KINGDOM OF TONGA

INFORMATION COLLECTION AND PRELIMINARY SURVEY FOR THE FORMATION OF DISASTER RECOVERY PROJECTS AGAINST VOLCANIC ERUPTIONS AND TSUNAMI DAMAGE IN KINGDOM OF TONGA

FINAL REPORT

(Appendix 3-2: Tsunami and Storm Surge Analysis)

OCTOBER 2023

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

ORIENTAL CONSULTANTS GLOBAL CO., LTD.
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Table of Contents

Page

List of Figures

List of Tables

Abbreviations

Abbreviation	Definition
SOPAC	South Pacific Applied Geoscience Commission
STOC	Storm Surge and Tsunami Simulator in Oceans and Costal Areas
USGS	United States Geological Survey
VEI	Volcanic Explosivity Index
USGS	United States Geological Survey
HTHH	Hunga Tonga Hunga Ha’apai
JNAP	Joint National Action Plan on Climate Change and Disaster Risk Management
M.S.L	Mean Sea Level
H.W.L	High Water Level

1. Introduction.

1.1 Objective

The objective of this work is to carry out tsunami and storm surge analyses and assess the hazard in the Kingdom of Tonga (hereinafter referred to as 'Tonga').

1.2 Study policy

The tsunami and storm surge analysis to be carried out in this work will take over the studies of the National Support Committee of academics.

1.2.1 Academic Review

The scope of the study of the academics is as follows.In this study, the tsunami and storm surge analysis will be carried out by taking over the results of the following studies of the members of Domestic Support Committee.

<Tsunami analysis>

① Analysis of tsunami arrival to the coast by the new wave source.
※ The point where arrival times do not match may be attributed to the impact of shock waves. In that case, an explanation may be given in combination with the results of the study by the experts (i.e. changing the amount of mountain body collapse ≒ changing the size of the wave source).

② Run-up analysis to Tongatapu Island based on the results of ①

③ Tsunami analysis with different wave source strength and volcano location due to this eruption (including run-up analysis to the island).
※ Tsunami analysis by changing the strength of the wave source and the location of the volcano due to the eruption this time (including analysis of the run-up to the island).
※ Advice will be sought from experts on multiple patterns of "Tsunami analysis: 15 volcanoes x multiple patterns", which should be carried out in the future as part of JICA work.
※ The frequency (probability) of eruption and size (mode) of collapse of the other 15 volcanoes will be confirmed by the experts. For each volcano, the mode of the worst-case scenario level may be considered and should be confirmed.

<Tidal surge analysis>

④ Cyclone scale with a 50-100 year probability (scale and sea level rise taking into account climate change effects).

⑤ Storm surge analysis to Tongatapu Island (Isaac 1982, Gita 2018)

⑥ Calculation of run-up to Tongatapu Island (1982 Isaac, 2018 Gita)

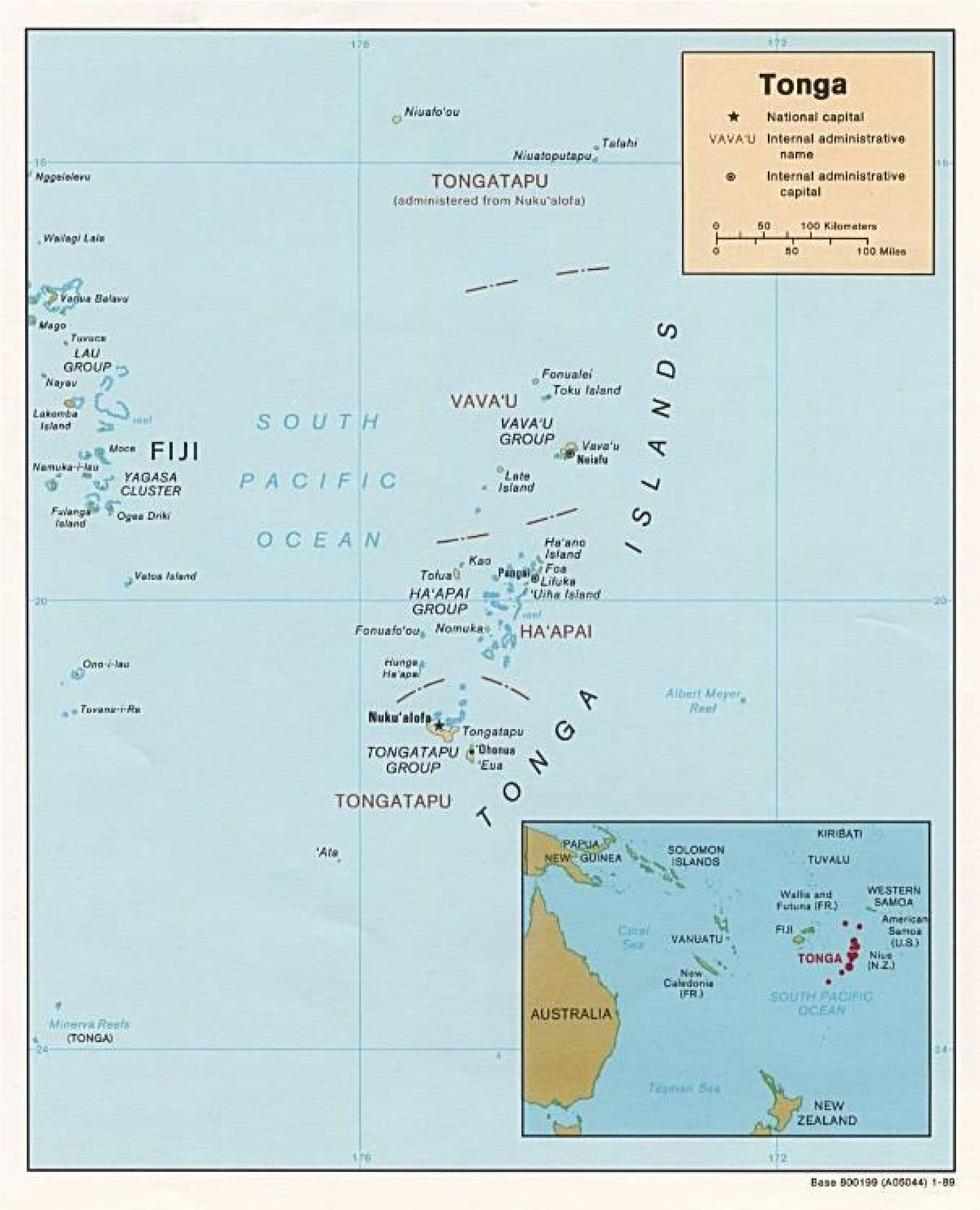
1.2.2 Study policy following the study of the Domestic Support Committee

The study policy in this study, which has been reviewed by Domestic Support Committee, is shown below.

- For Tongatapu and Eua islands, quantitative assessment of tsunami and storm surge hazards (inundation area, depth of inundation, etc.) will be carried out and the necessary measures to be taken in the future will be discussed.
- For Tonga as a whole, only the recommendations as a general coastal disaster prevention could be studied.

1.3 Target area

The target area for tsunami and storm surge analysis is shown in Figure 1.3.1. The analysis will cover the whole of Tonga Country, but two islands, Tongatapu and Eua, will be considered with a detailed mesh size.



Source: The map collection of the Perry–Castañeda Library (PCL) of the University of Texas at Austin, https://maps.lib.utexas.edu/maps/islands_oceans_poles/tonga.jpg

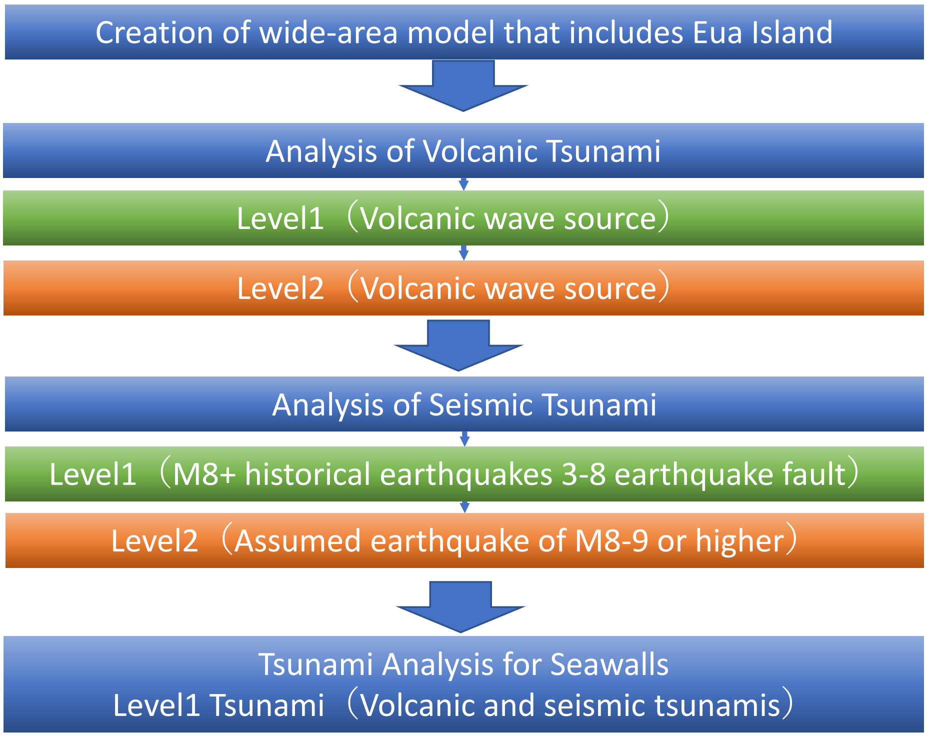
Figure 1.3.1 Location Map of the Study Area

2. Tsunami Analysis

2.1 Study flow

The flow of tsunami analysis is shown in Figure 2.1.1.

In this work, tsunami analysis is carried out for volcanic and seismic tsunamis, with tsunami sizes of Level 1 (volcanic tsunami and seismic tsunami of about M8) and Level 2 (volcanic tsunami and seismic tsunami of M8-9 or higher).



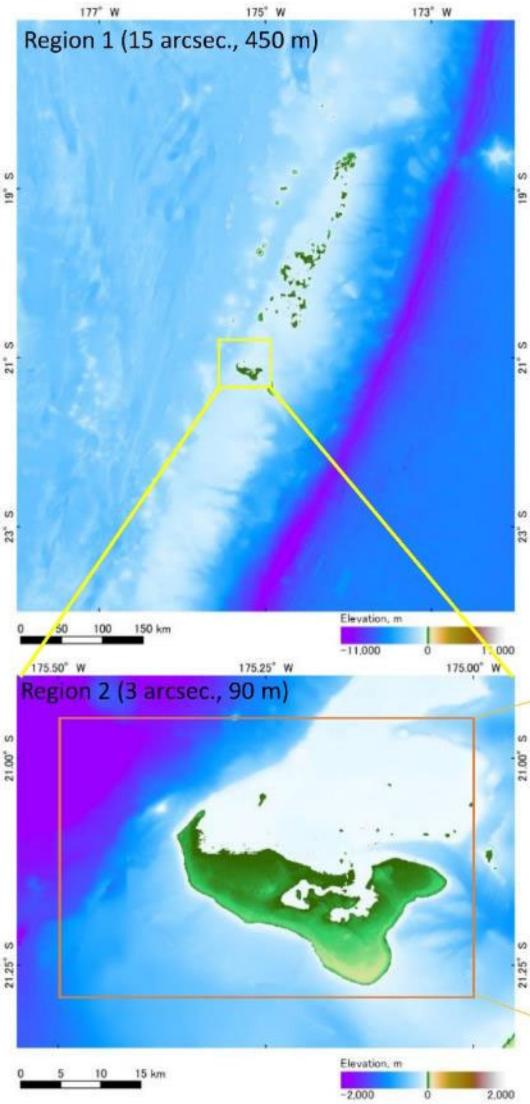
Source: JICA Study Team.

Figure 2.1.1 Tsunami Analysis Implementation Flow Diagram

2.2 Eua Island topographic data preparation

Based on the data provided by the Domestic Support Committee and the topographic data collected from Tonga, calculation data including Eua Island will be prepared for the tsunami analysis model created mainly for Tongatapu Island. The topographical data and other data collected from Tongatapu Island shall be used.

The topographical data provided by Tohoku University is shown in Figure 2.2.1. Using this data as a basis, the area shall be extended to include the island of Eua. The elevation of the extended area will be based on one-second mesh topographic data from NASA's Space Shuttle onboard radar elevation data (SRTM: Shuttle Rader Topography Mission). Bathymetry data provided by Tonga government was used for shallow water bathymetry, and bathymetry data from the General Bathymetric Chart of the Oceans (GEBCO) will be used for offshore bathymetry.



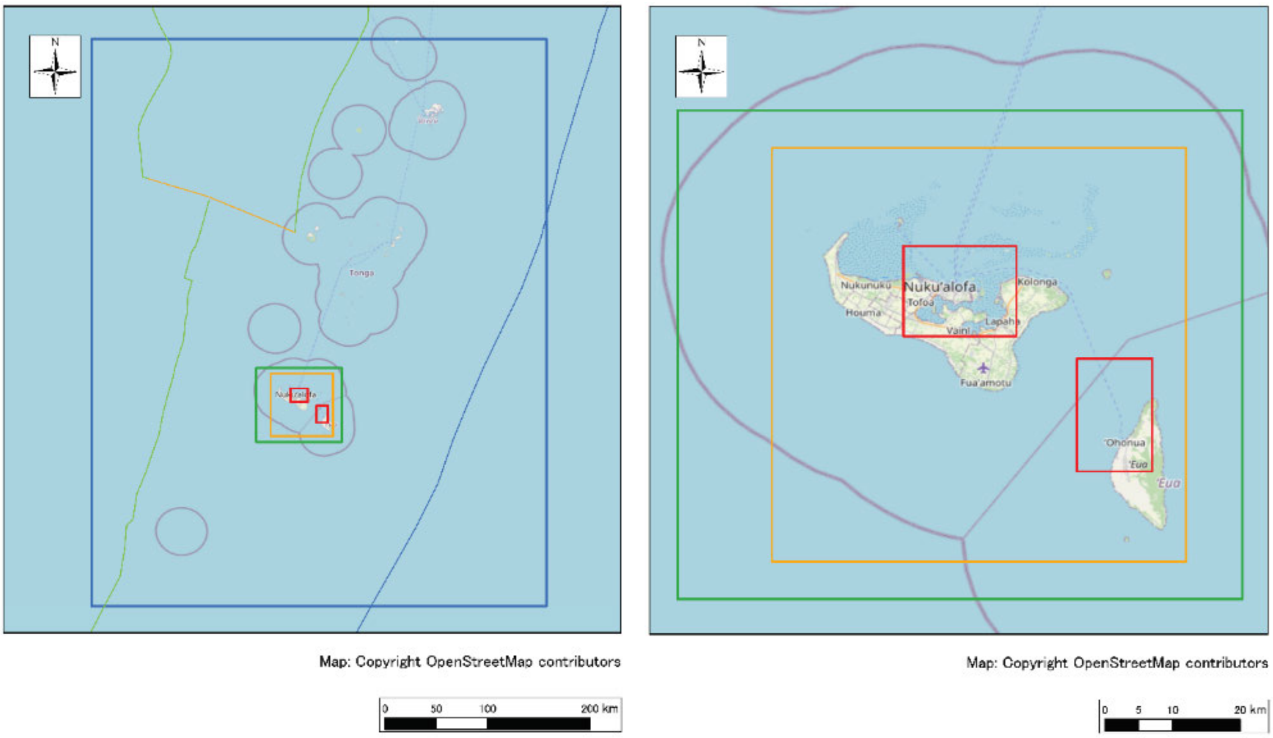
Source: Tohoku University.

Figure 2.2.1 Topographical Data

2.3 Creating a wide-area model

Using the calculation data created in the previous section, a wide-area tsunami analysis model is created by adding Eua Island to the 1-second (approx. 30 m) and 1/3-second (approx. 10 m) mesh areas. The 1/3-second (approx. 10 m) mesh area of Eua Island is defined as the northern coastal area with many houses.

Model domains are shown in Figure 2.3.1 and the model domain parameters are aloso shown in Table 2.3.1



Source: JICA Study Team.

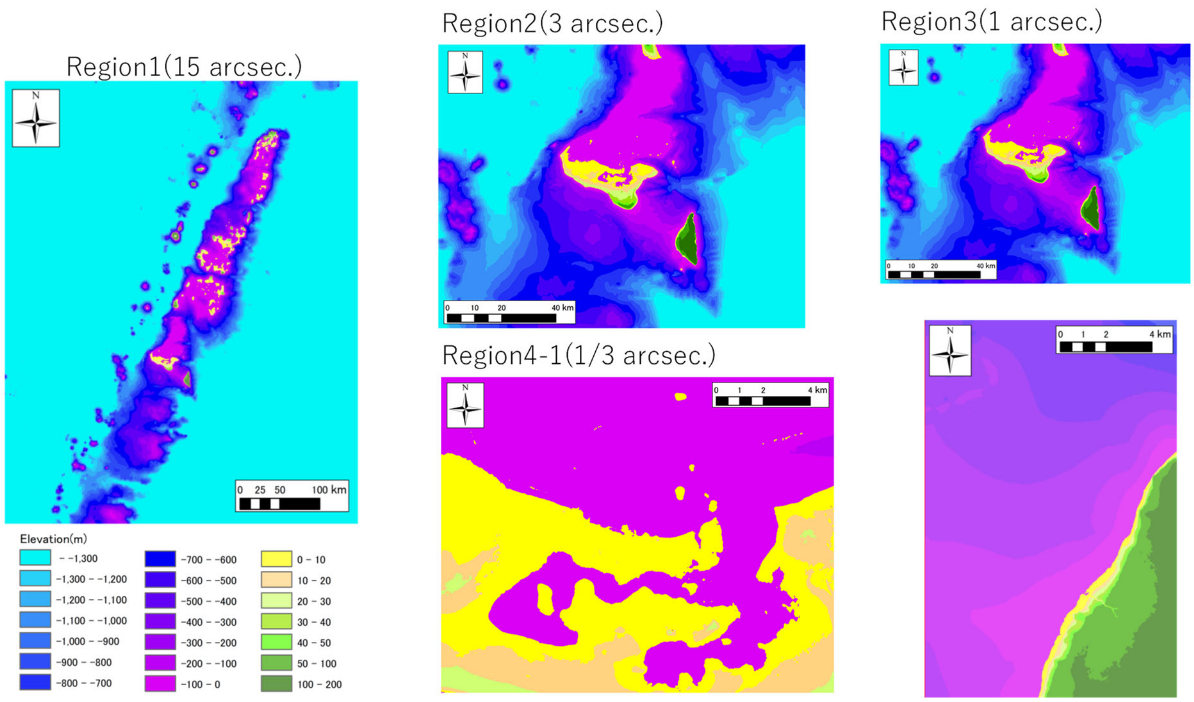
Figure 2.3.1 Model Domain Diagram

Table 2.3.1 Model Region Parameters

Region	Coordinate, degree				Size, pixel		Mesh size
	West	South	East	North	Width	Height	
Region1	-177	-23	-173	-18	960	1200	15 arcsec. (450m)
Region2	-175.55	-21.55	-174.8	-20.9	900	780	3 arcsec. (90m)
Region3	-175.43	-21.5	-174.88	-20.95	1980	1980	1 arcsec. (30m)
Region4-1	-175.25	-21.2	-175.1	-21.08	1620	1296	1/3 arcsec. (10m)
Region4-2	-175.02	-21.38	-174.92	-21.23	1080	1620	1/3 arcsec. (10m)

Source: JICA Study Team.

The topographic data for each area created is shown in Figure 2.3.2.



Source: JICA Study Team

Figure 2.3.2 Computational Terrain Model

2.4 Reproduction calculation by using the wide-area model

The tsunami caused by the January 2022 eruption is reproduced and calculated with the created wide-area model. STOC-ML[1] is used as the analytical model. For the basic STOC model, the model provided by Professor Arikawa of Chuo University, a member of the Domestic Support Committee, was used.

2.4.1 Analysis model

STOC-ML is a quasi-three-dimensional model using the hydrostatic approximation to calculate fluid motion due to tsunamis. As previous studies have shown that the hydrostatic approximation is a good approximation for offshore tsunamis, STOC-ML is applied for the calculation of tsunamis propagating in the Pacific Ocean and elsewhere.

In STOC-ML, the basic equation is the momentum conservation equation (Navier-Stokes equation), a three-dimensional continuity equation that takes the porous into account. Porous values are used to represent terrain below the resolution of the mesh. When spherical coordinates are introduced, the radius of the earth is assumed to be constant irrespective of water depth, and the longitude, latitude and longitudinal velocity components are assumed to be (eastward positive) and latitudinal velocity component (northward positive). The basic equations of STOC-ML in the spherical coordinate system are shown below.

[1] Tomita and Kakinuma:"Development of Storm Surge and Tsunami Numerical Simulator STOC Considering 3-Dimentionality of Seawater Flow and Its Application to Tsunami Analysis", Report of Port Airport Research Institute, Vol44, pp.83-98, 2005.

(1) Continuity equation

$$\frac{1}{R\cos\theta}\frac{\partial}{\partial\phi}(\gamma_x u)+\frac{1}{R\cos\theta}\frac{\partial}{\partial\theta}(\gamma_y v\cos\theta)+\frac{\partial}{\partial z}(\gamma_z w)=0 \quad \text{(2.4.1)}$$

(2) Momentum conservation equation

1) Longitude direction (positive eastward)

$$\begin{aligned}
&\gamma_v\frac{\partial u}{\partial t}+\frac{1}{R\cos\theta}\frac{\partial}{\partial\phi}(\gamma_x uu)+\frac{1}{R\cos\theta}\frac{\partial}{\partial\theta}(\gamma_y uv\cos\theta)+\frac{\partial}{\partial z}(\gamma_z uw)\\
&-\gamma_v 2\Omega\sin\theta\, v\\
&=-\gamma_v\frac{1}{\rho}\frac{1}{R\cos\theta}\frac{\partial p}{\partial\phi}+\frac{1}{R\cos\theta}\frac{\partial}{\partial\phi}\left(\gamma_x\nu_H\frac{2}{R\cos\theta}\frac{\partial u}{\partial\phi}\right) \quad \text{(2.4.2)}\\
&+\frac{1}{R\cos\theta}\frac{\partial}{\partial\theta}\left\{\gamma_y\nu_H\cos\theta\left(\frac{1}{R}\frac{\partial u}{\partial\theta}+\frac{1}{R\cos\theta}\frac{\partial v}{\partial\phi}\right)\right\}\\
&+\frac{\partial}{\partial z}\left\{\gamma_z\nu_V\left(\frac{\partial u}{\partial z}+\frac{1}{R\cos\theta}\frac{\partial w}{\partial\phi}\right)\right\}
\end{aligned}$$

2) Latitudinal direction (positive north direction))

$$\begin{aligned}
&\gamma_v\frac{\partial v}{\partial t}+\frac{1}{R\cos\theta}\frac{\partial}{\partial\phi}(\gamma_x vu)+\frac{1}{R\cos\theta}\frac{\partial}{\partial\theta}(\gamma_y vv\cos\theta)+\frac{\partial}{\partial z}(\gamma_z vw)\\
&+\gamma_v 2\Omega\sin\theta\, u\\
&=-\gamma_v\frac{1}{\rho}\frac{1}{R}\frac{\partial p}{\partial\theta}+\frac{1}{R\cos\theta}\frac{\partial}{\partial\phi}\left\{\gamma_x\nu_H\left(\frac{1}{R\cos\theta}\frac{\partial v}{\partial\phi}+\frac{1}{R}\frac{\partial u}{\partial\theta}\right)\right\} \quad \text{(2.4.3)}\\
&+\frac{1}{R\cos\theta}\frac{\partial}{\partial\theta}\left(\gamma_y\nu_H\cos\theta\frac{2}{R}\frac{\partial v}{\partial\theta}\right)+\frac{\partial}{\partial z}\left\{\gamma_z\nu_V\left(\frac{\partial v}{\partial z}+\frac{1}{R}\frac{\partial w}{\partial\theta}\right)\right\}
\end{aligned}$$

Here,

D: Total water depth [m] ($=\eta+h$)

f_0: Coriolis parameter [1/s] ($=2\Omega\sin\theta$)

g: Gravitational acceleration [m/s2] (≈ -9.8)

h: ratio of the thickness of the water in the calculation cell (hereafter referred to as the layer thickness ratio) [-])

H: Depth of water [m]

p: Pressure [Pa]

p_{atm}: Pressure [Pa]

R: Earth radius [m] (assuming a sphere, not an ellipsoid)

u: x-directional component of flow velocity [m/s].

v: y-directional component of flow velocity [m/s].

w: z-directional component of flow velocity [m/s].

ϕ: Longitude [rad] (eastward is positive)

γ_v: Earth's rotation speed [1/s] ($0 \le \gamma_v \le 1$)

$\gamma_x, \gamma_y, \gamma_z$: Porous value (surface transmissivity by direction) [-] ($0 \le \gamma_x, \gamma_y \le 1, \gamma_z = 1$)

η: Water level [m]

ν_H: kinematic viscosity in horizontal direction [m2/s]

ν_V: Vertical kinematic viscosity [m2/s]

Ω: Earth's rotation speed [1/s]

θ: Latitude [rad] (north direction is positive)

ρ: Density of seawater [kg/m^3].

