segmentation of Thiessen in each year</td></tr>
<tr><td rowspan="5">Inundation Area</td><td>Elevation</td><td>Average elevation of each 100m grid (based on LiDAR data)</td></tr>
<tr><td>Roughness Coefficient</td><td>It will be set based on bottom surface coefficient and the relation between building occupancy ration and inundation depth
Bottom Surface Coefficient: Grassland, Farmland, Paddy field: 0.060
Water area, Golf course: 0.050, Airport: 0.047</td></tr>
<tr><td>Condition of overflow</td><td>Higher-value comparing bank elevation to elevation of protected land</td></tr>
<tr><td>Facility</td><td>Road embankment: 3, Water channel: 7</td></tr>
<tr><td>Rainfall Pattern</td><td>According to the segmentation of Thiessen in each flood</td></tr>
<tr><td rowspan="3">River Channel</td><td>Cross-section</td><td>Actual surveyed data in 2014 and LiDAR data of 2012</td></tr>
<tr><td>Boundary Condition</td><td>End of downstream: Observed tidal level at Lautoka,
End of upstream: Calculation result of runoff analysis</td></tr>
<tr><td>Roughness Coefficient</td><td><table>
<tr><th rowspan="2">River</th><th rowspan="2">Section</th><th colspan="2">Roughness Coefficients</th></tr>
<tr><th>Low-water Channel</th><th>High-Water Channel</th></tr>
<tr><td rowspan="3">Nadi River</td><td>0.0k～4.0k</td><td>0.035</td><td>死水域</td></tr>
<tr><td>4.0k～25.25k</td><td>0.043</td><td>0.060</td></tr>
<tr><td>25.25k～</td><td>0.047</td><td>0.060</td></tr>
<tr><td>Namosi River</td><td>0.0k～4.0k</td><td>0.042</td><td>0.060</td></tr>
<tr><td>Nawaka River</td><td>0.0k～8.5k</td><td>0.046</td><td>0.060</td></tr>
<tr><td>Malakua River</td><td>0.0k～8.0k</td><td>0.047</td><td>0.060</td></tr>
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