In STOC-ML, the momentum conservation equation in the z-direction is not solved, but is calculated from the continuity equation (by substituting '+' into the continuity equation, the integral is calculated sequentially from the seabed surface upwards).

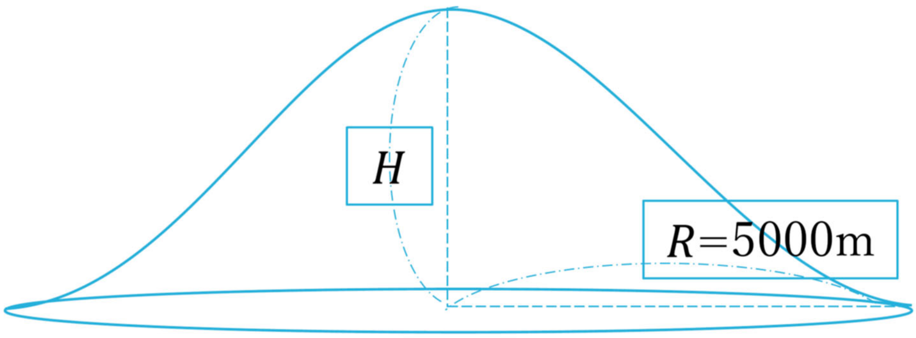
In STOC-ML, hydrostatic pressure is assumed, so pressure is expressed as a function of vertical distance from the water surface,

$$p(z) = p_{atm} - \rho g(\eta - z) \qquad (2.4.4)$$

Source: STOC User Manual)

2.4.2 Wave source model

A cone-shaped tsunami wave source is set as the wave source model for volcanic tsunamis in this study (Figure 2.4.1). Based on the study results by Domestic Support Committee, the cone shape is assumed to be a sine curve, with a radius of 5 km and a Max water level rise of 30 m, in order to reproduce the tsunami height caused by the Hunga-Tonga Hunga-Ha'apai volcanic eruption in January 2022. In Domestic Support Committee's study, the Max water level rise of 30 m is the condition that most reproduces the observed waveform of the tidal level of Nukualofa. The inundation extent for the entire island of Nukualofa is considered to be reproducible for the entire case with H=30-90m.



R : distance from the burst center [m]
H : Maximum rise [m]

Source: Domestic Support Committee

Figure 2.4.1 Diagram of Tsunami Wave Source

2.4.3 Calculation conditions

Table 2.4.1 shows the calculation conditions for the re-production calculations.

Table 2.4.1 Calculation Conditions

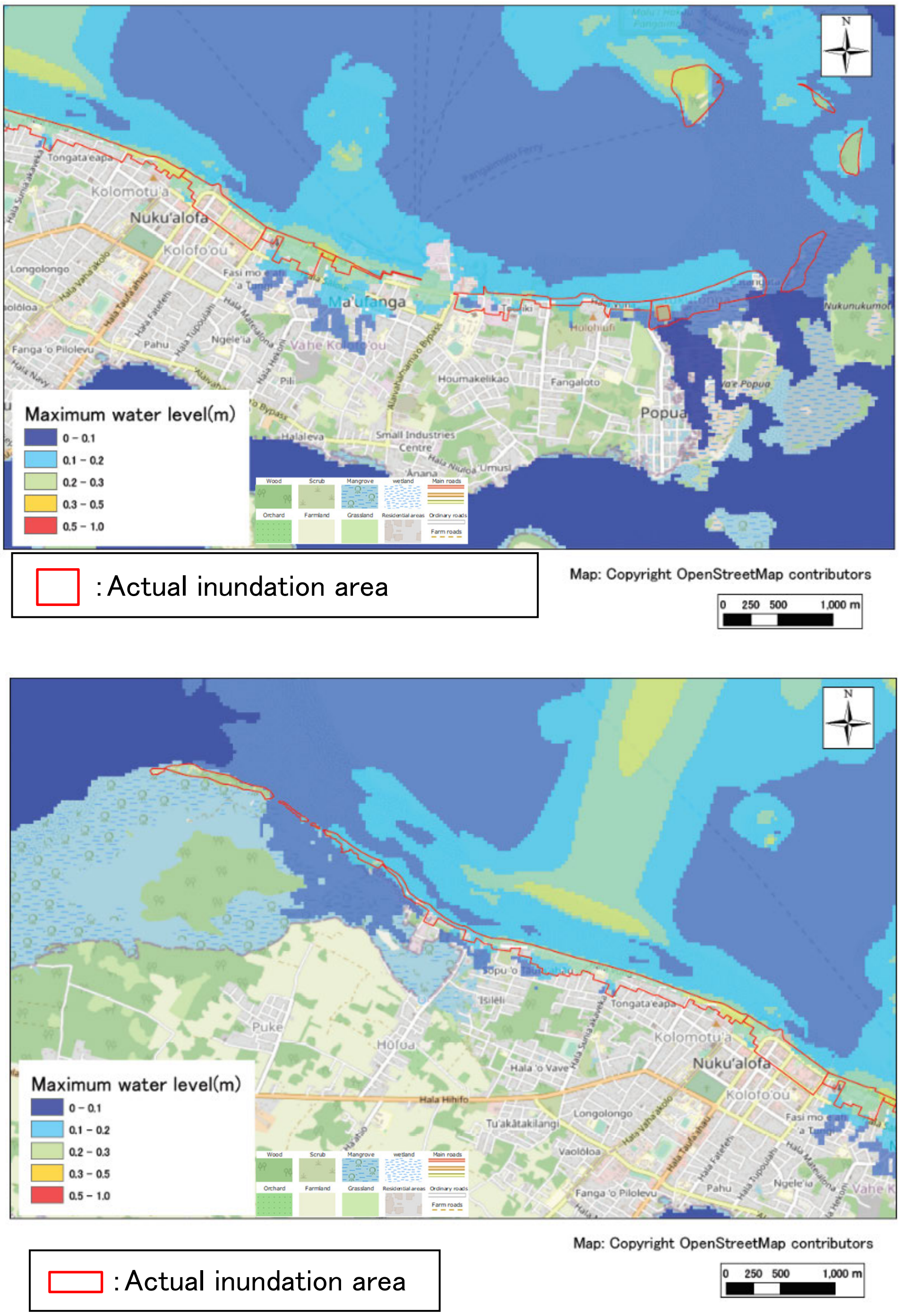
Items	Calculation Conditions
Composition of Mesh	Region1(15sec(around450m)mesh)：Tonga Trench area
	Region2(3sec around 90m)mesh)：Tongatapu Island、Eua Island area
	Region3(1sec(around 30m) mesh)：Tongatapu island、Eua island area
	Region4(1/3sec(around10m)mesh)：Tongataup island、Eua island urban area
Analytical Method	STOC-ML(Tomita and Kakinuma, 2005)[2]
Tsunami	January 15, 2022 HTHH volcanic eruption
Wave source	Chuo University Model
	(Hunga Tonga-Hunga Ha'apai volcanic tsunami wave source with a radius of 5 km and a Max water level rise of 30 m is set at the volcano.)
Geological conditions	Based on topographical data of Tohoku University, the range of 'Eua Island is added to the 90m mesh area and 30m mesh area.
Water level conditions	M.S.L.+0m
Time of calculation	After earthquake：5 hours
	time resolution：minimum 0.01sec
Others	Structure measures：None

Source: JICA Study Team

[2] Tomita and Kakinuma:"Development of Storm Surge and Tsunami Numerical Simulator STOC Considering 3-Dimentionality of Seawater Flow and Its Application to Tsunami Analysis", Report of Port Airport Research Institute, Vol44, pp.83-98, 2005.

2.5 Evaluation of wide-area model repeatability

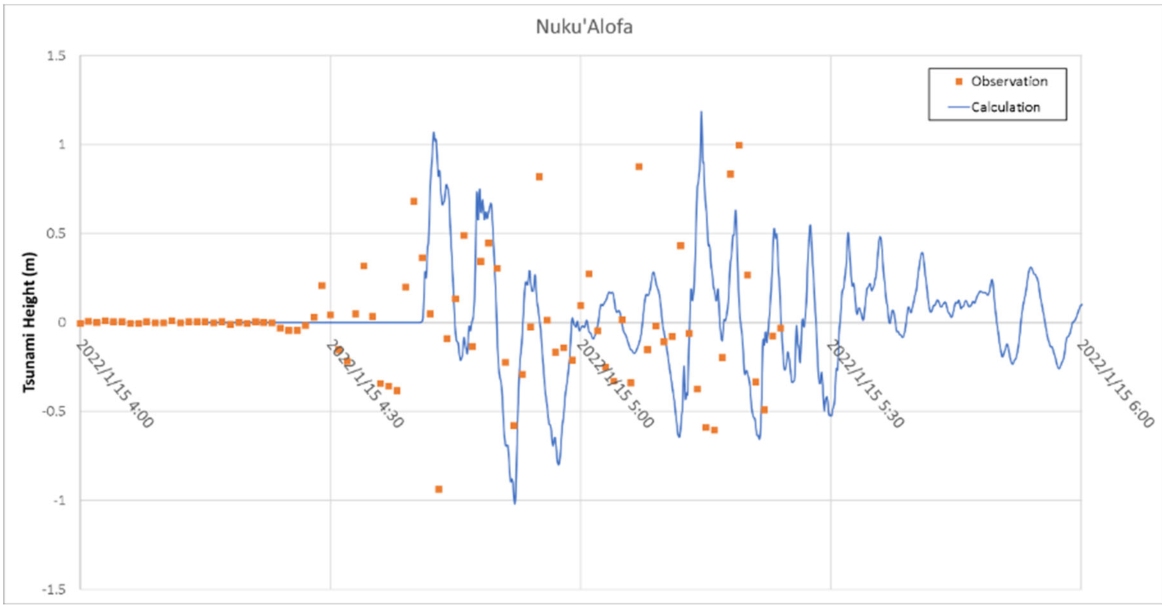
Based on the calculation results in the previous section, the reproducibility is evaluated in comparison with the inundation area and run-up height of Tongatapu Island. Figure 2.5.1 shows the results of the comparison between the calculation results and the actual inundation extent. Although the calculated inundation area is excessive in some areas, the inundation extent around the Nukualofa urban area is generally reproduced.



Source: JICA Study Team.

Figure 2.5.1 Comparison of Calculated and Actual Inundation Area

Figure 2.5.2 shows the comparison results between the observed and calculated tsunami water level at the Nuku'Alofa tide station. The magnitude of the tsunami water level peaks is generally reproduced.



Source: JICA Study Team.

Figure 2.5.2 Comparison of Observed and Calculated Tsunami Water Level Time Series (Calculated Results for 1 s (30 m) Mesh)

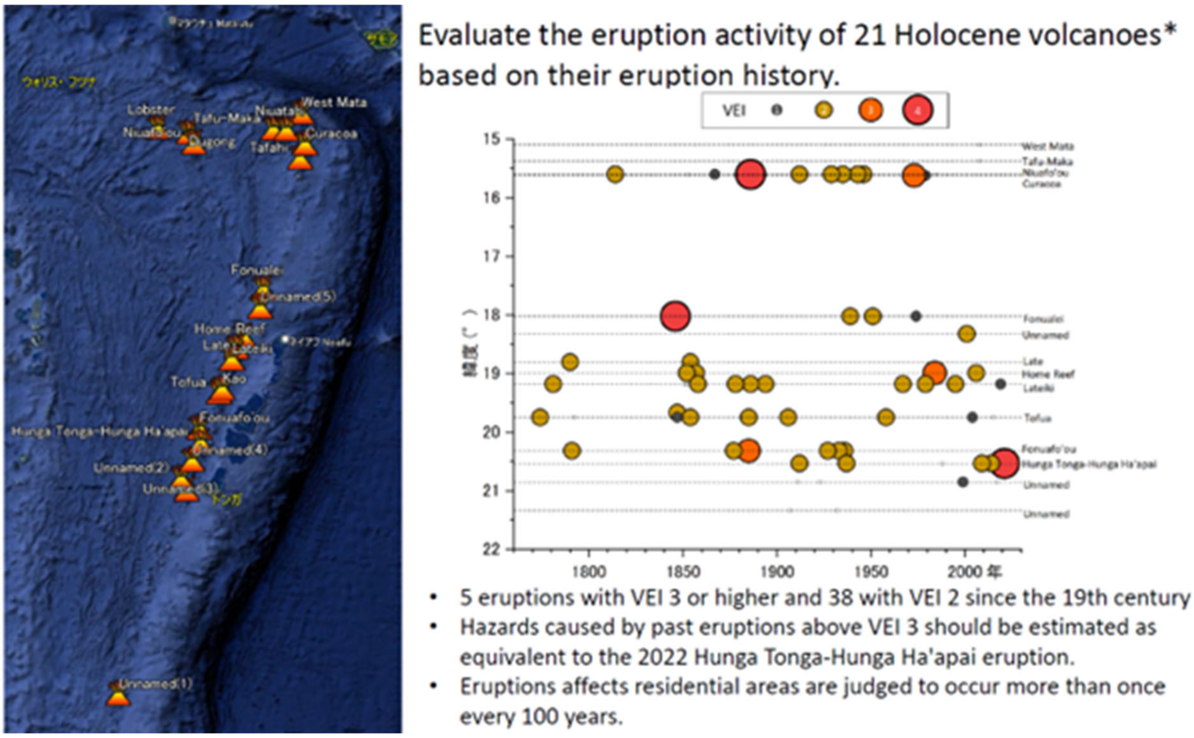
2.6 Volcanic tsunami analysis

2.6.1 Tsunami analysis with volcanic wave sources

Volcanic tsunami calculations are carried out for eight volcanoes and submarine volcanoes in the vicinity of Tongatapu and Eua islands.

(1) Target volcanoes

The frequency and magnitude of past volcanic eruptions have been organised by the members of the Domestic Support Committee (Figure 2.6.1). According to this, six volcanic eruptions of the same magnitude as the current eruption (VEI 3 or higher) have occurred over a period of approximately 200 years, and there is a possibility that volcanic eruptions of the same magnitude will occur in the future.



Source: Domestic Support Committee

Figure 2.6.1 Results of Organising the Frequency of Past Volcanic Eruptions around T Country.

Table 2.6.1 also lists the volcanoes in the vicinity of Tonga. From this, nine out of 21 volcanoes are submarine volcanoes, which means that volcanic tsunamis are highly likely to occur. In this work, tsunami analysis is carried out for eight of these submarine volcanoes that are included within the offshore 15 s mesh area and are considered to have a significant impact on Tongatapu Island. The locations of the volcanoes to be calculated are shown in Figure 2.6.2.

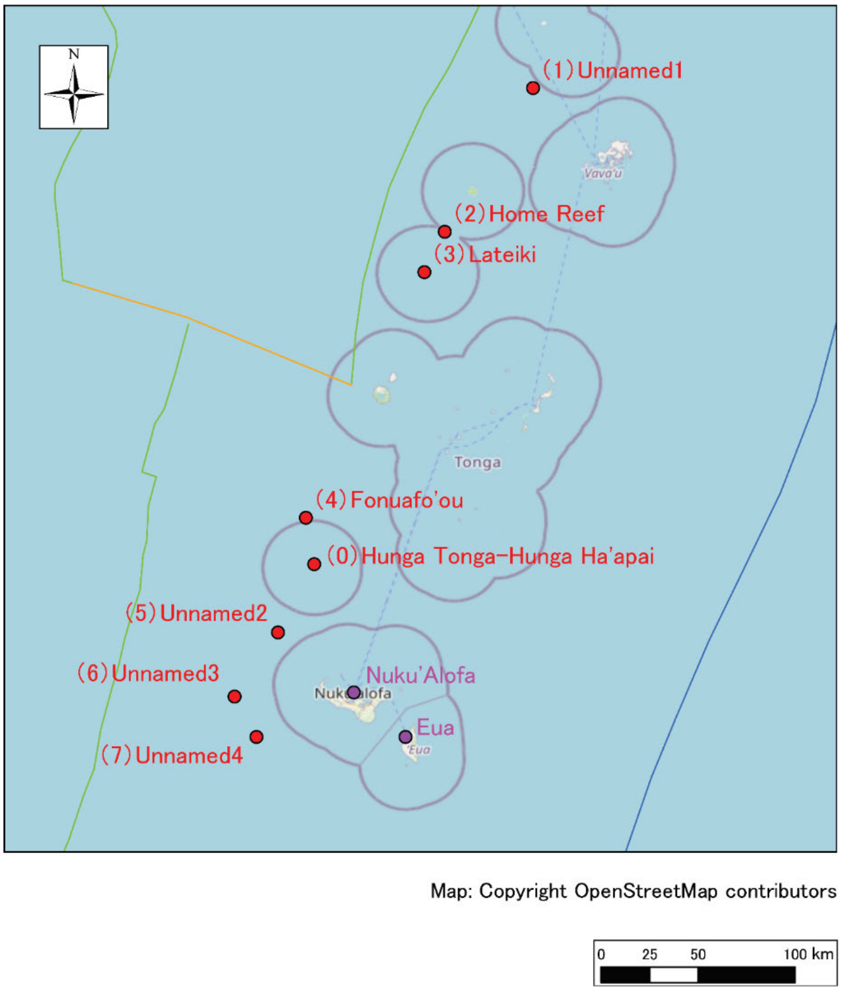
Table 2.6.1 List of Volcanoes around Tonga

Volcano Name	Location	Last Eruption	Primary Volcano Type	Lat (degree)		Long (degree)		Elevation (m)
Lobster	Northwest Lau Basin	Unknown - Evidence Uncertain	submarine	15.333	S	176.283	W	-1500
Dugong	Northwest Lau Basin	Unknown - Evidence Uncertain	submarine	15.431	S	175.725	W	-1170
Niuafo'ou	Tonga Ridge	1985 CE	shield	15.6	S	175.63	W	260
Tafu-Maka	Northwest Lau Basin	2008 CE	submarine	15.37	S	174.23	W	-1400
Niuatahi	Northwest Lau Basin(Tonga)	Unknown - Unrest / Holocene	caldera	15.379	S	174.003	W	-1270
West Mata	Tonga Ridge	2009 CE	submarine	15.1	S	173.75	W	-1174
Tafahi	Tonga Ridge	Unknown - Evidence Uncertain	stratovolcano	15.85	S	173.72	W	560
Curacoa	Tonga Ridge	1979 CE	submarine	15.62	S	173.67	W	-33

Volcano Name	Location	Last Eruption	Primary Volcano Type	Lat (degree)		Long (degree)		Elevation (m)
Fonualei	Tonga Ridge	1957 CE	stratovolcano	18.023	S	174.317	W	188
Unnamed1	Tonga Ridge	2001 CE	submarine	18.325	S	174.365	W	-40
Late	Tonga Ridge	1854 CE	stratovolcano	18.806	S	174.65	W	540
Home Reef	Tonga Ridge	2006 CE	submarine	18.992	S	174.775	W	-10
Lateiki	Tonga Ridge	2019 CE	submarine	19.18	S	174.87	W	43
Kao	Tonga Ridge	1847 CE	stratovolcano	19.668	S	175.016	W	1009
Tofua	Tonga Ridge	2022 CE	caldera	19.75	S	175.07	W	515
Fonuafo'ou	Tonga Ridge	1936 CE	submarine	20.32	S	175.42	W	-17
HTHH	Tonga Ridge	2022 CE	submarine	20.536	S	175.382	W	114
Unnamed2	Tonga Ridge	2017 CE	submarine	20.852	S	175.55	W	-296
Unnamed3	Tonga Ridge	Unknown - Evidence Uncertain	submarine	21.15	S	175.75	W	-65
Unnamed4	Tonga Ridge	1932 CE	submarine	21.338	S	175.65	W	-68
Unnamed5	Tonga Ridge	Unknown - Unrest / Holocene	submarine	24.8	S	177.02	W	-385

☐ :Submarine volcanoes, red: volcanoes to be calculated

Source: Domestic Support Committee



Source: JICA Study Team.

Figure 2.6.2 Location of Volcanoes

(2) Calculation case

The numerical analysis cases are as follows.

Table 2.6.2 Numerical Analysis Cases

Source	CASE	Volcano name	Tsunami Source	Structure	Minimum Region
Volcanic Tsunami	Volc0-1-1	Hunga Tonga-Hunga Ha'apai	R=5km、H=30m	Exitsting Seawall (Tongatapu Island)	reg4-1(Tongatapu Island 1/3sec grid (10m grid)
	Volc1-1-1	Unnamed1			
	Volc2-1-1	Home Reef			
	Volc3-1-1	Lateiki			
	Volc4-1-1	Fonuafo'ou			
	Volc5-1-1	Unnamed2			
	Volc6-1-1	Unnamed3			
	Volc7-1-1	Unnamed4			
	Volc0-1-2	Hunga Tonga-Hunga Ha'apai		-	reg4-2(Eua Island) 1/3sec grid (10m grid)
	Volc1-1-2	Unnamed1			
	Volc2-1-2	Home Reef			
	Volc3-1-2	Lateiki			
	Volc4-1-2	Fonuafo'ou			
	Volc5-1-2	Unnamed2			
	Volc6-1-2	Unnamed3			
	Volc7-1-2	Unnamed4			
	Volc0-2-1	Hunga Tonga-Hunga Ha'apai	R=5km、H=60m	Exitsting Seawall (Tongatapu Island)	reg4-1(Tongatapu Island 1/3sec grid (10m grid)
	Volc1-2-1	Unnamed1			
	Volc2-2-1	Home Reef			
	Volc3-2-1	Lateiki			
	Volc4-2-1	Fonuafo'ou			
	Volc5-2-1	Unnamed2			
	Volc6-2-1	Unnamed3			
	Volc7-2-1	Unnamed4			
	Volc0-2-2	Hunga Tonga-Hunga Ha'apai		-	reg4-2(Eua Island) 1/3sec grid (10m grid)
	Volc1-2-2	Unnamed1			
	Volc2-2-2	Home Reef			
	Volc3-2-2	Lateiki			
	Volc4-2-2	Fonuafo'ou			
	Volc5-2-2	Unnamed2			
	Volc6-2-2	Unnamed3			
	Volc7-2-2	Unnamed4			
	Volc0-3-1	Hunga Tonga-Hunga Ha'apai	R=5km、H=90m	Exitsting Seawall (Tongatapu Island)	reg4-1(Tongatapu Island 1/3sec grid (10m grid)
	Volc1-3-1	Unnamed1			
	Volc2-3-1	Home Reef			
	Volc3-3-1	Lateiki			
	Volc4-3-1	Fonuafo'ou			
	Volc5-3-1	Unnamed2			
	Volc6-3-1	Unnamed3			
	Volc7-3-1	Unnamed4			
	Volc0-3-2	Hunga Tonga-Hunga Ha'apai		-	reg4-2(Eua Island) 1/3sec grid (10m grid)
	Volc1-3-2	Unnamed1			
	Volc2-3-2	Home Reef			
	Volc3-3-2	Lateiki			
	Volc4-3-2	Fonuafo'ou			
	Volc5-3-2	Unnamed2			
	Volc6-3-2	Unnamed3			
	Volc7-3-2	Unnamed4			

Source: JICA Study Team.

(3) Calculation results

1) Max tsunami Water Level Distribution

The calculation results of the Max tsunami Water Level Distribution by wave source for each target volcano are shown below.

a. Regional Max Water Level Distribution including wave sources

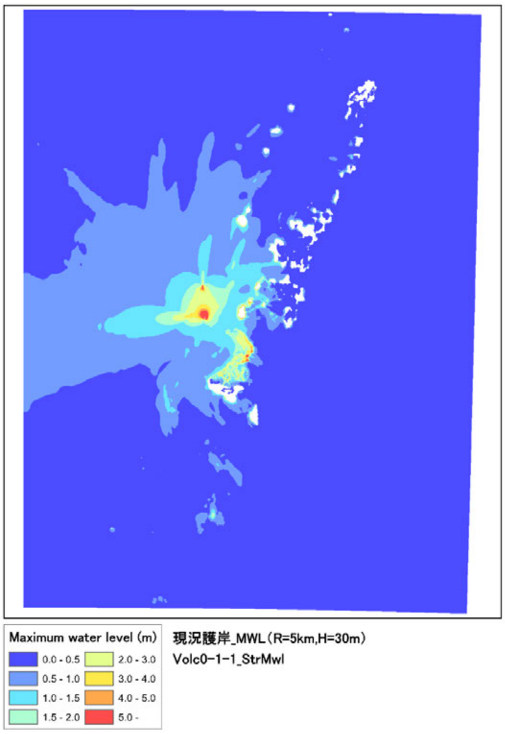


Figure 2.6.3 Maxi Water Level Distribution (Hunga Tonga-Hunga Ha'pai, H=30m)

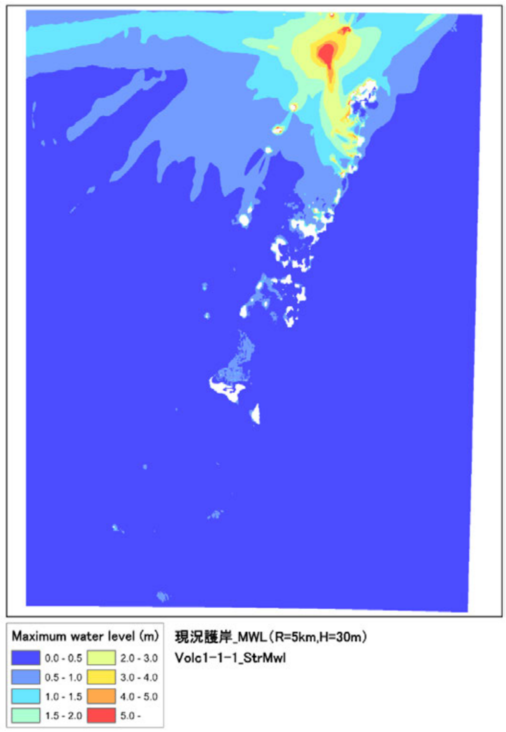


Figure 2.6.4 Max Water Level Distribution (Unnamed1, H=30m)

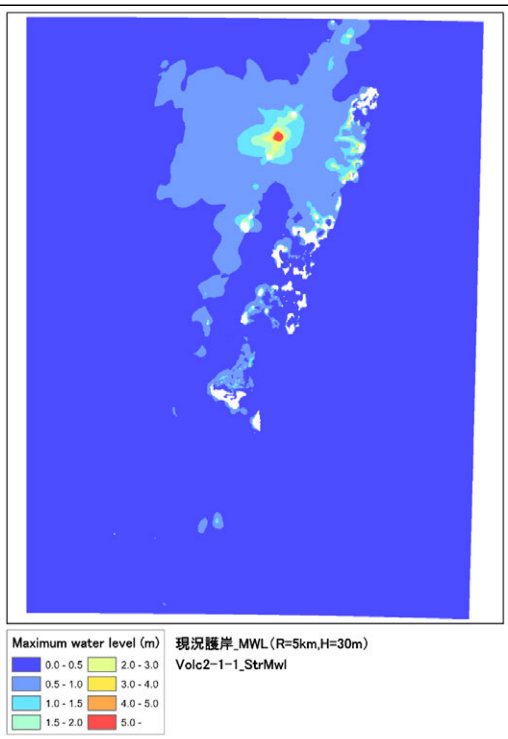


Figure 2.6.5 Max Water Level Distribution (HomeReef, H=30m)

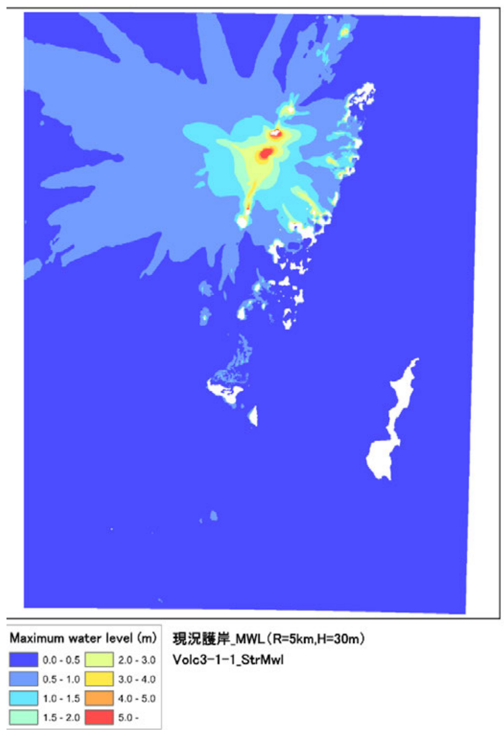


Figure 2.6.6 Max Water Level Distribution (Lateiki, H=30m)

Source: JICA Study Team

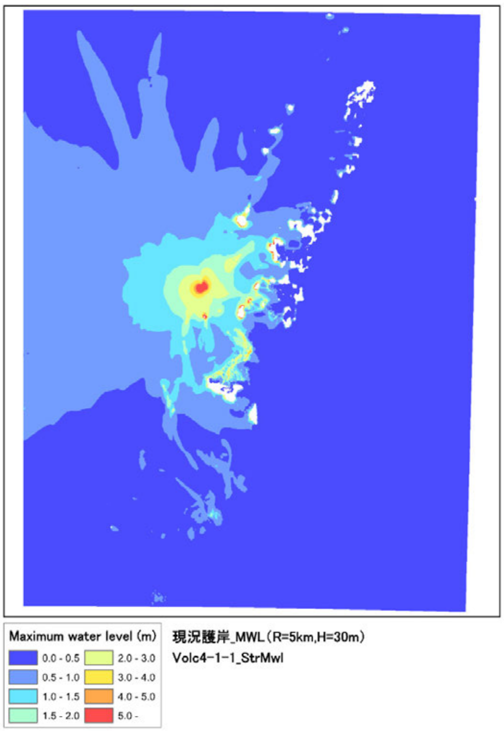


Figure 2.6.7 Max Water Level Distribution (Fonuafo'ou H=30m)

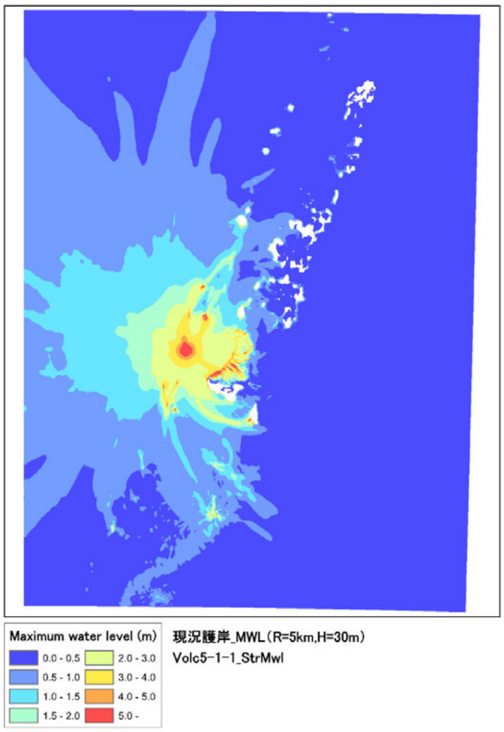


Figure 2.6.8 Max Water Level Distribution (Unamed2, H=30m)

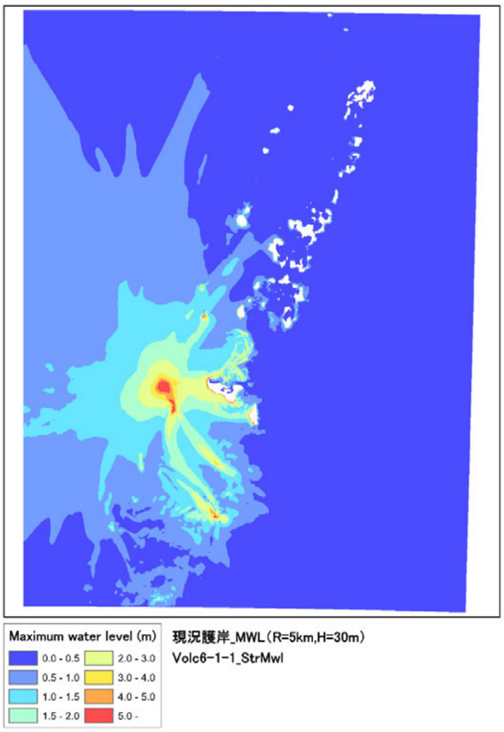


Figure 2.6.9 Max Water Level Distribution (Unamed3, H=30m)

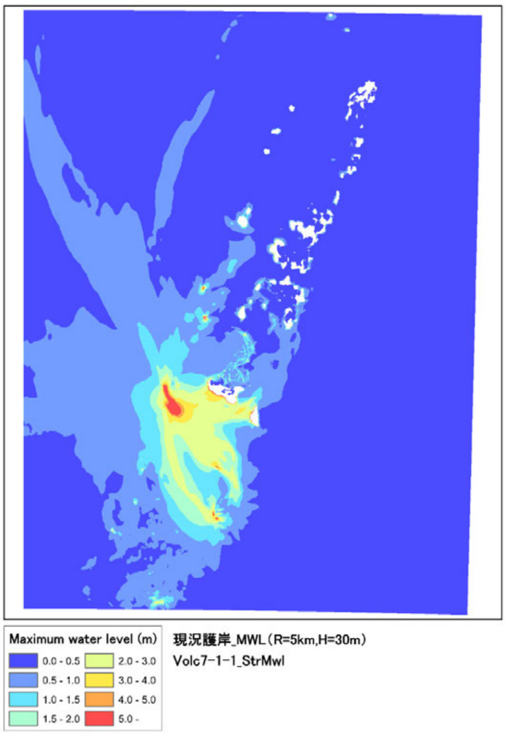


Figure 2.6.10 Max Water Level Distribution (Unamed4, H=30m)

Source: JICA Study Team

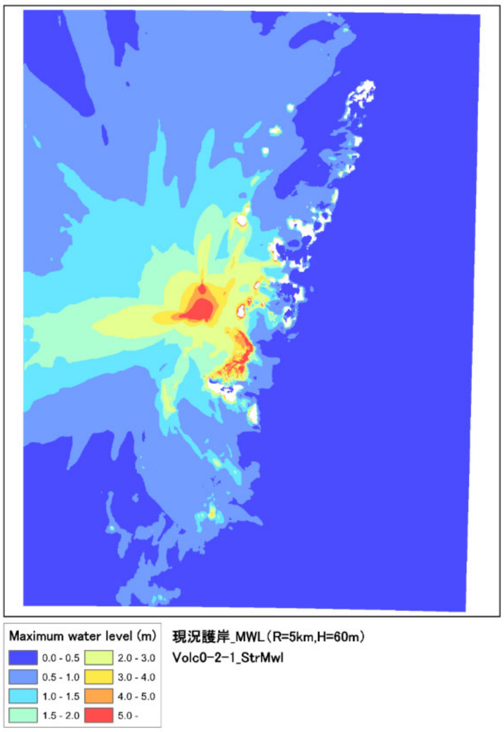


Figure 2.6.11 Max Water Level Distribution (Hunga Tonga-Hunga Ha'pai, H=60m)

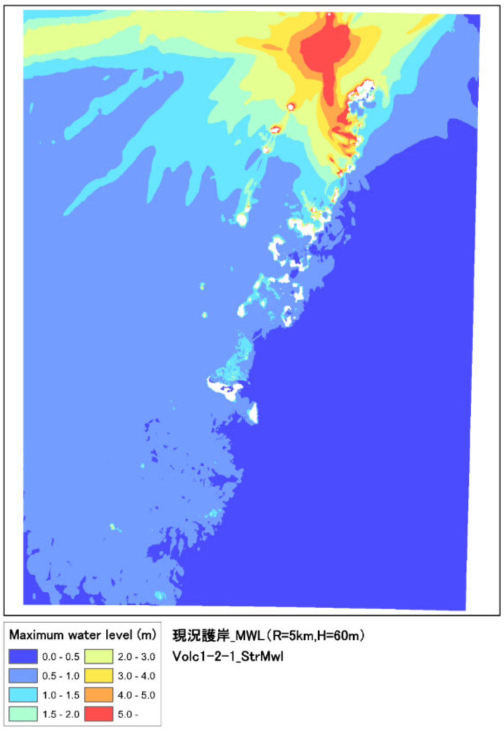


Figure 2.6.12 Max Water Level Distribution (Unnamed1, H=60m)

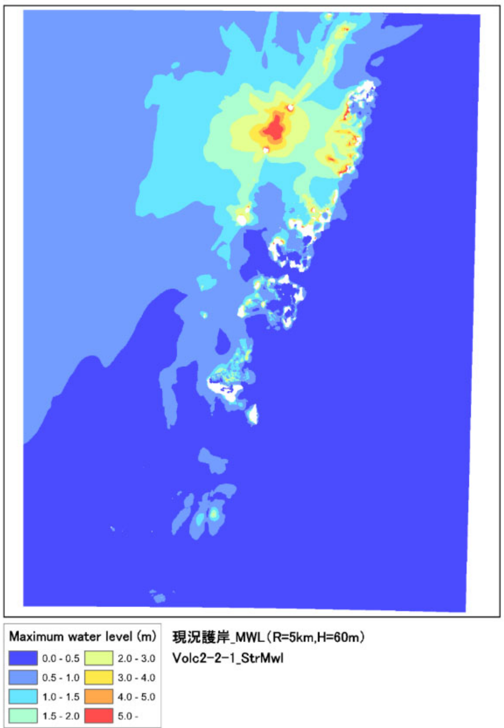


Figure 2.6.13 Max Water Level Distribution (HomeReef, H=60m)

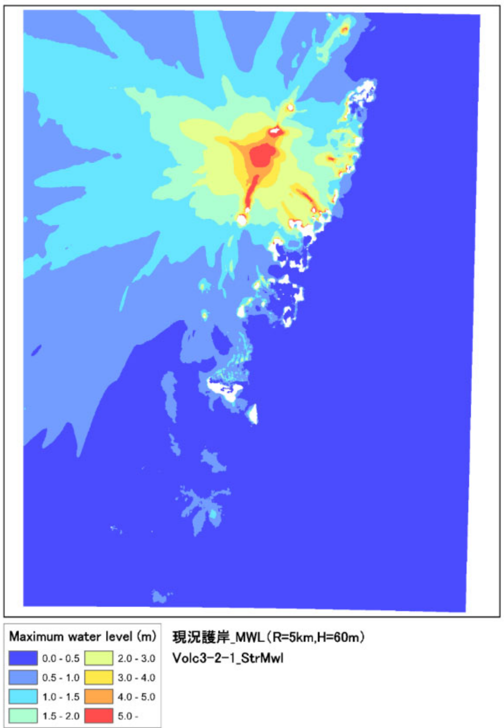


Figure 2.6.14 Max Water Level Distribution (Lateiki, H=60m)

Source: JICA Study Team

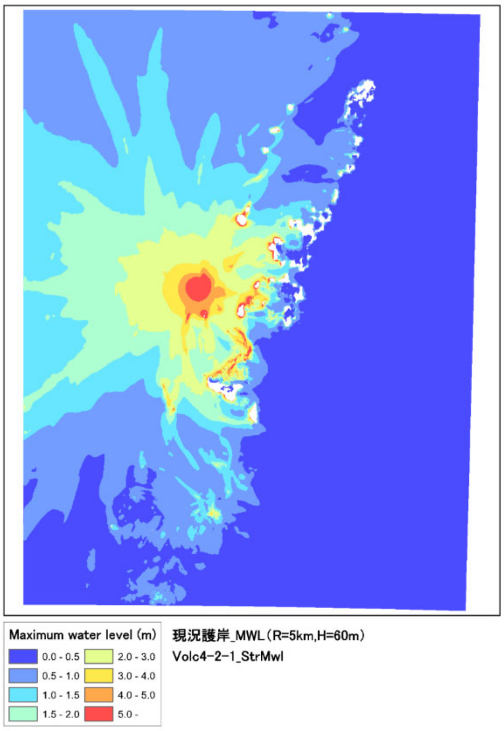


Figure 2.6.15 Max Water Level Distribution (Fonuafo'ou, H=60m)

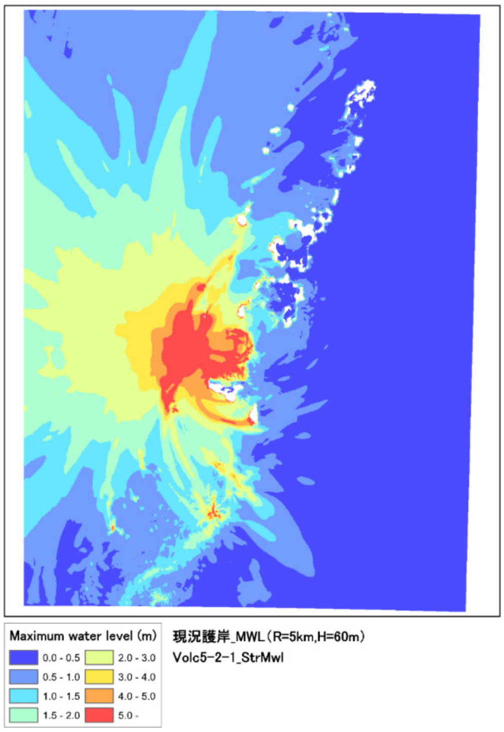


Figure 2.6.16 Max Water Level Distribution (Unamed2, H=60m)

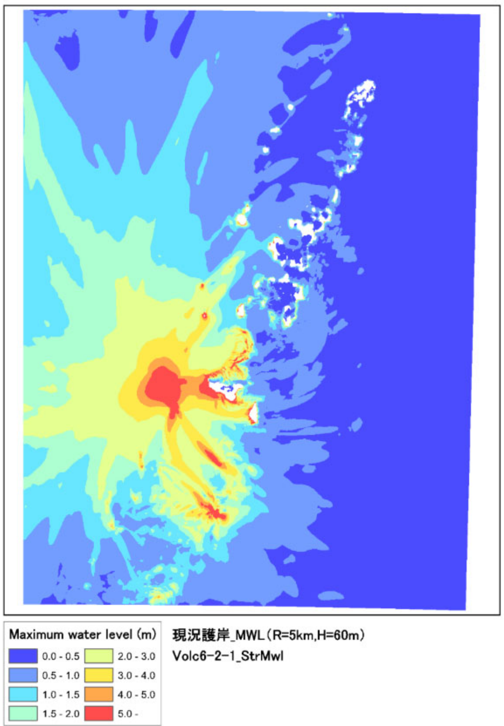


Figure 2.6.17 Max Water Level Distribution (Unamed3, H=60m)

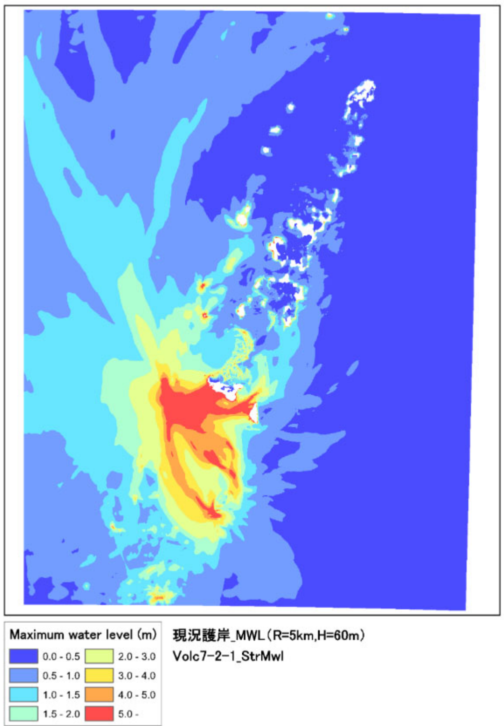


Figure 2.6.18 Max Water Level Distribution (Unamed4, H=30m)

Source: JICA Study Team

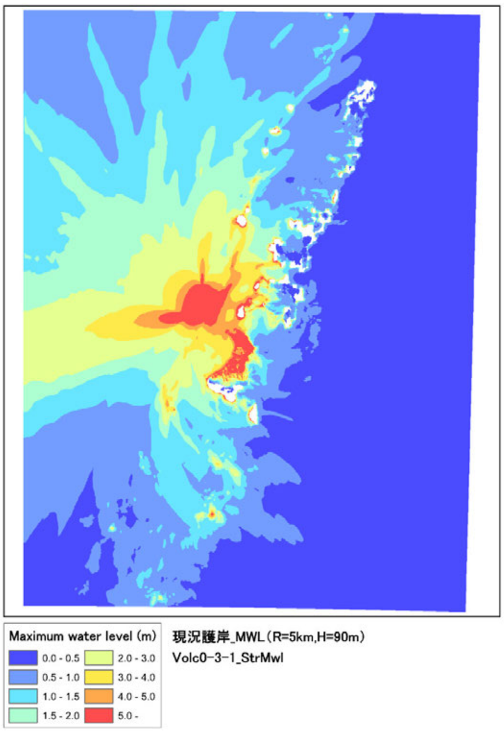


Figure 2.6.19 Max Water Level Distribution (Hunga Tonga-Hunga Ha'pai, H=90m)

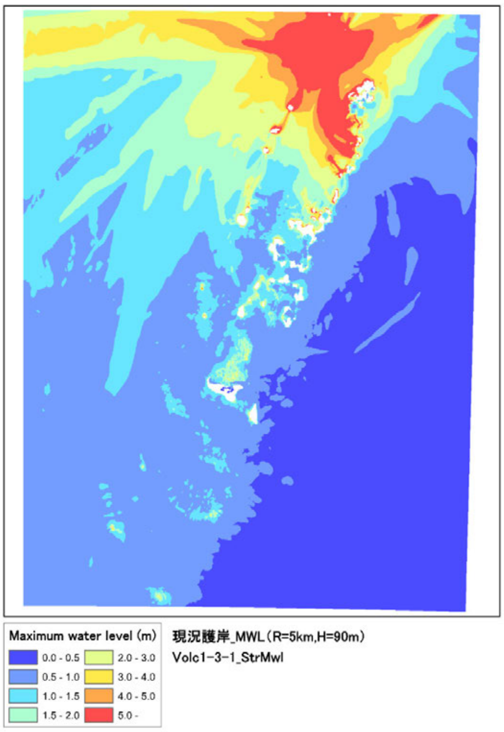


Figure 2.6.20 Max Water Level Distribution (Unnamed1, H=90m)

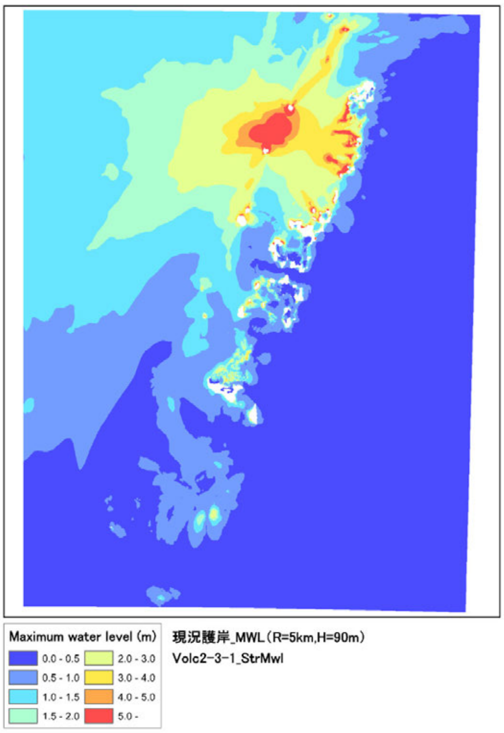


Figure 2.6.21 Max Water Level Distribution (HomeReef, H=90m)

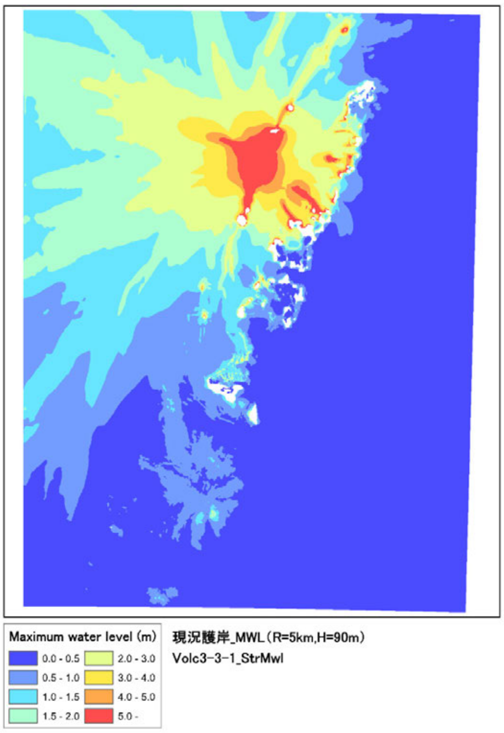


Figure 2.6.22 Max Water Level Distribution (Lateiki, H=90m)

Source: JICA Study Team

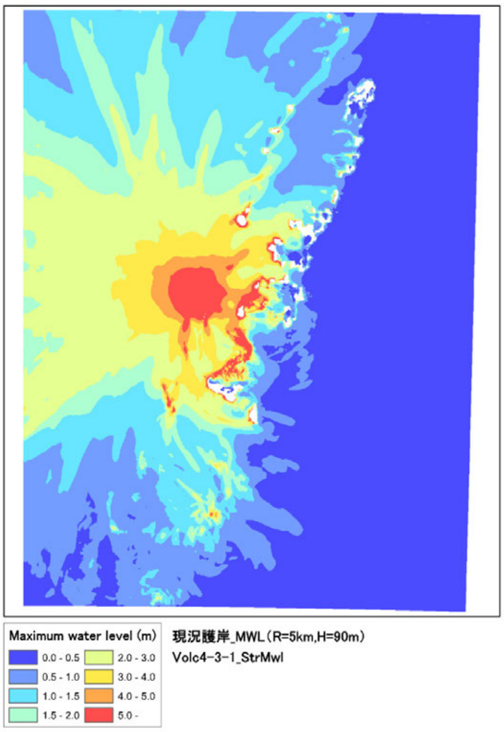


Figure 2.6.23 Max Water Level Distribution (Fonuafo'ou, H=90m)

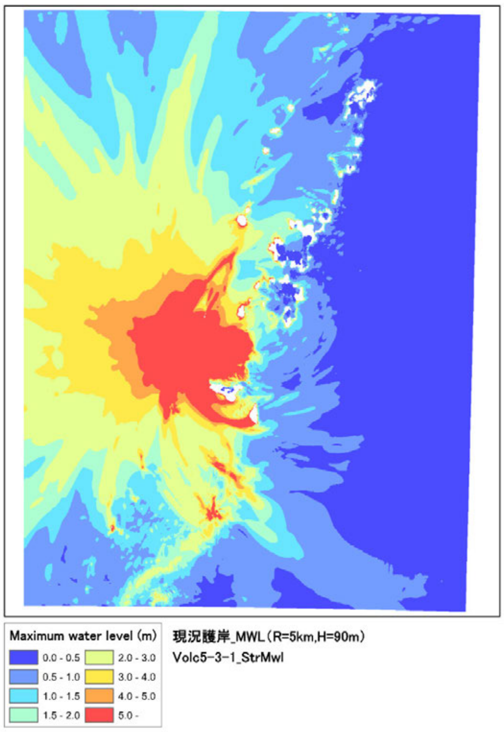


Figure 2.6.24 Max Water Level Distribution (Unamed2, H=90m)

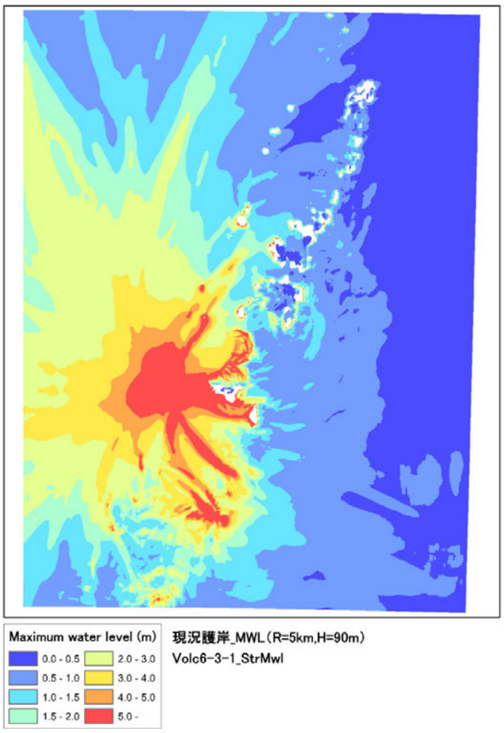


Figure 2.6.25 Max Water Level Distribution (Unamed3, H=90m)

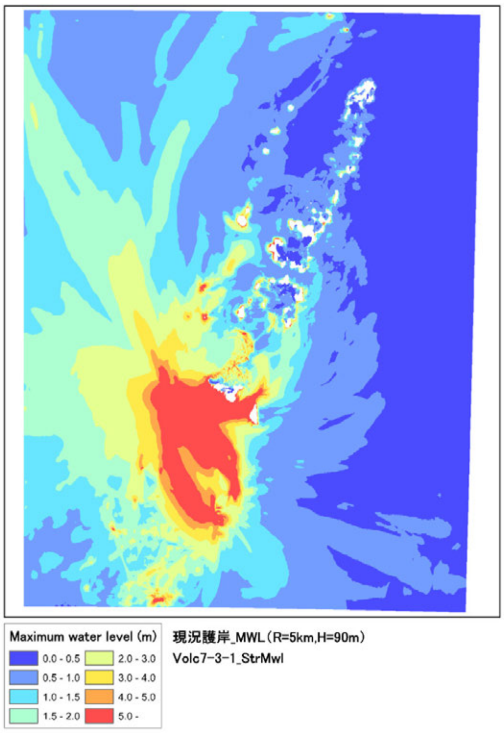
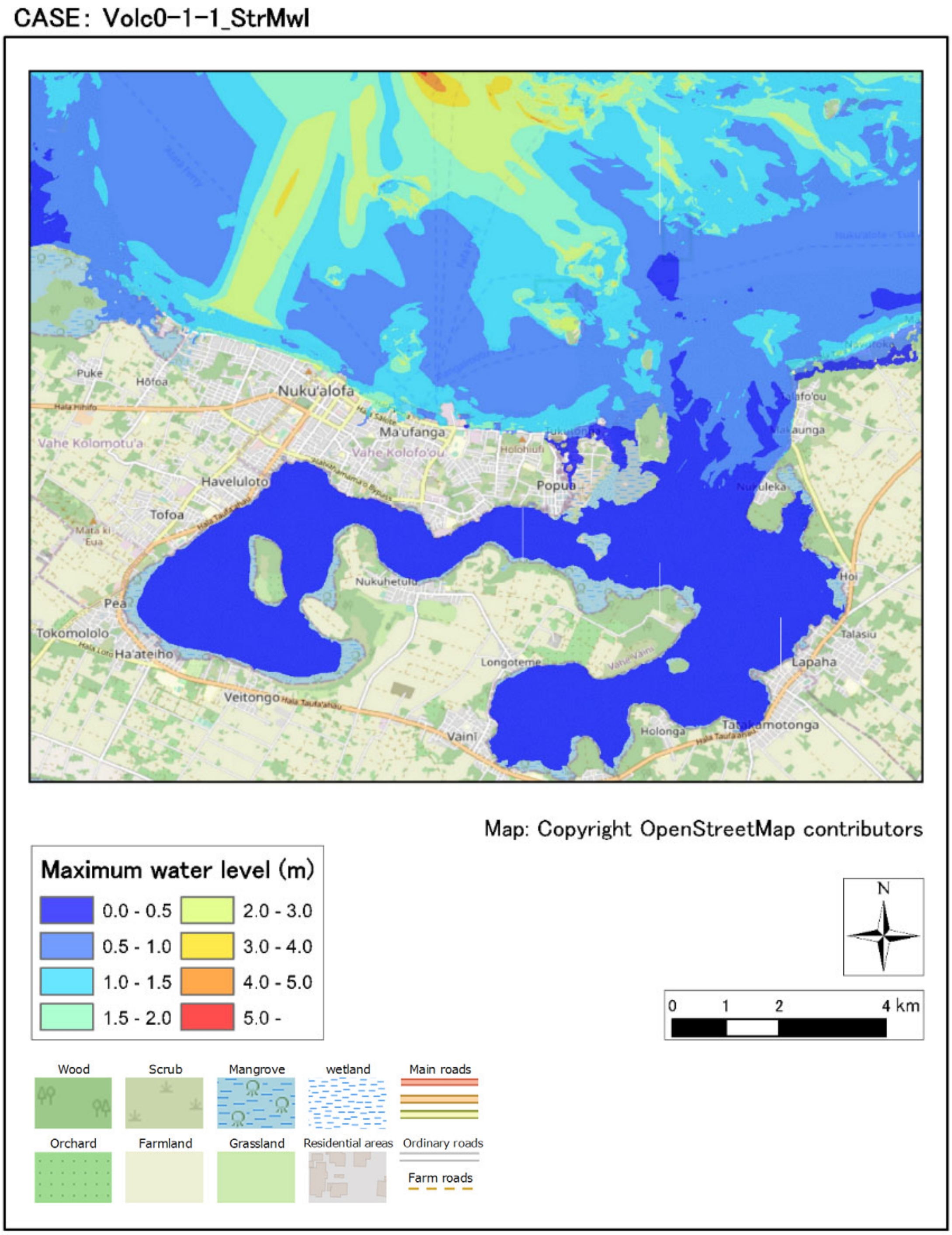


Figure 2.6.26 Max Water Level Distribution (Unamed4, H=90m)

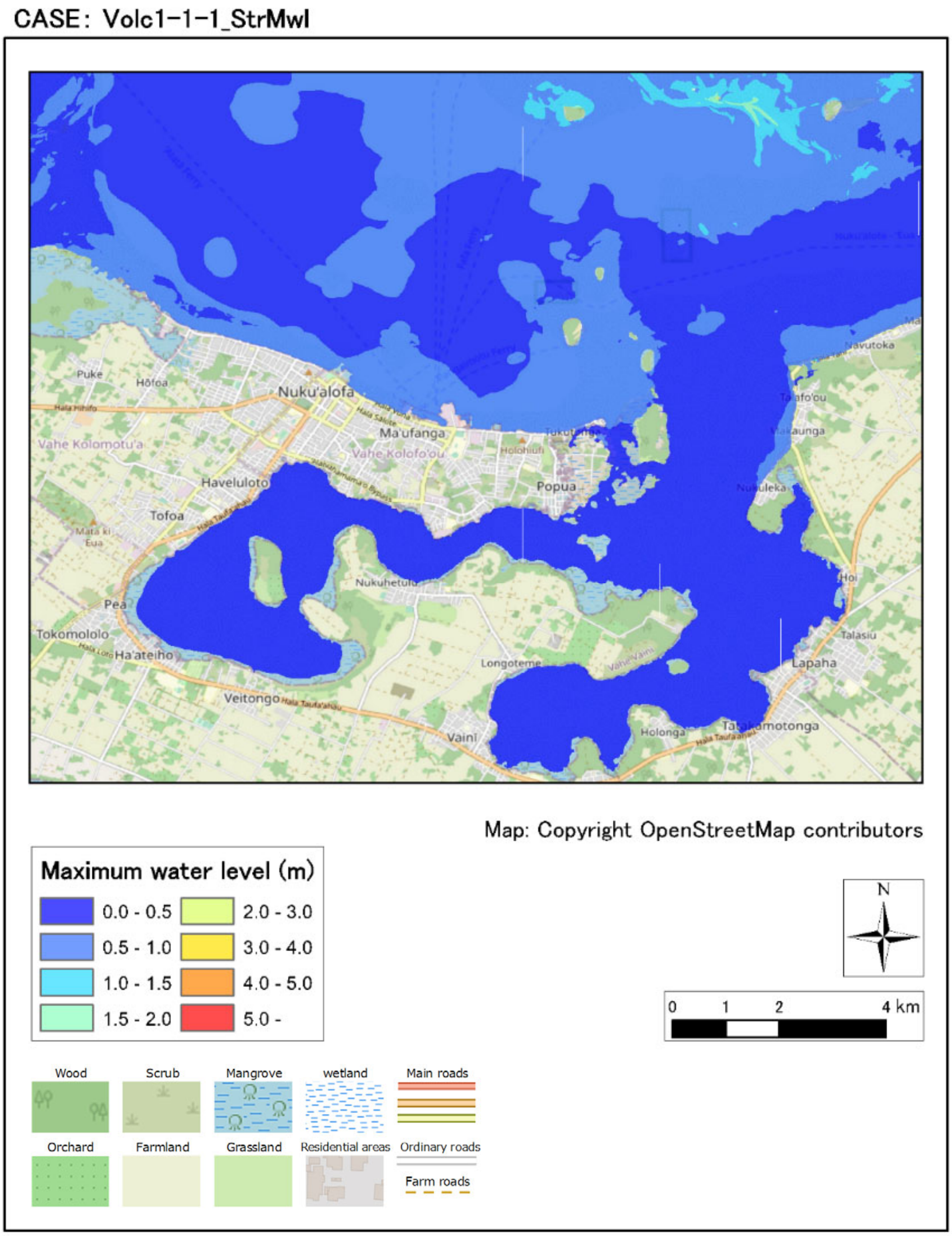
Source: JICA Study Team

b. Max Water Level Distribution (Nukualofa, Tongatapu Island).



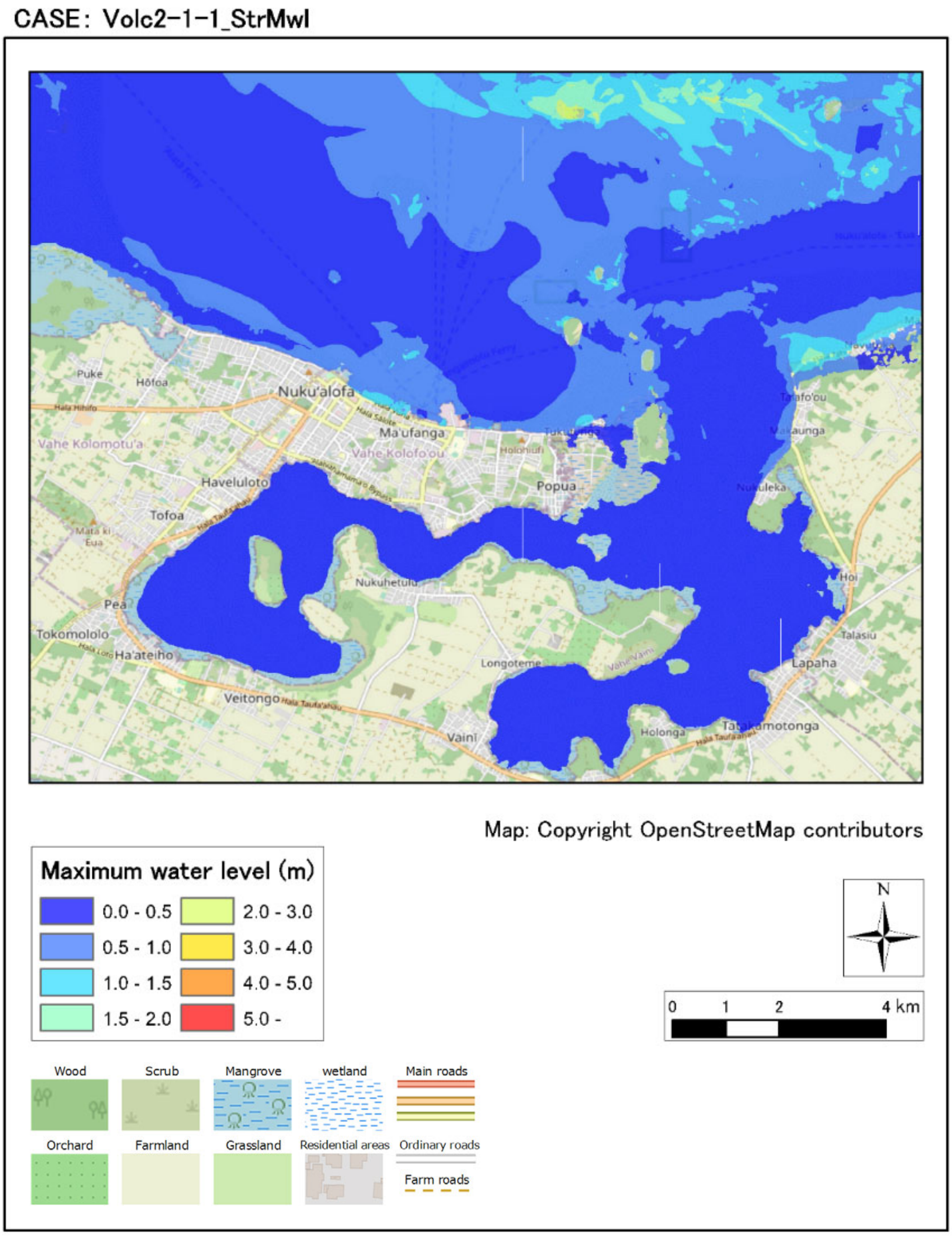
Source: JICA Study Team

Figure 2.6.27 Max Water Level Distribution (Hunga Tonga-Hunga Ha'pai, H=30m)



Source: JICA Study Team

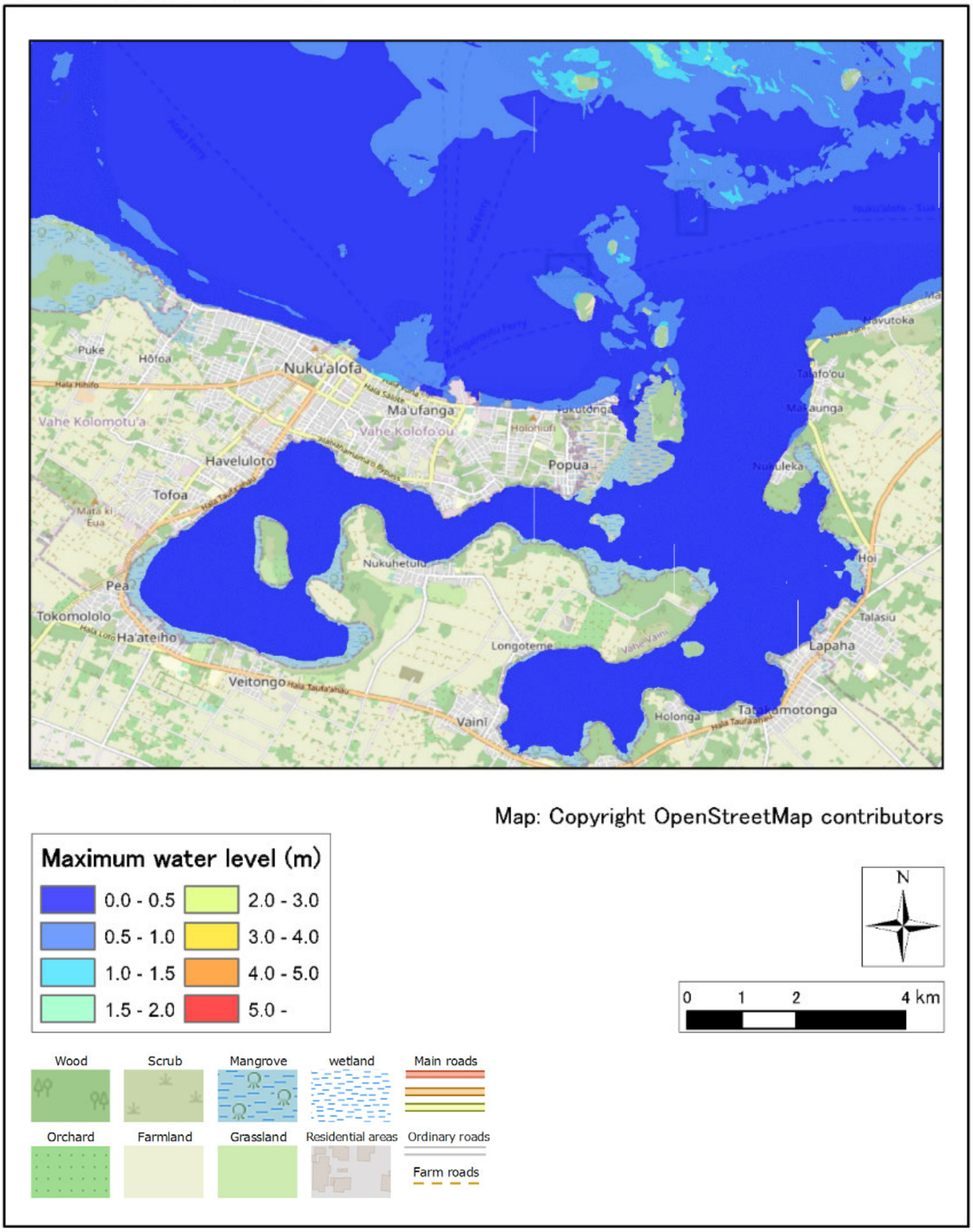
Figure 2.6.28　Max Water Level Distribution (Unnamed1, H=30m)



Source: JICA Study Team

Figure 2.6.29 Max Water Level Distribution (HomeReef, H=30m)

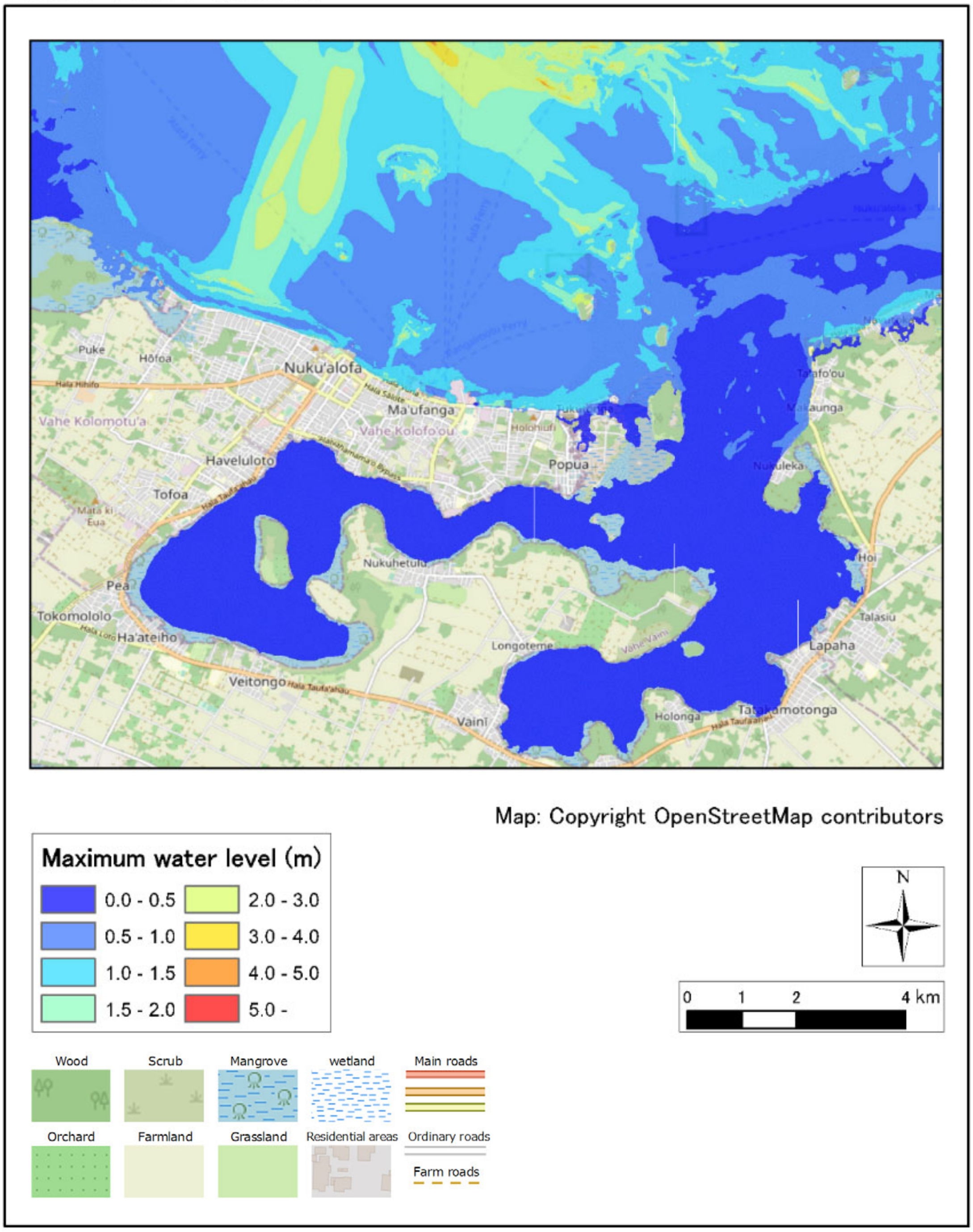
CASE: Volc3-1-1_StrMwl



Source: JICA Study Team

Figure 2.6.30 Max Water Level Distribution (Lateiki, H=30m)

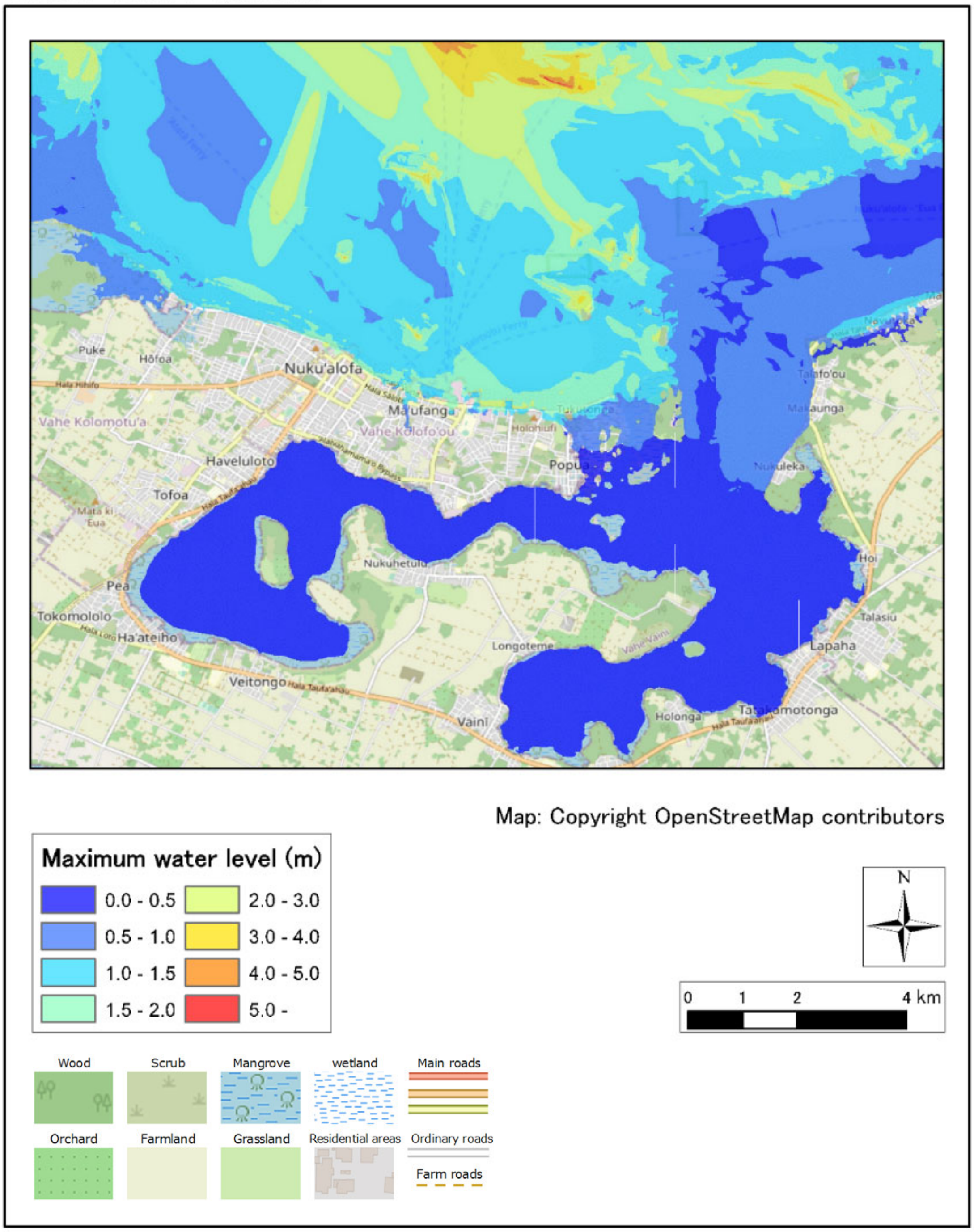
CASE: Volc4-1-1_StrMwl



Source: JICA Study Team

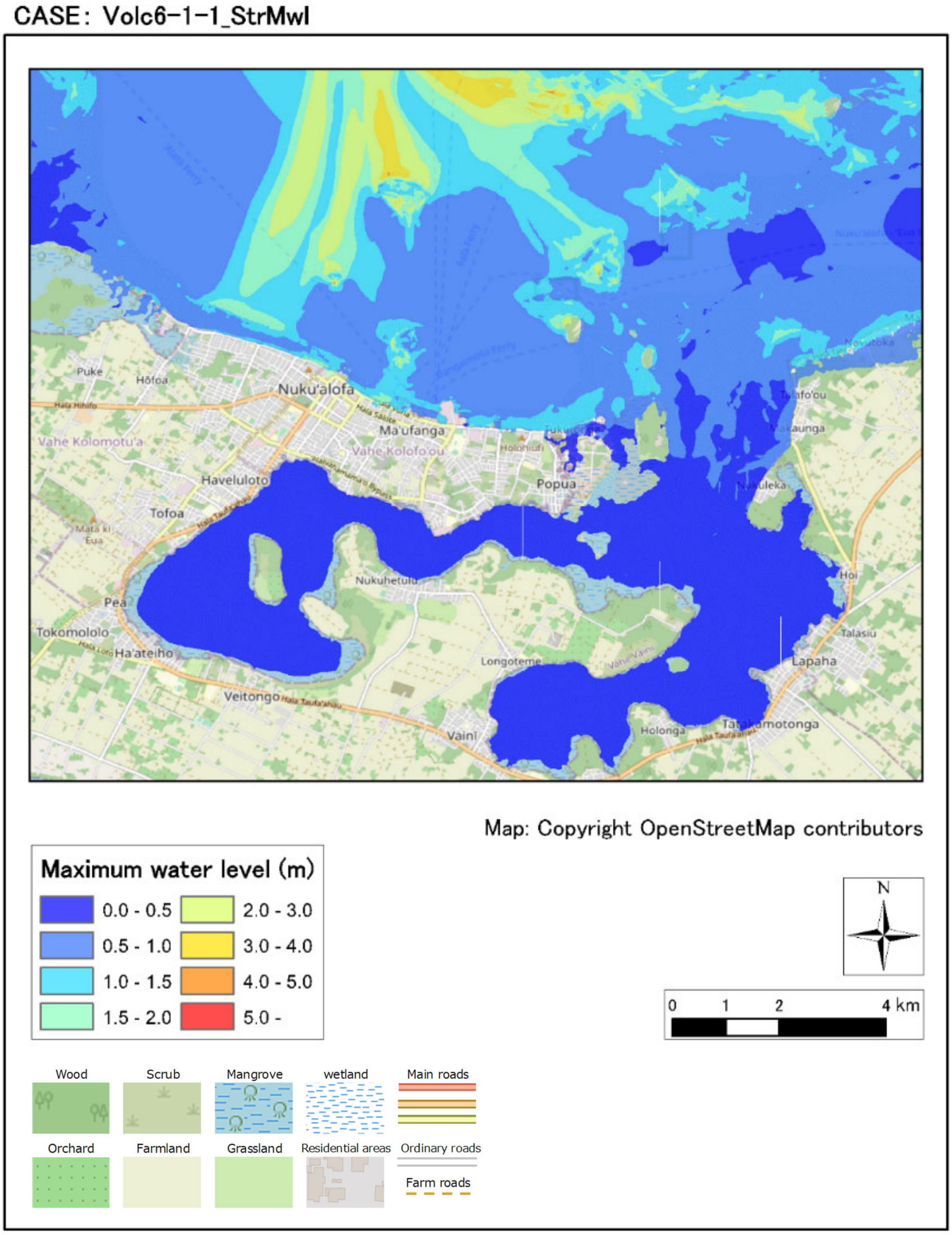
Figure 2.6.31 Max Water Level Distribution (Fonuafo'ou H=30m)

CASE：Volc5-1-1_StrMwl



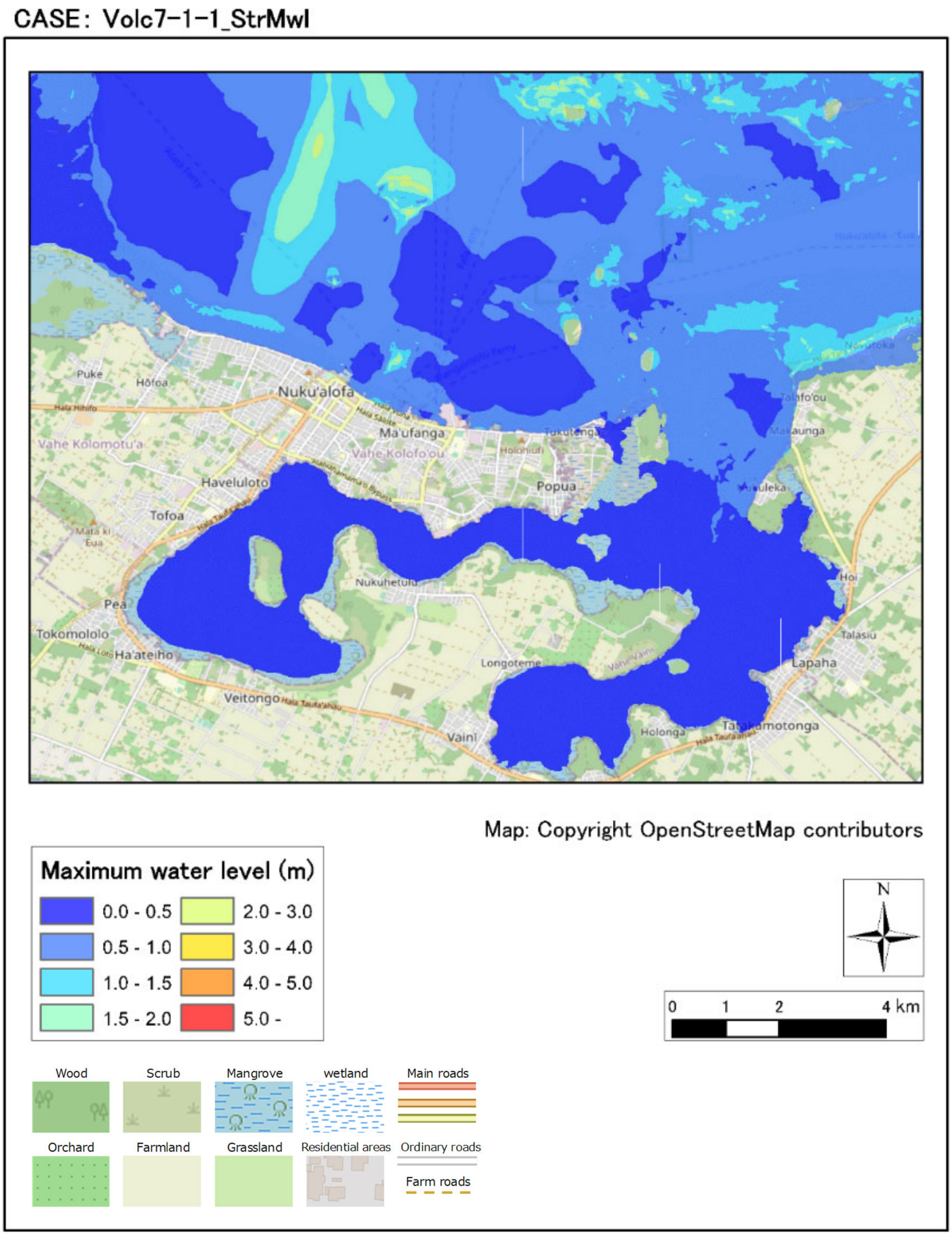
Source: JICA Study Team

Figure 2.6.32 Max Water Level Distribution (Unamed2, H=30m)



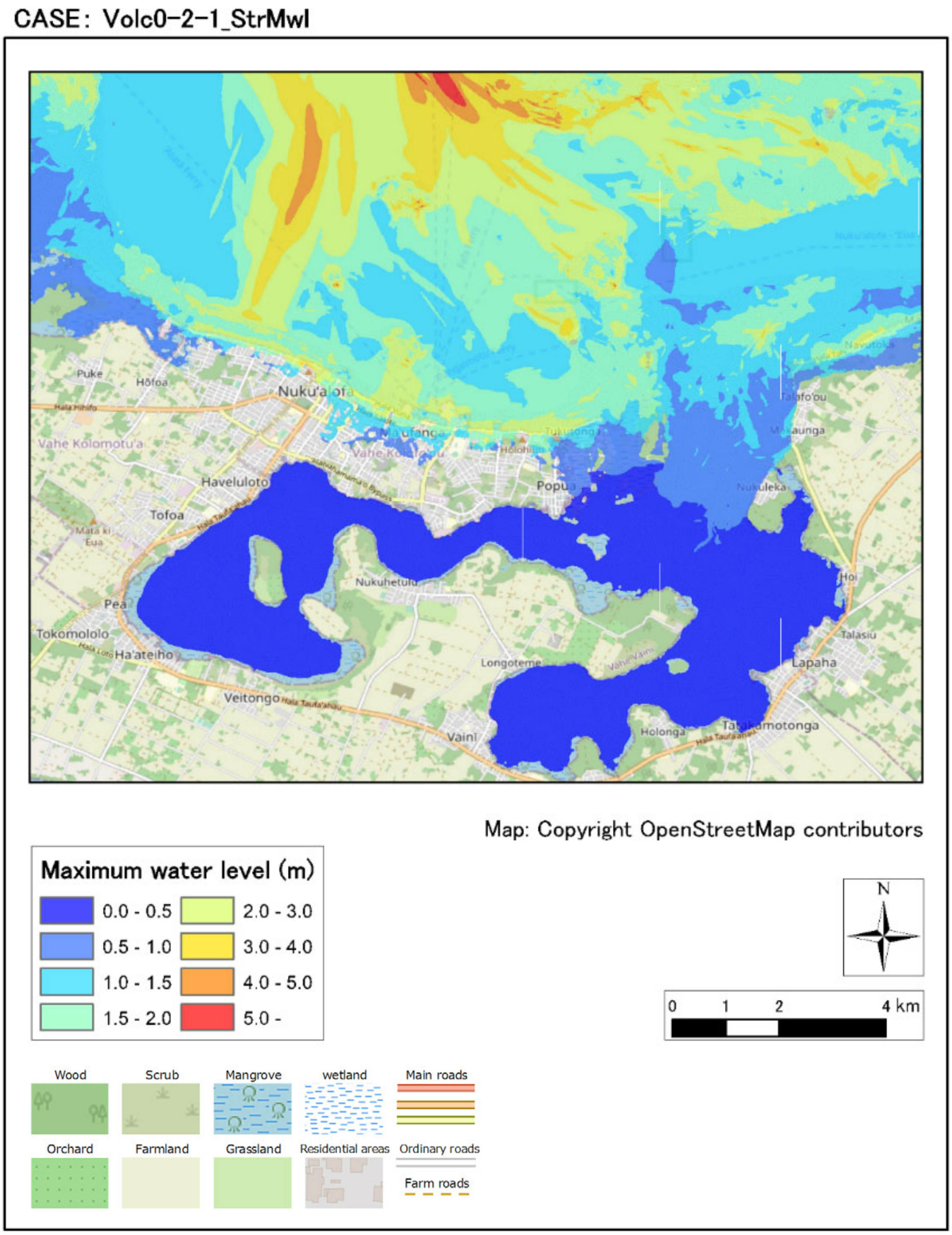
Source: JICA Study Team

Figure 2.6.33 Max Water Level Distribution (Unamed3, H=30m)



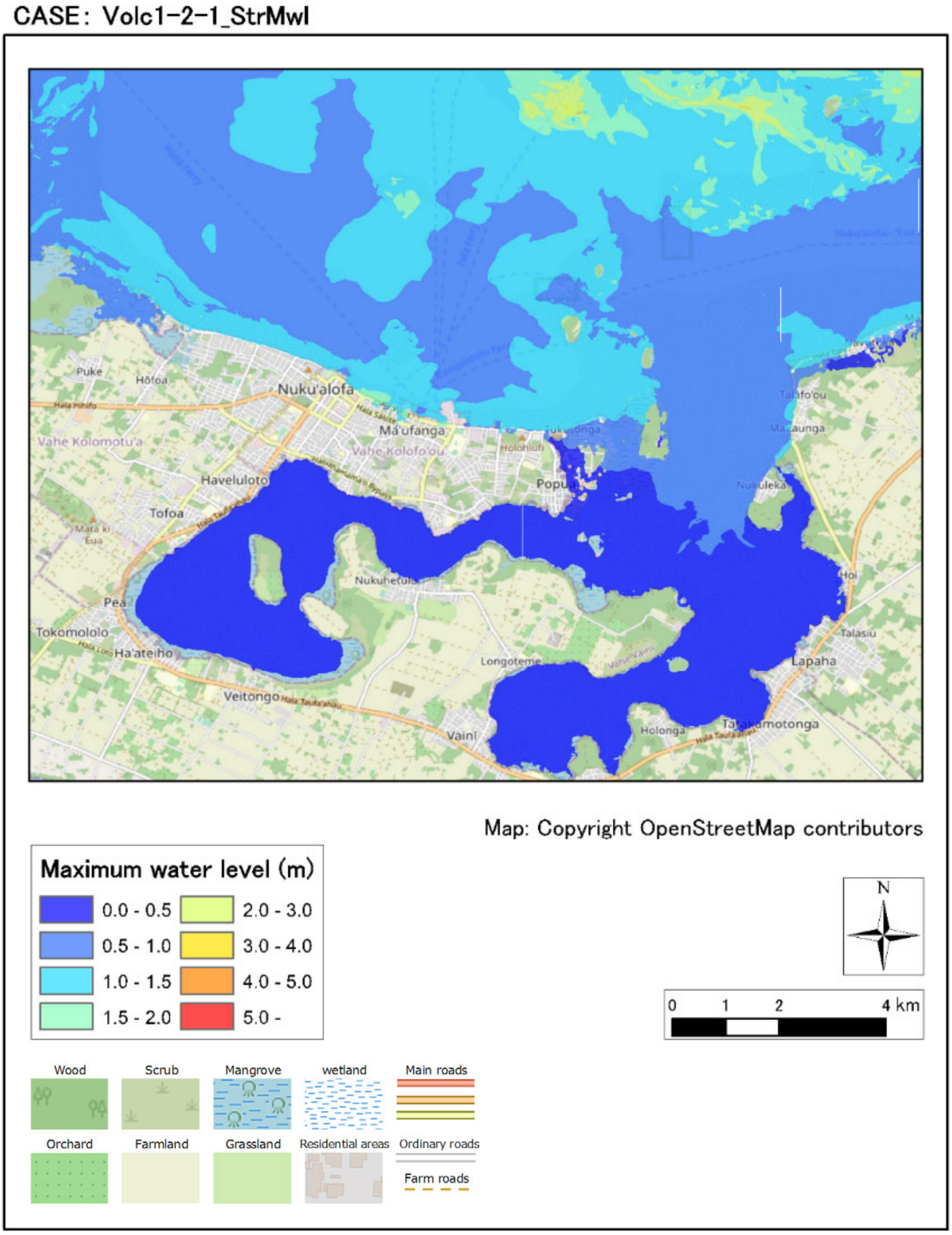
Source: JICA Study Team

Figure 2.6.34 Max Water Level Distribution (Unamed4, H=30m)



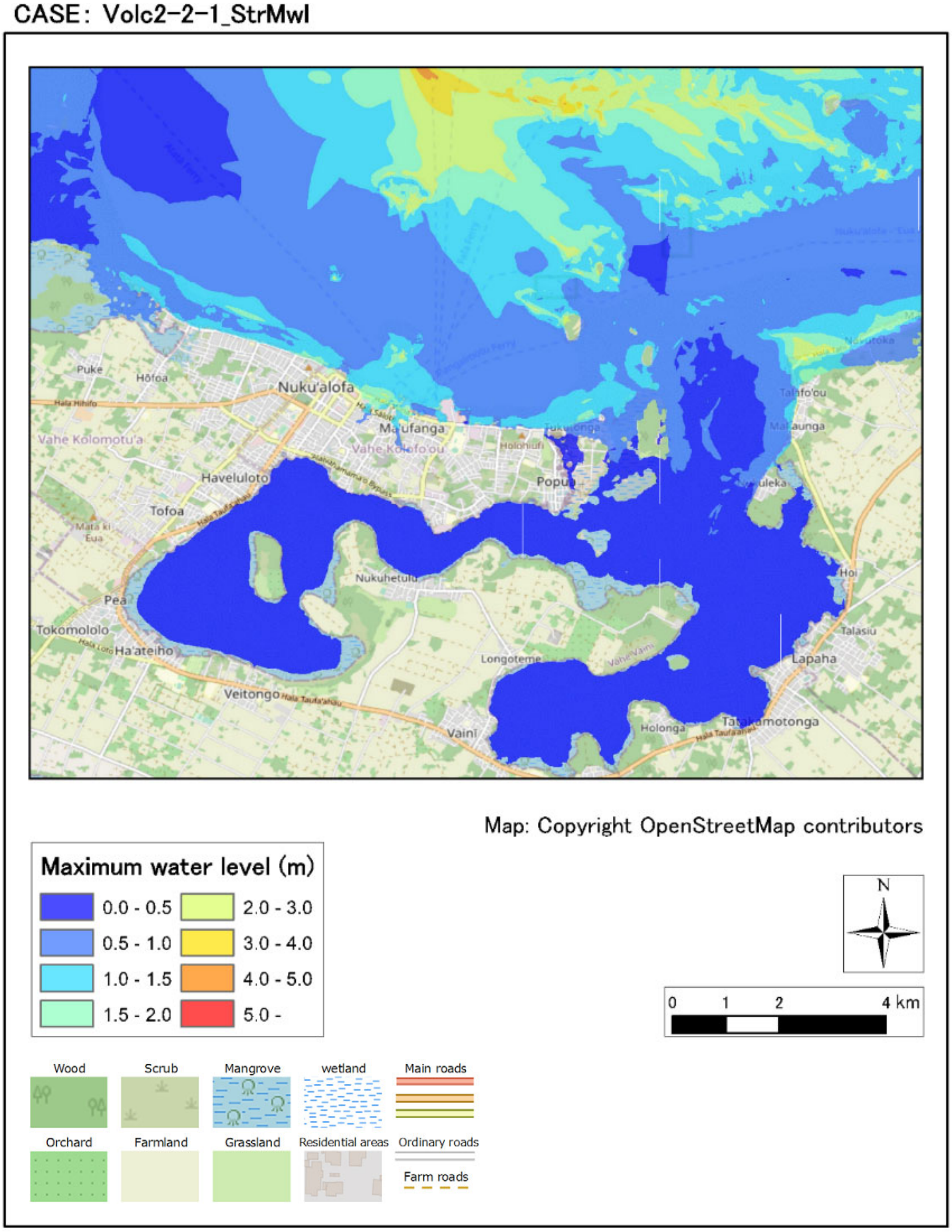
Source: JICA Study Team

Figure 2.6.35 Max Water Level Distribution (Hunga Tonga-Hunga Ha'pai, H=60m)



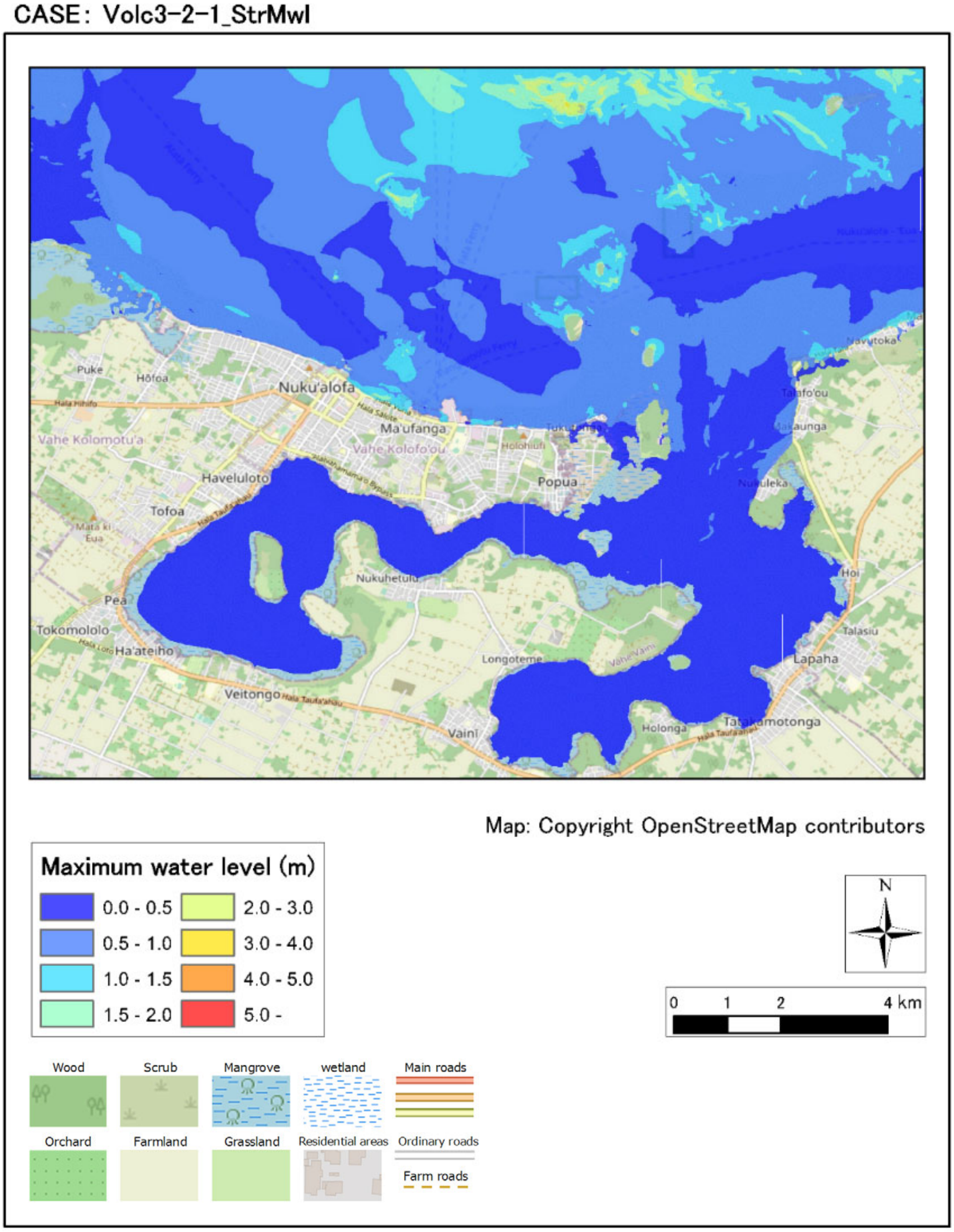
Source: JICA Study Team

Figure 2.6.36 Max Water Level Distribution (Unnamed1, H=60m)



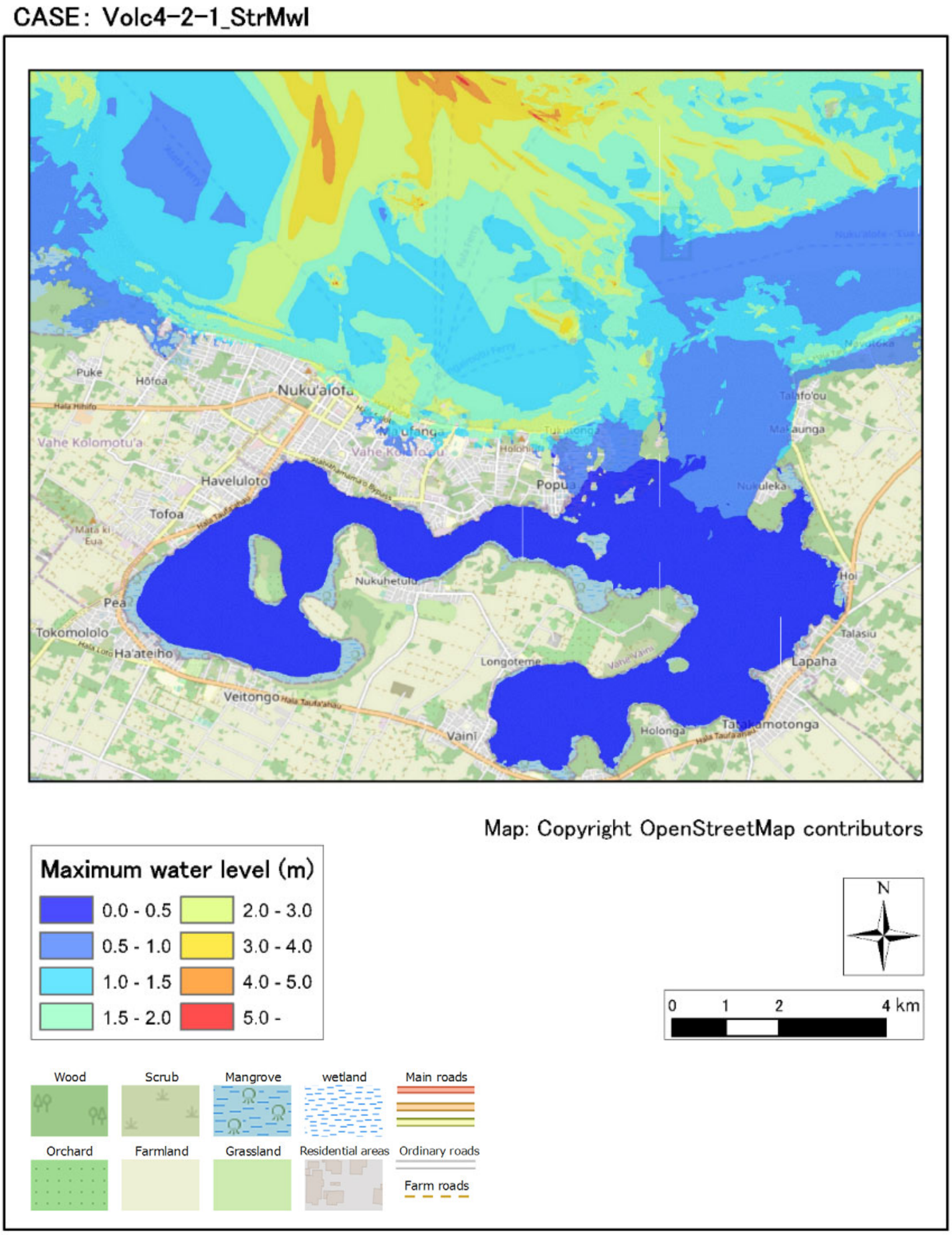
Source: JICA Study Team

Figure 2.6.37 Max Water Level Distribution (HomeReef, H=60m)



Source: JICA Study Team

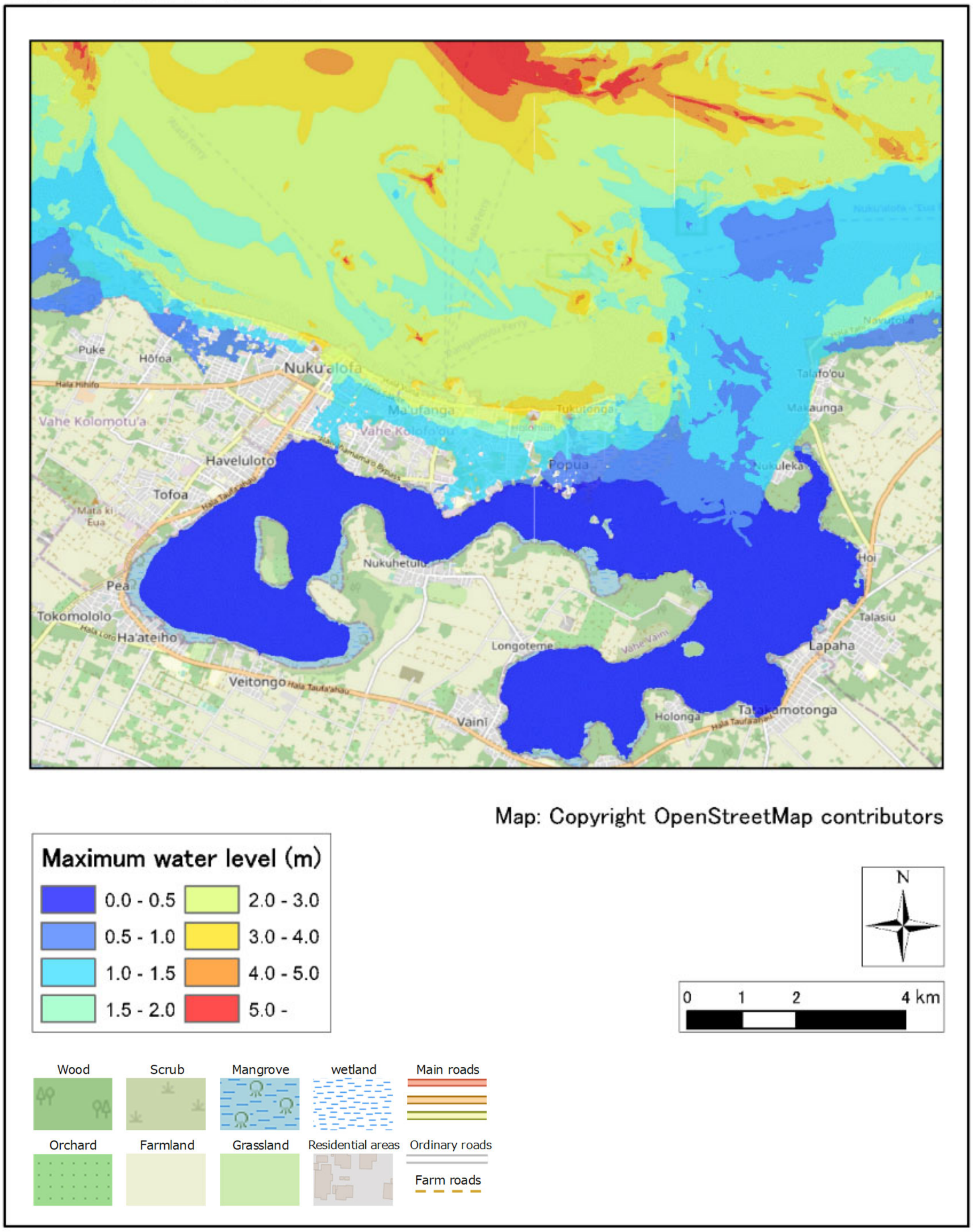
Figure 2.6.38 Max Water Level Distribution (Lateiki, H=60m)



Source: JICA Study Team

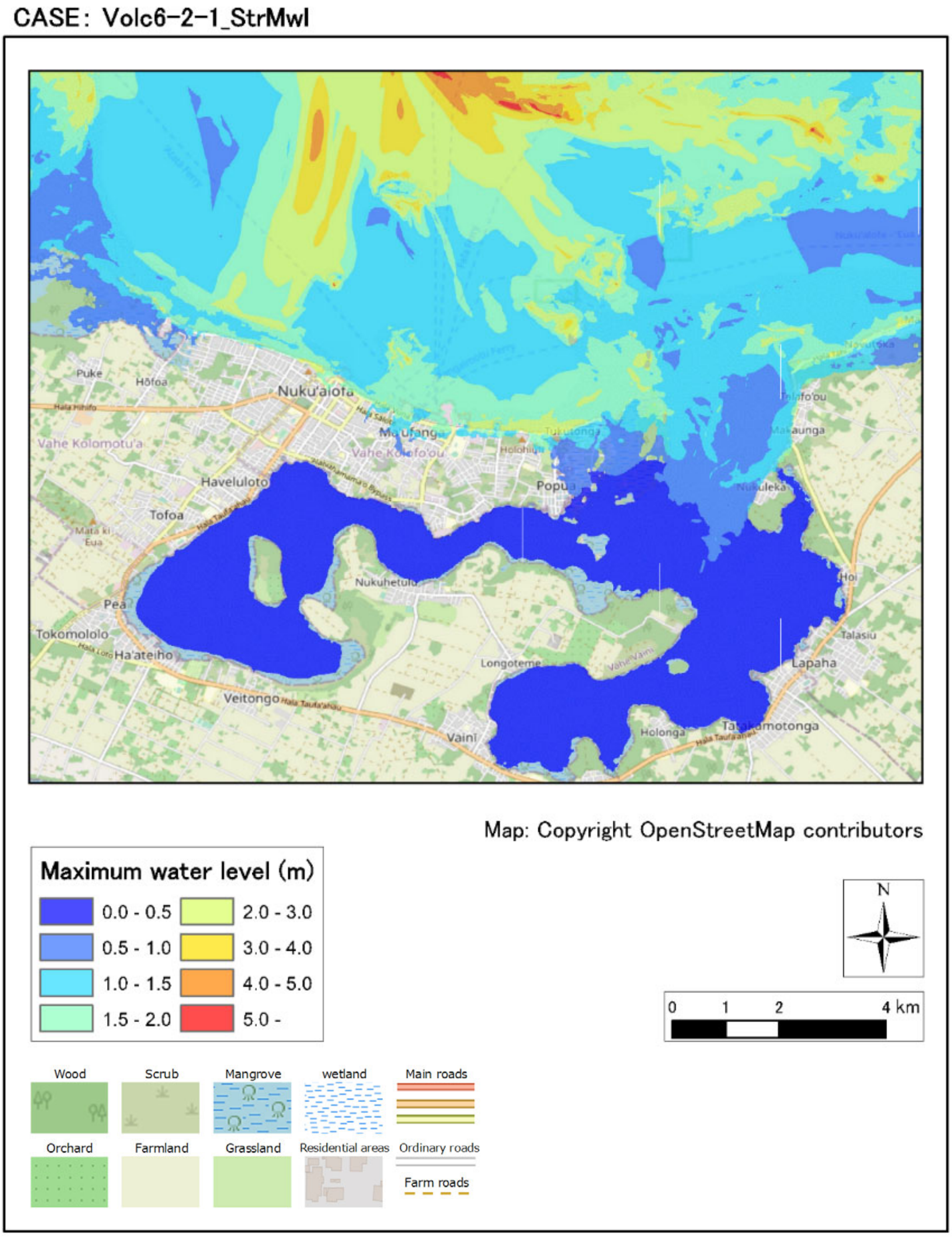
Figure 2.6.39 Max Water Level Distribution (Fonuafo'ou, H=60m)

CASE: Volc5-2-1_StrMwl



Source: JICA Study Team

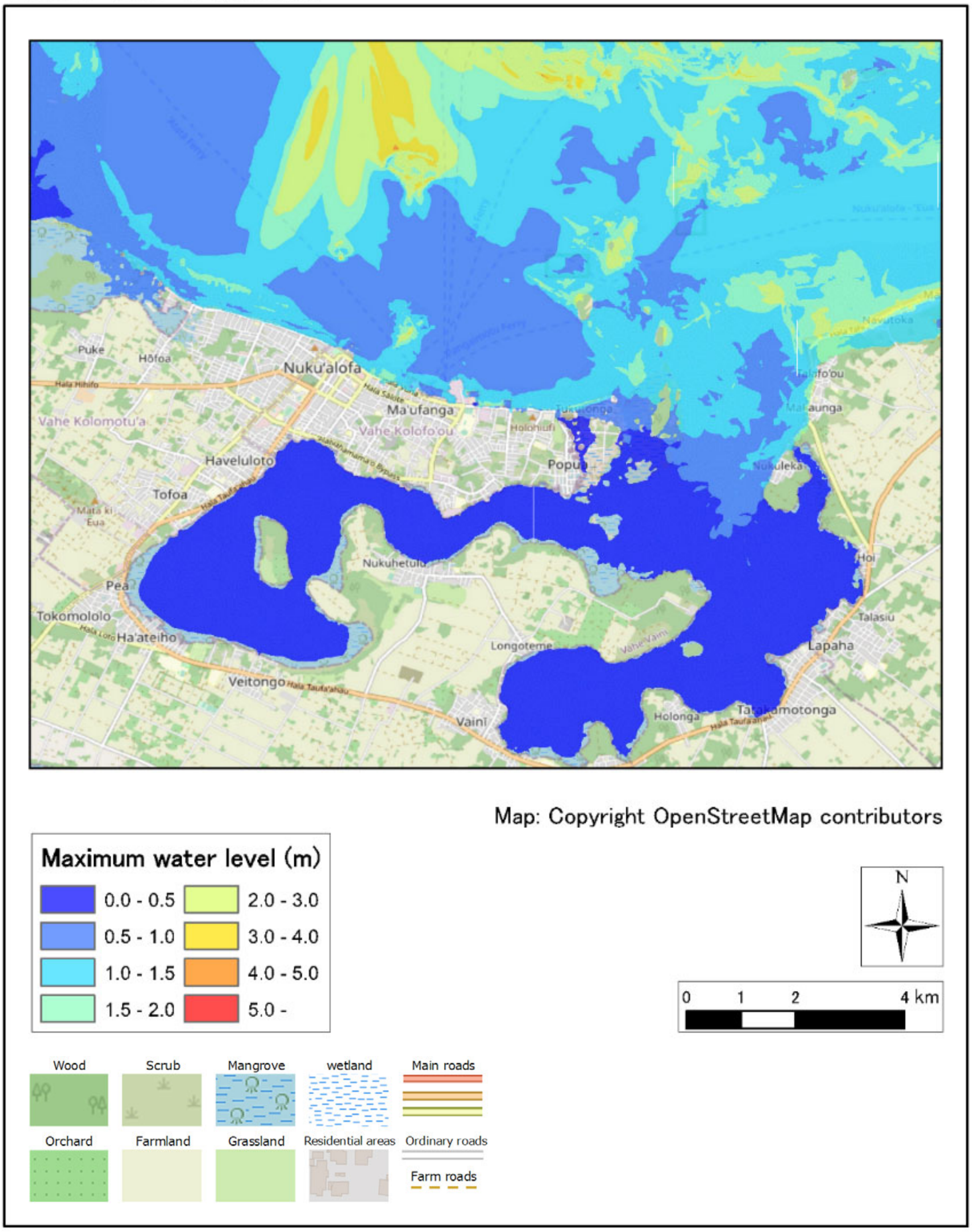
Figure 2.6.40 Max Water Level Distribution (Unamed2, H=60m)



Source: JICA Study Team

Figure 2.6.41 Max Water Level Distribution (Unamed3, H=60m)

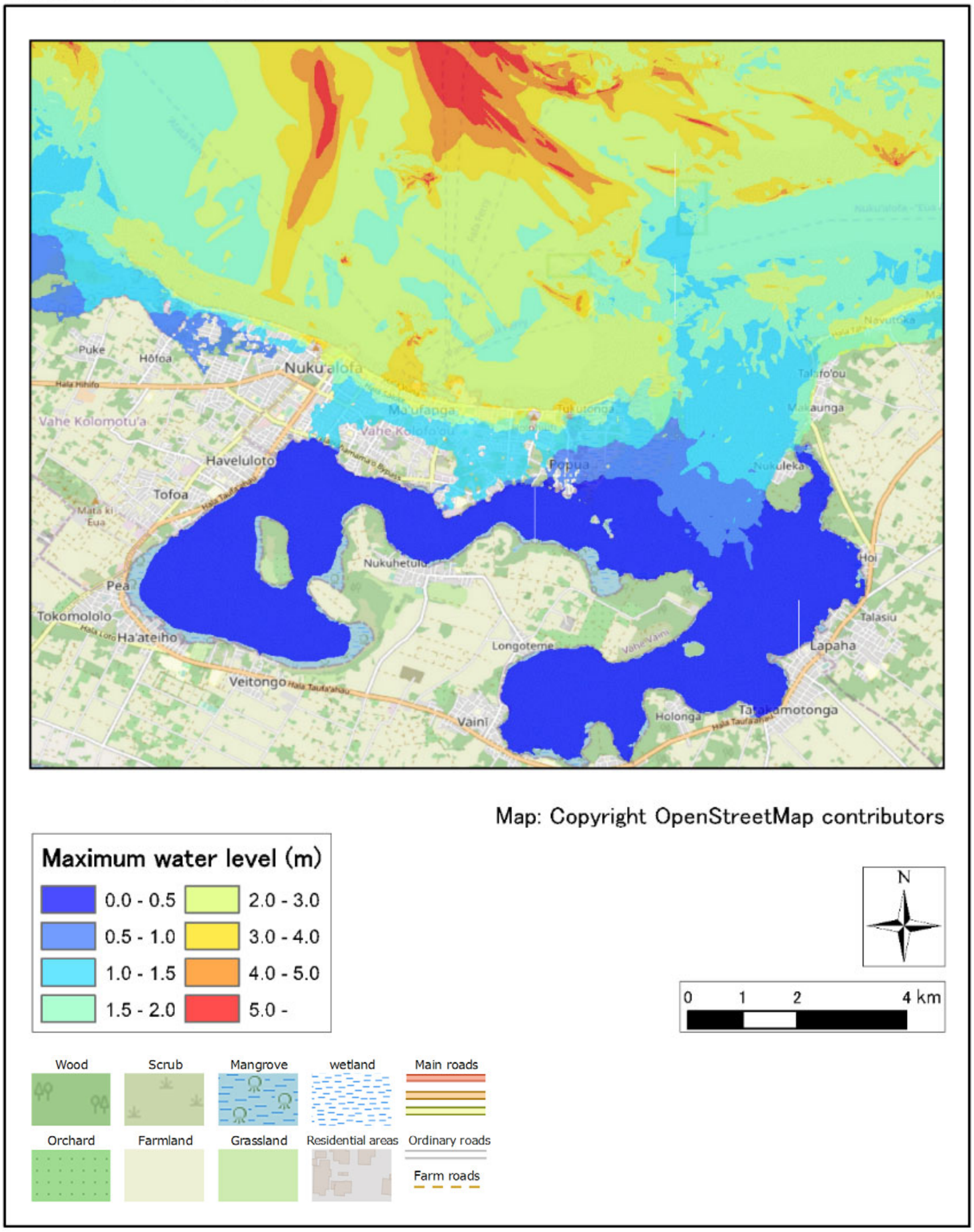
CASE: Volc7-2-1_StrMwl



Source: JICA Study Team

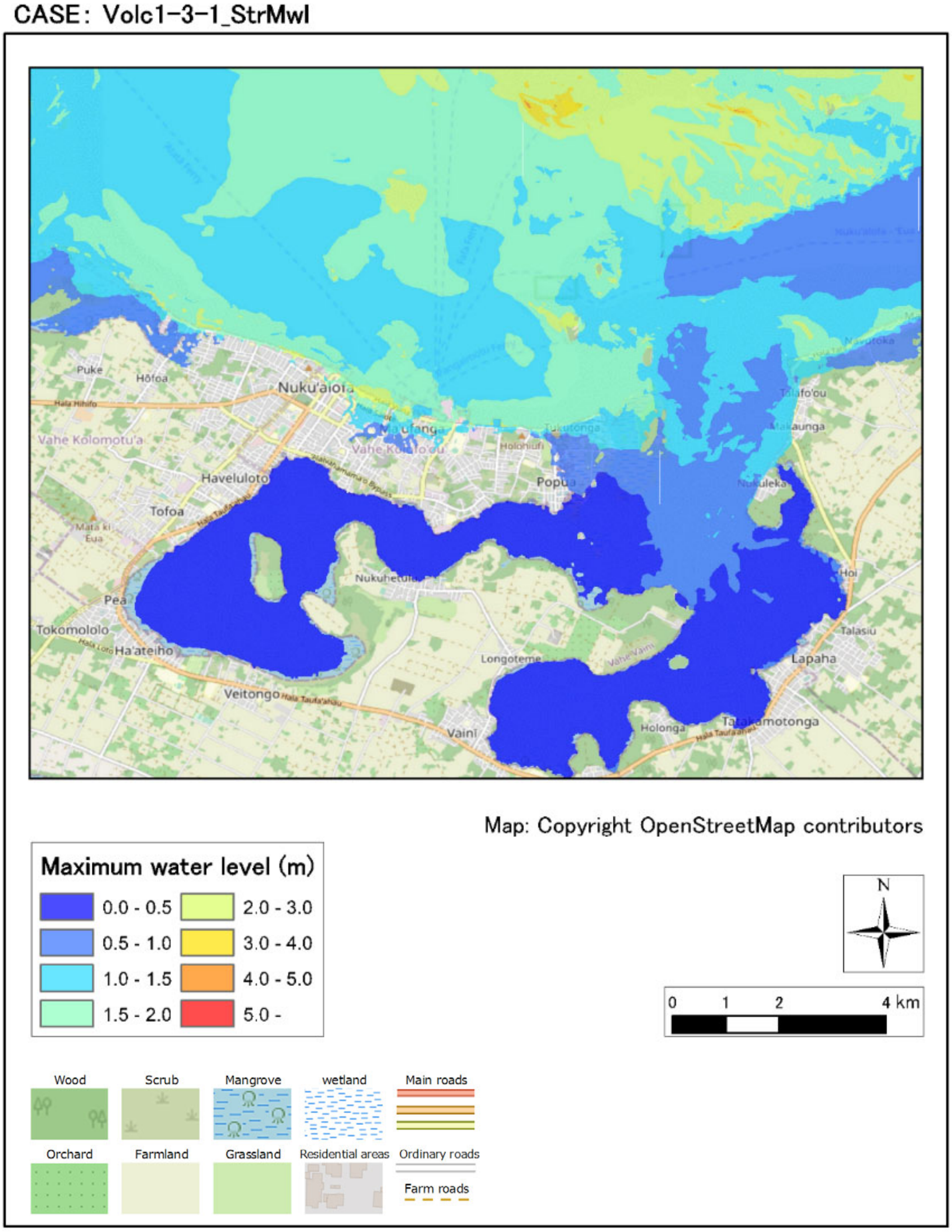
Figure 2.6.42 Max Water Level Distribution (Unamed4, H=30m)

CASE : Volc0-3-1_StrMwl



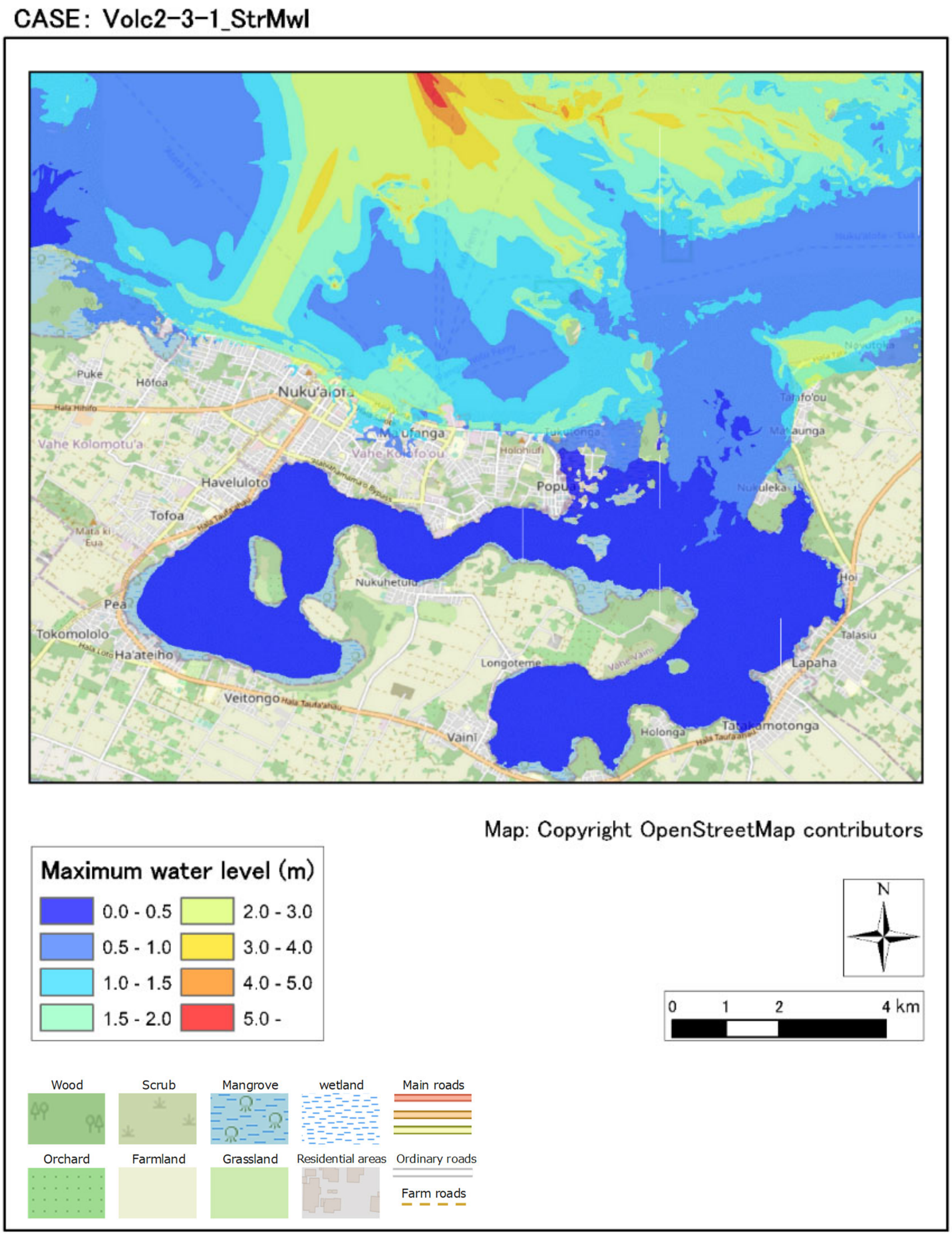
Source: JICA Study Team

Figure 2.6.43 Max Water Level Distribution (Hunga Tonga-Hunga Ha'pai, H=90m)



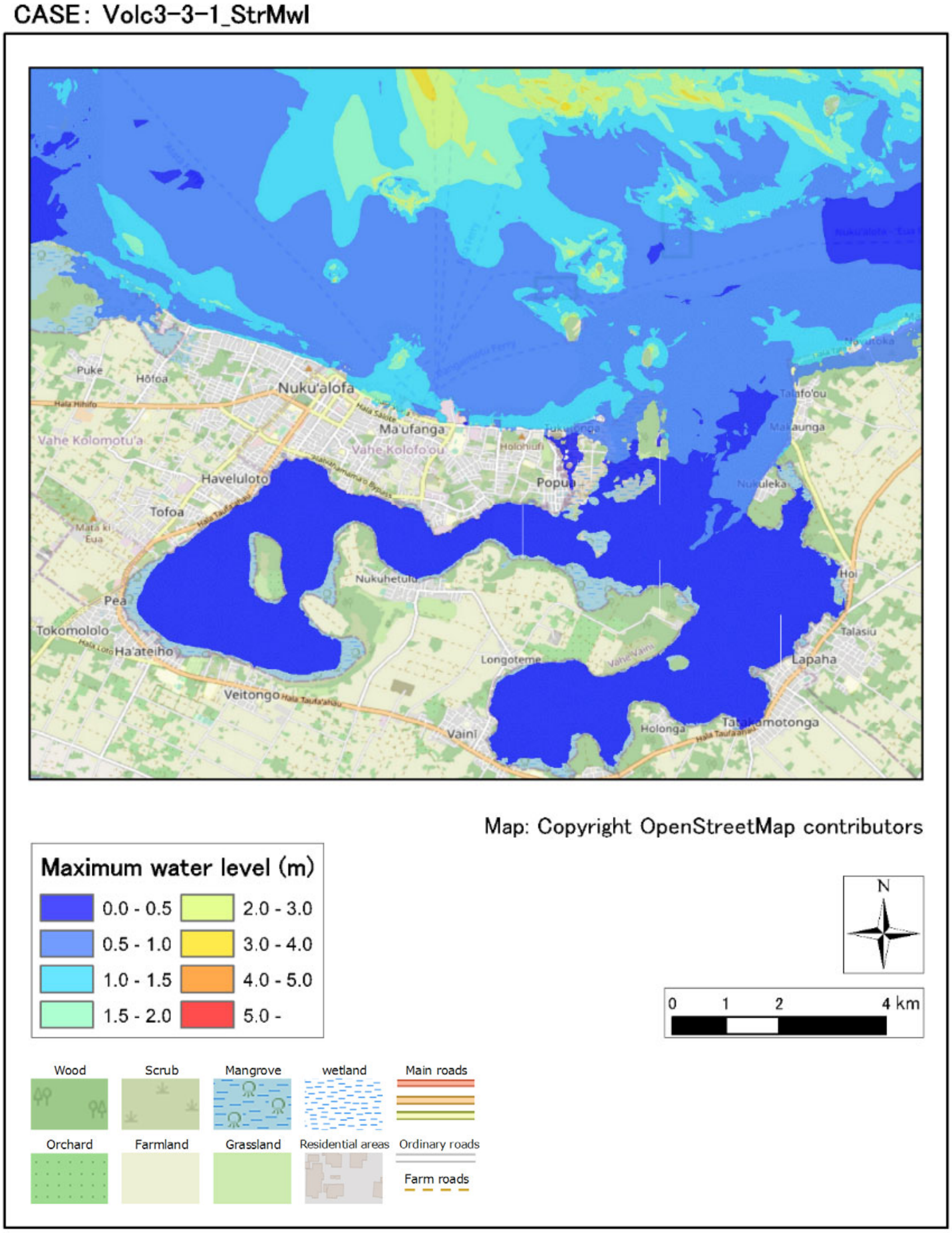
Source: JICA Study Team

Figure 2.6.44 Max Water Level Distribution (Unnamed1, H=90m)



Source: JICA Study Team

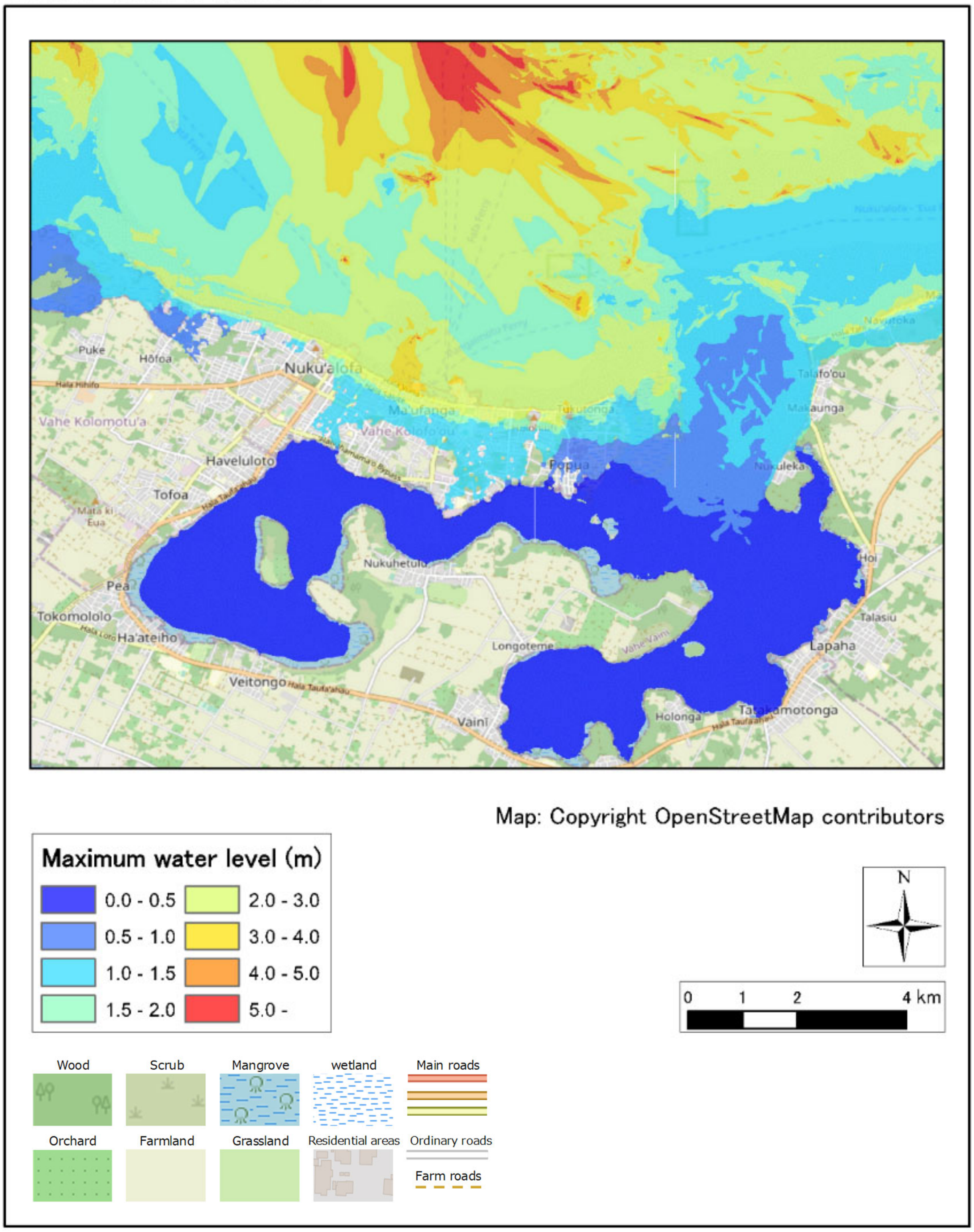
Figure 2.6.45 Max Water Level Distribution (HomeReef, H=90m)



Source: JICA Study Team

Figure 2.6.46 Max Water Level Distribution (Lateiki, H=90m)

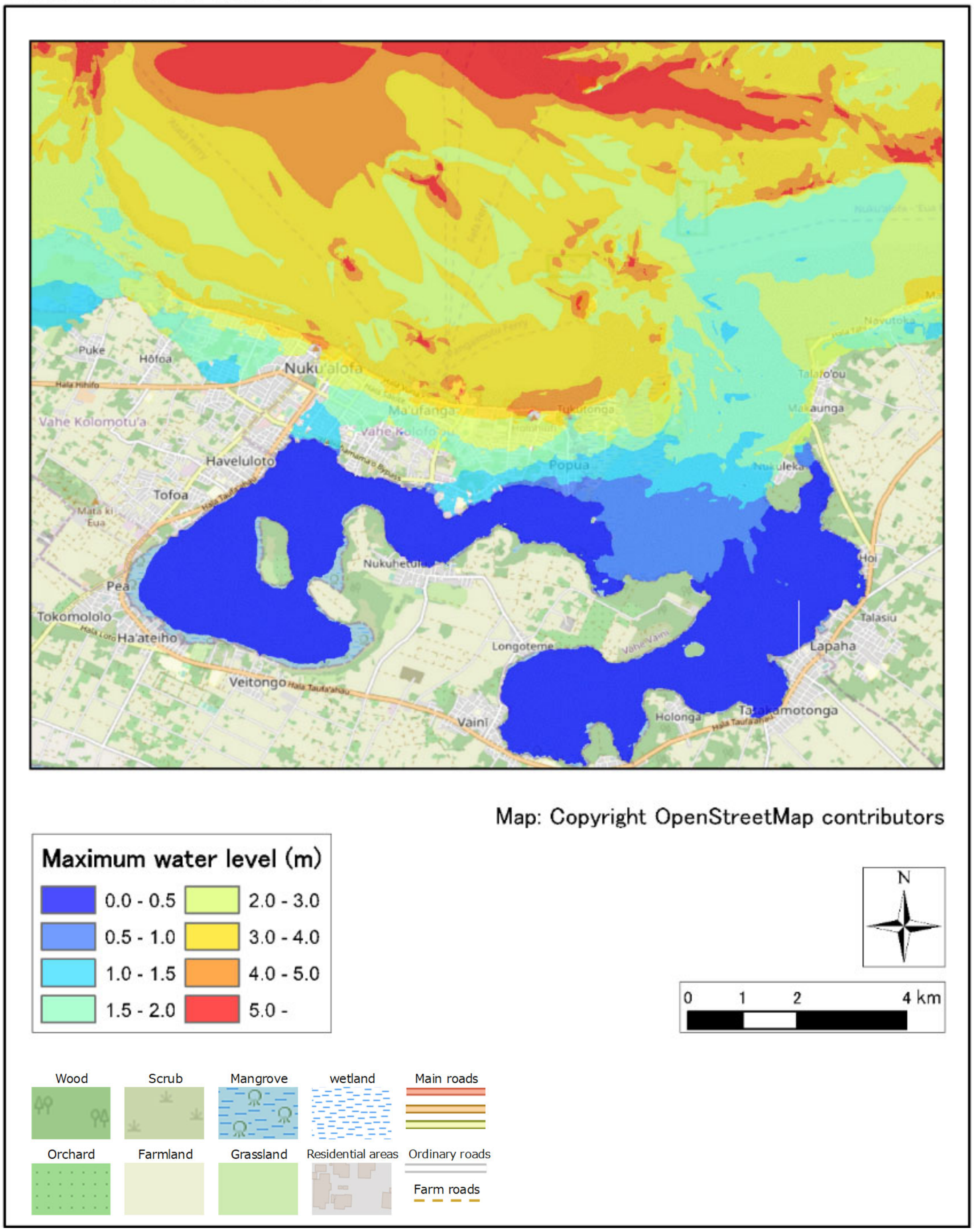
CASE：Volc4-3-1_StrMwl



Source: JICA Study Team

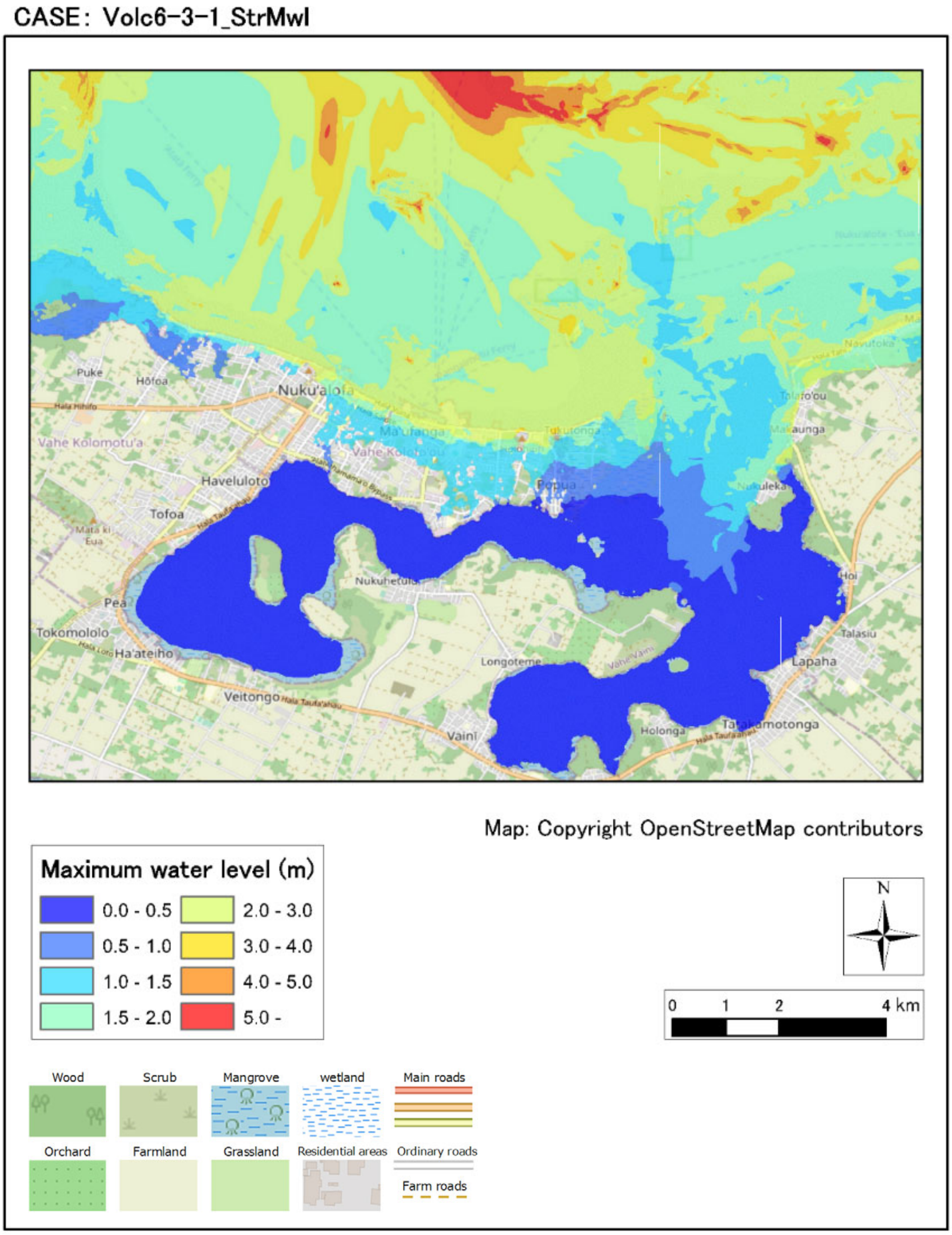
Figure 2.6.47 Max Water Level Distribution (Fonuafo'ou, H=90m)

CASE：Volc5-3-1_StrMwl



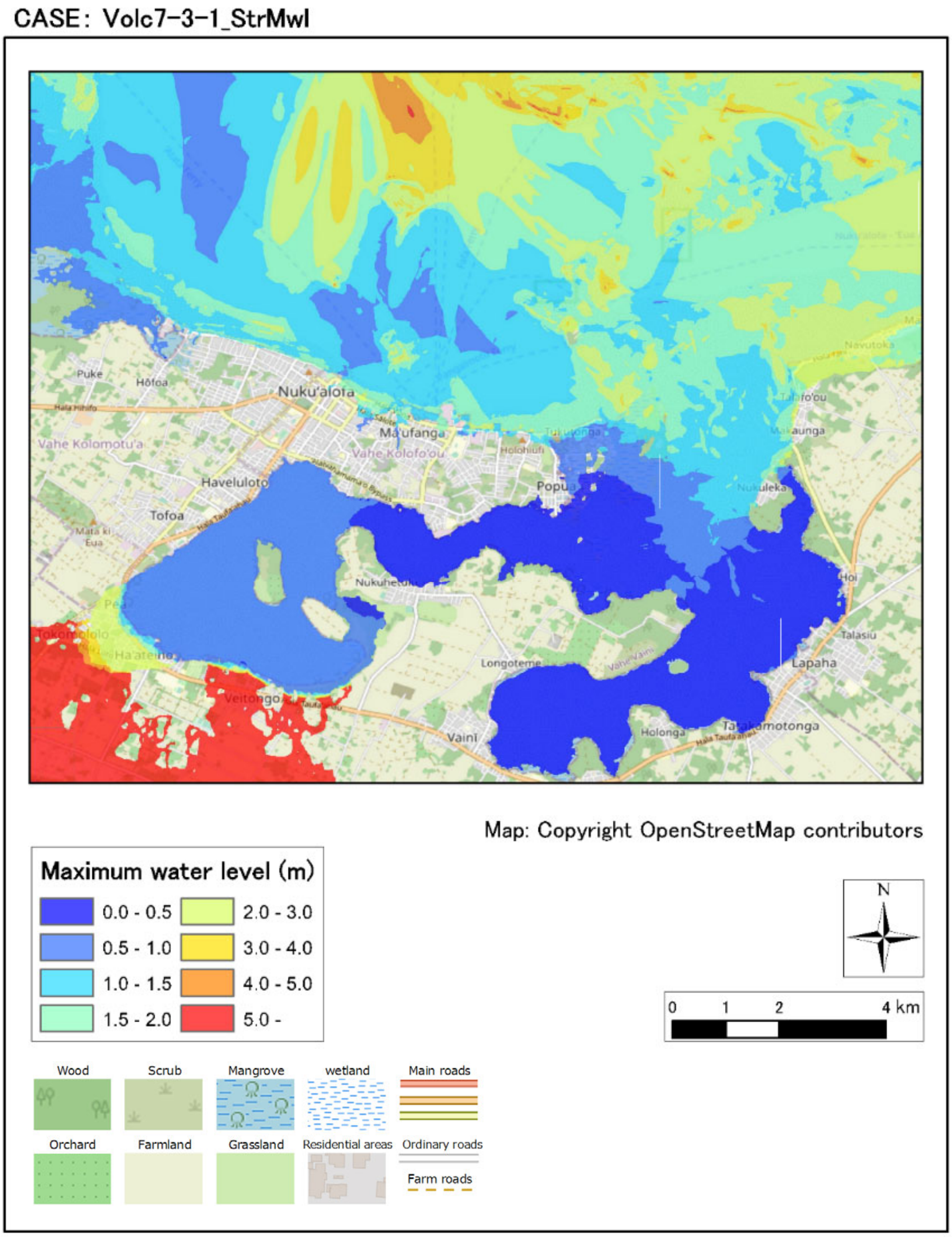
Source: JICA Study Team

Figure 2.6.48 Max Water Level Distribution (Unamed2, H=90m)



Source: JICA Study Team

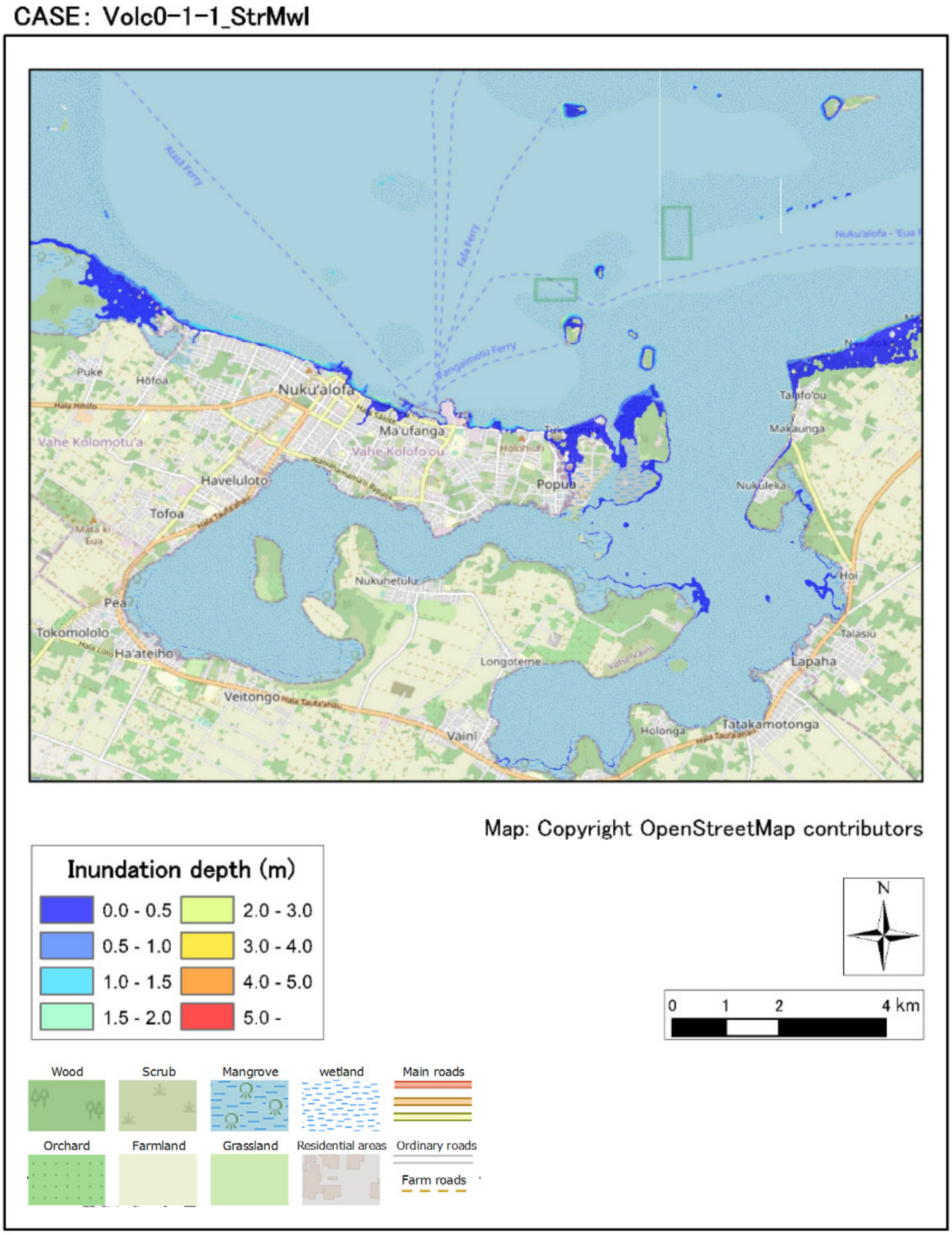
Figure 2.6.49 Max Water Level Distribution (Unamed3, H=90m)



Source: JICA Study Team

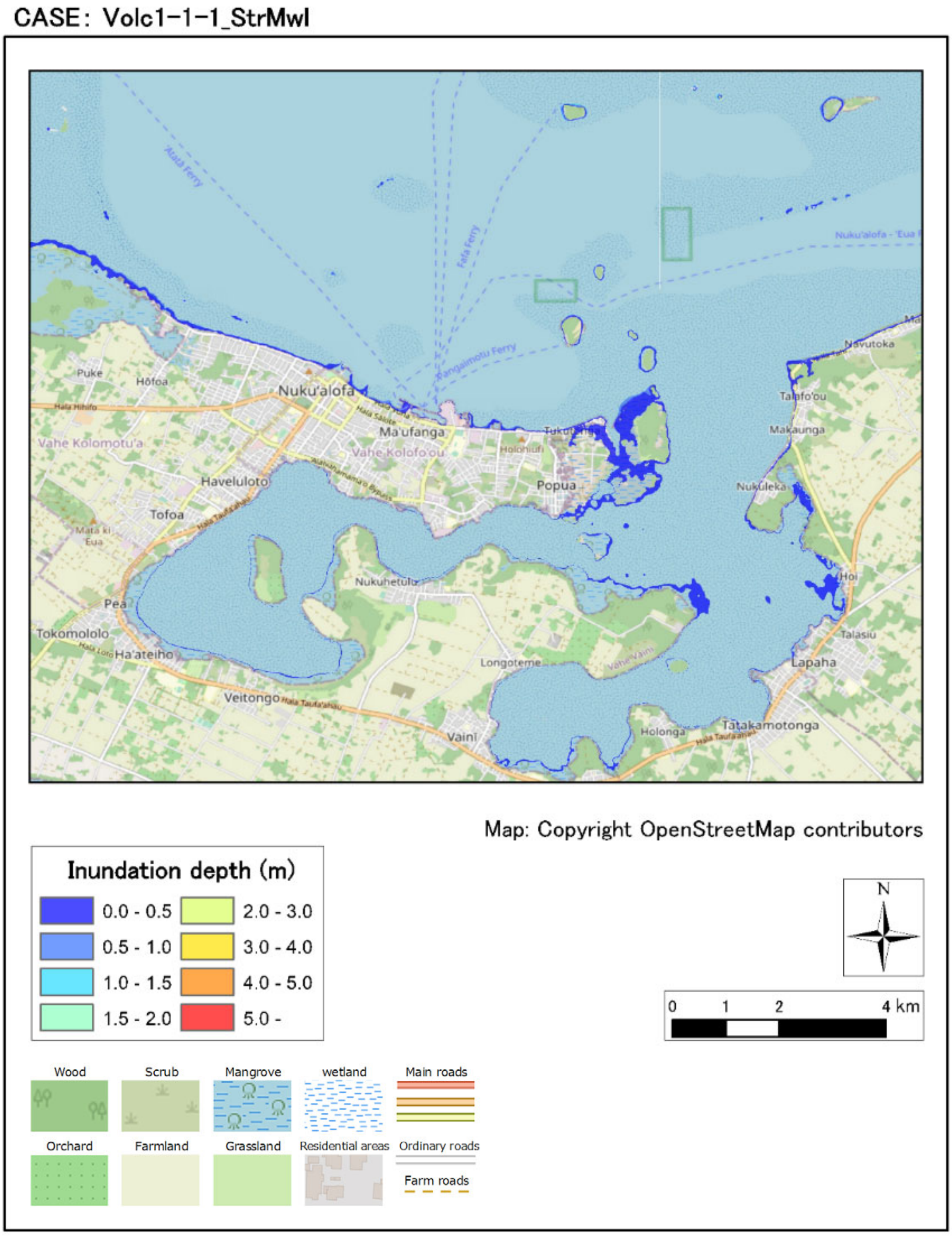
Figure 2.6.50 Max Water Level Distribution (Unamed4, H=90m)

2) Max inundation depth distribution (Nukualofa, Tongatapu Island)



Source: JICA Study Team

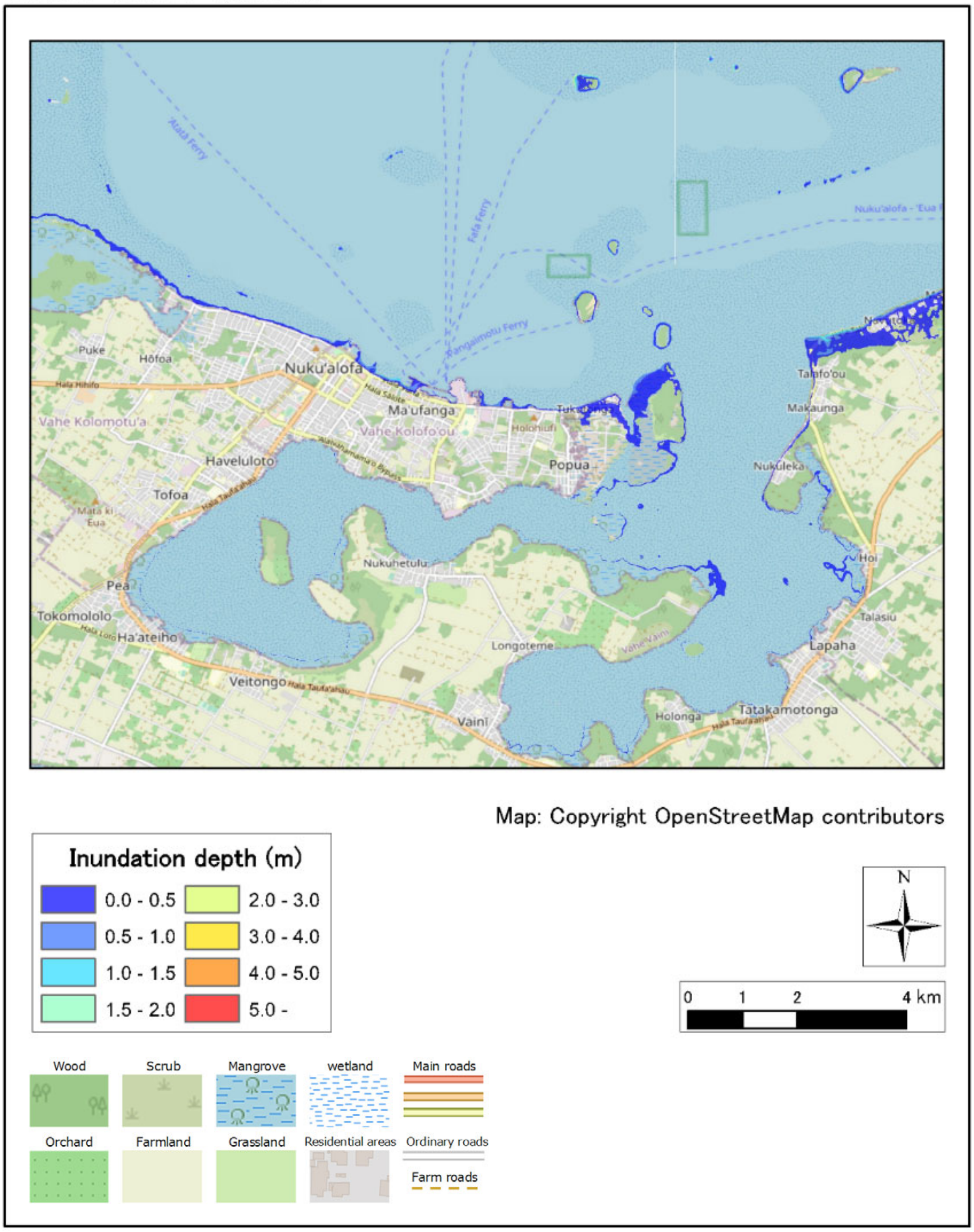
Figure 2.6.51 Max inundation depth distribution (Hunga Tonga-Hunga Ha'pai, H=30m)



Source: JICA Study Team

Figure 2.6.52 Max inundation depth distribution (Unnamed1, H=30m)

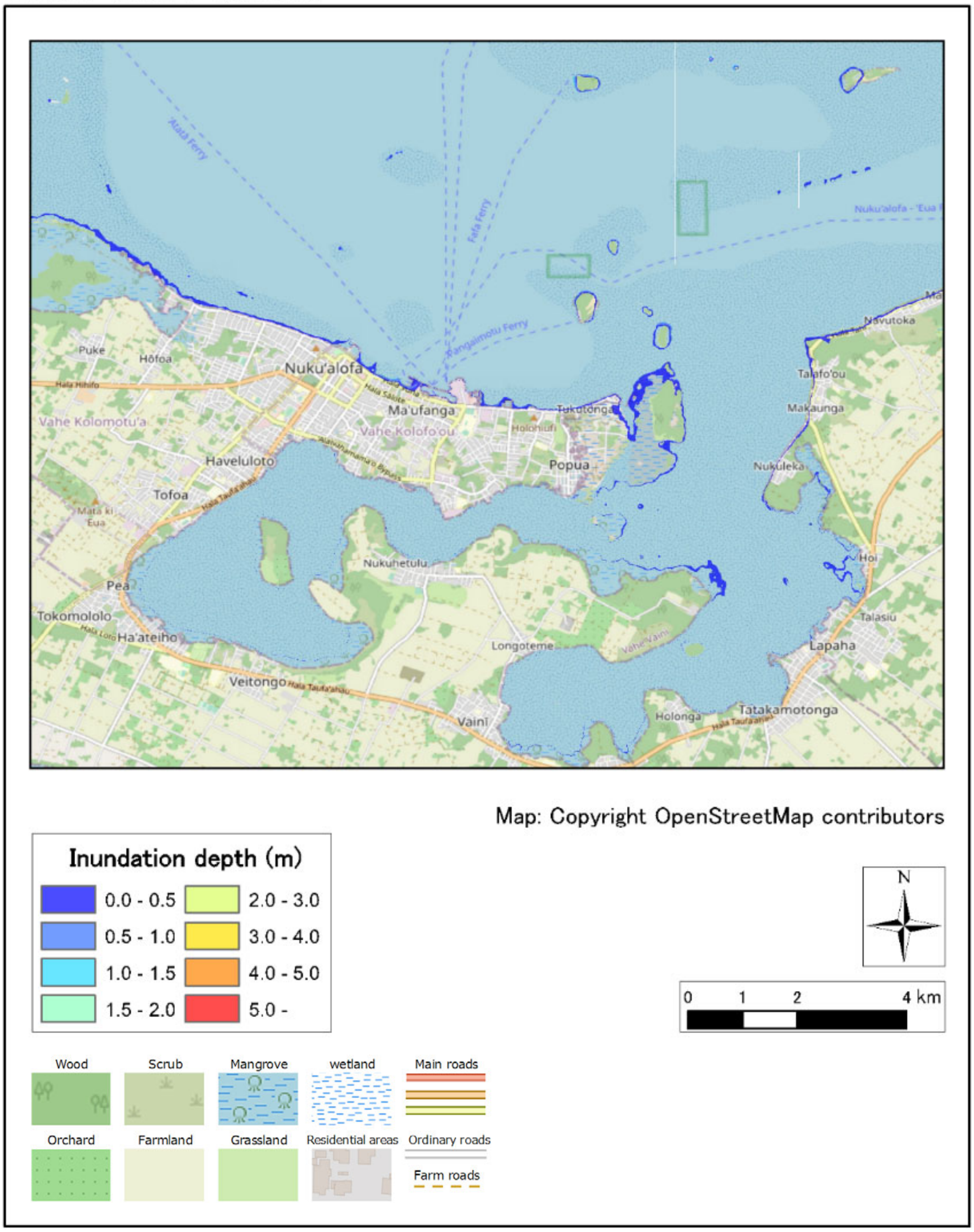
CASE: Volc2-1-1_StrMwl



Source: JICA Study Team

Figure 2.6.53 Max inundation depth distribution (HomeReef, H=30m)

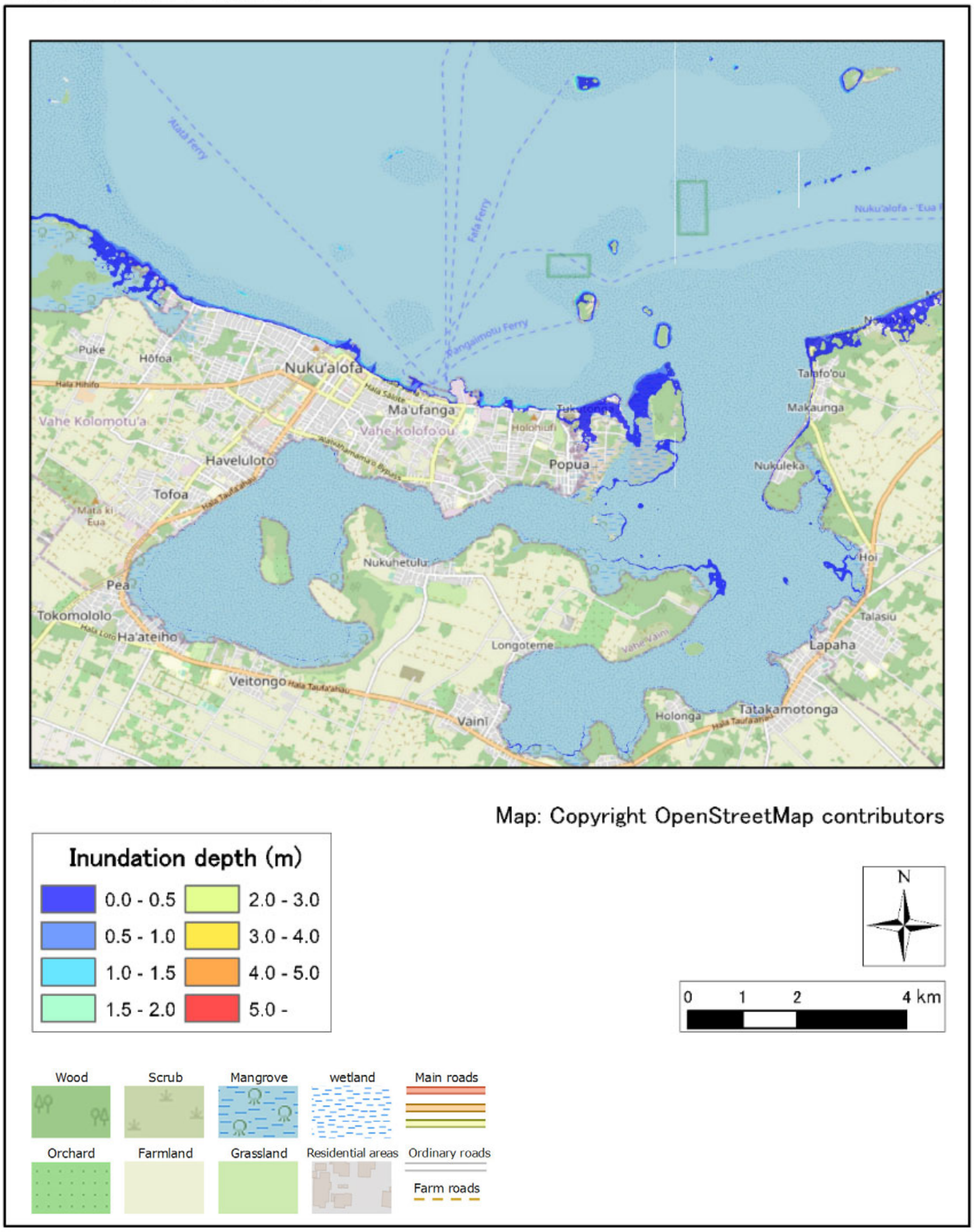
CASE: Volc3-1-1_StrMwl



Source: JICA Study Team

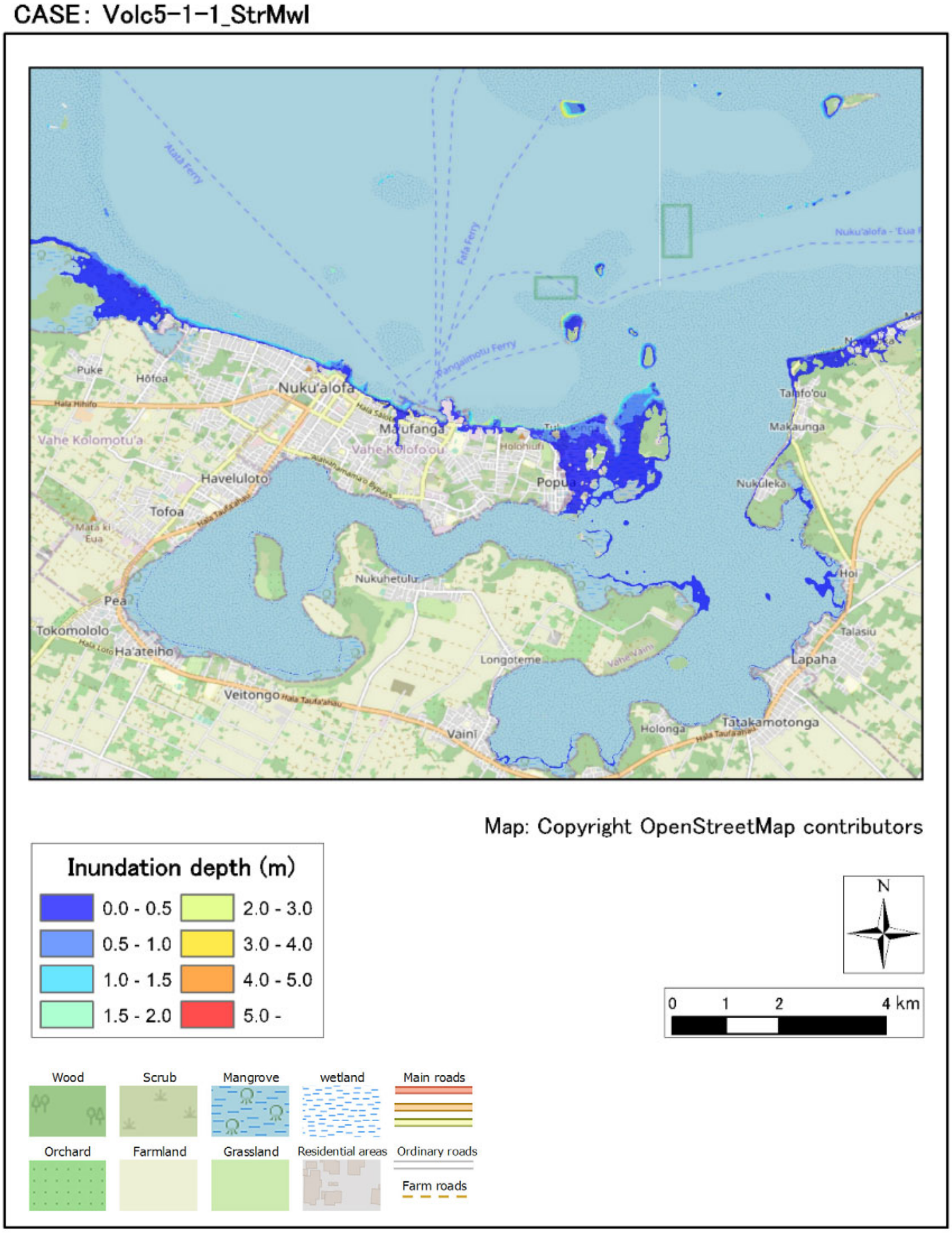
Figure 2.6.54 Max inundation depth distribution (Lateiki, H=30m)

CASE: Volc4-1-1_StrMwl



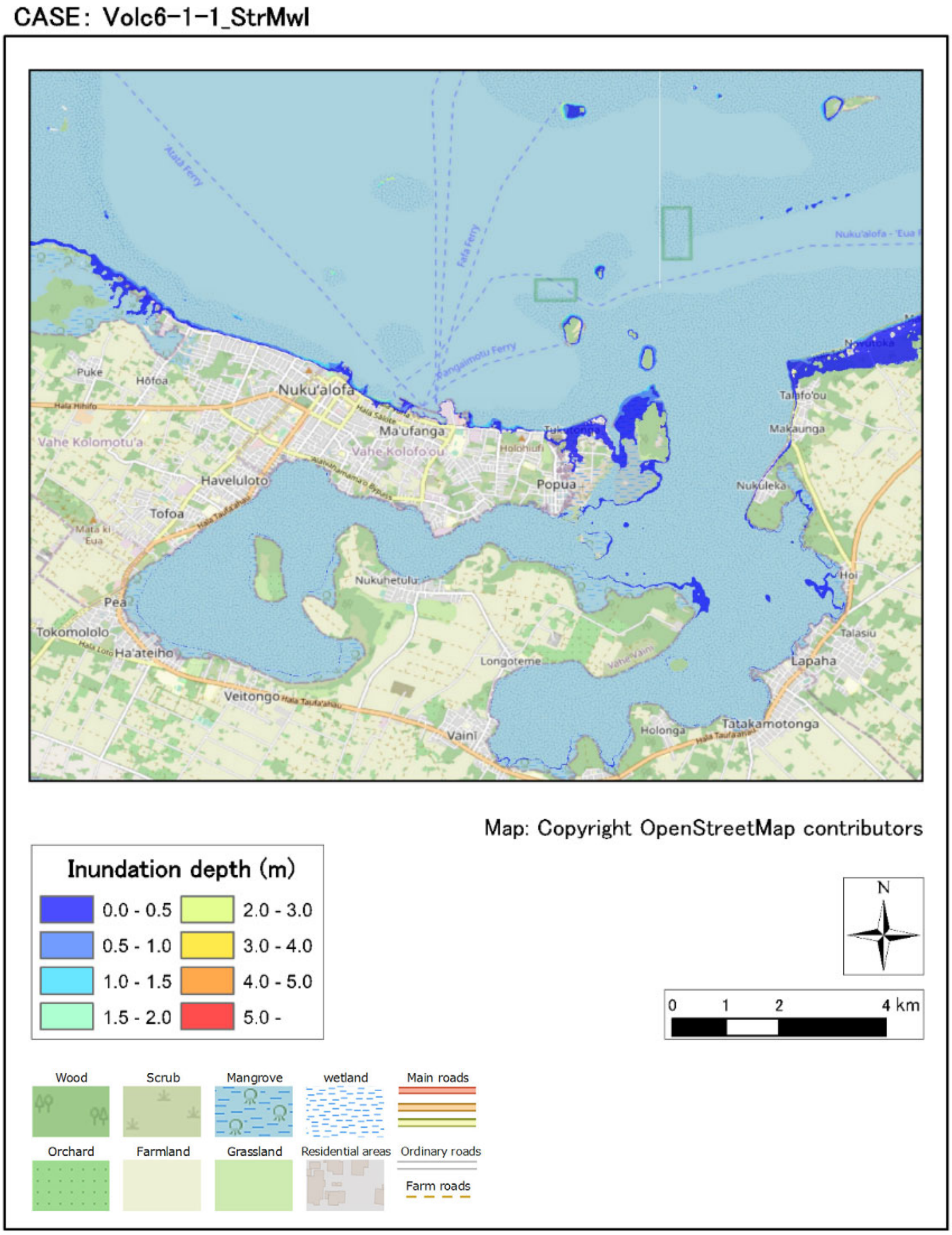
Source: JICA Study Team

Figure 2.6.55 Max inundation depth distribution (Fonuafo'ou H=30m)



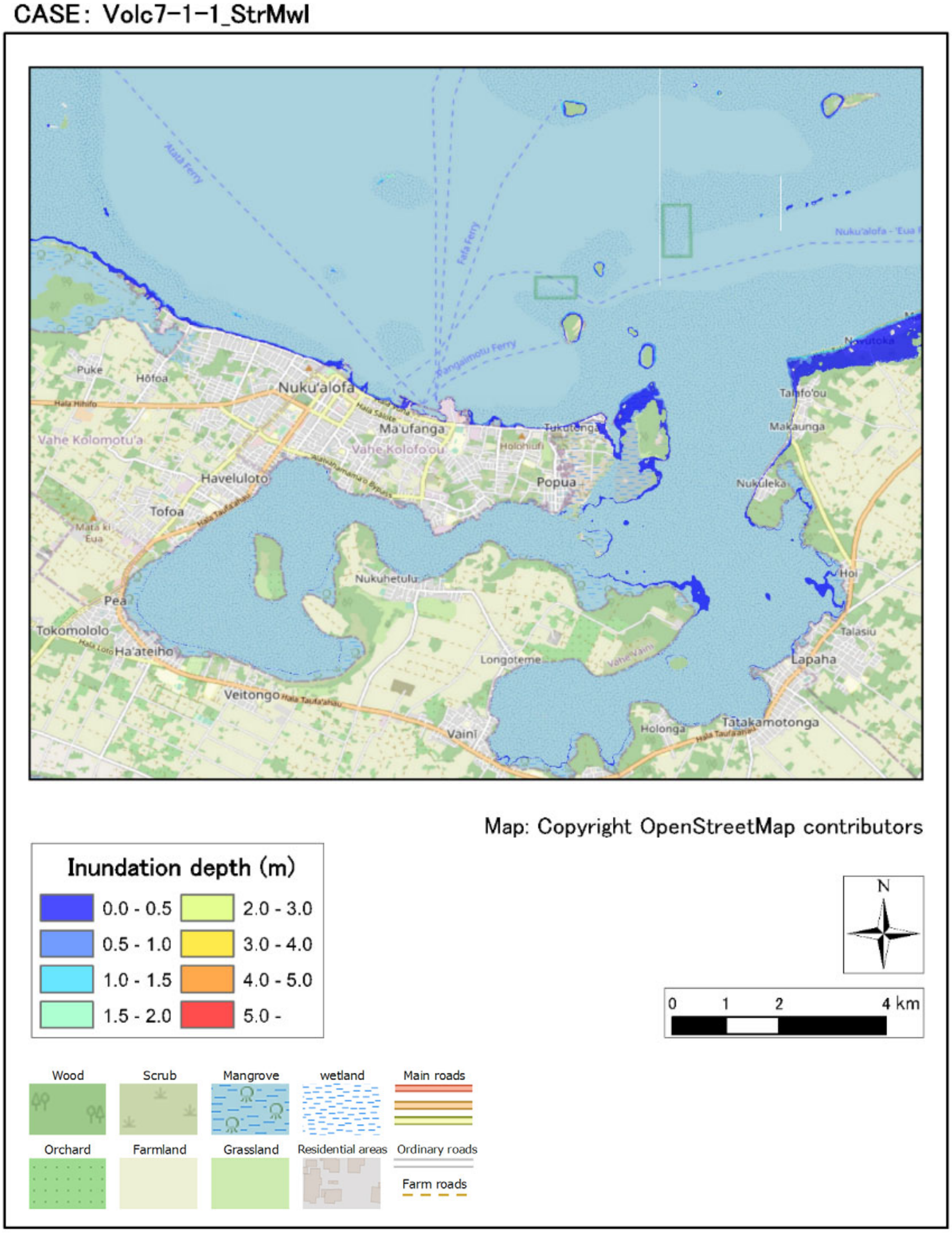
Source: JICA Study Team

Figure 2.6.56 Max inundation depth distribution (Unamed2, H=30m)



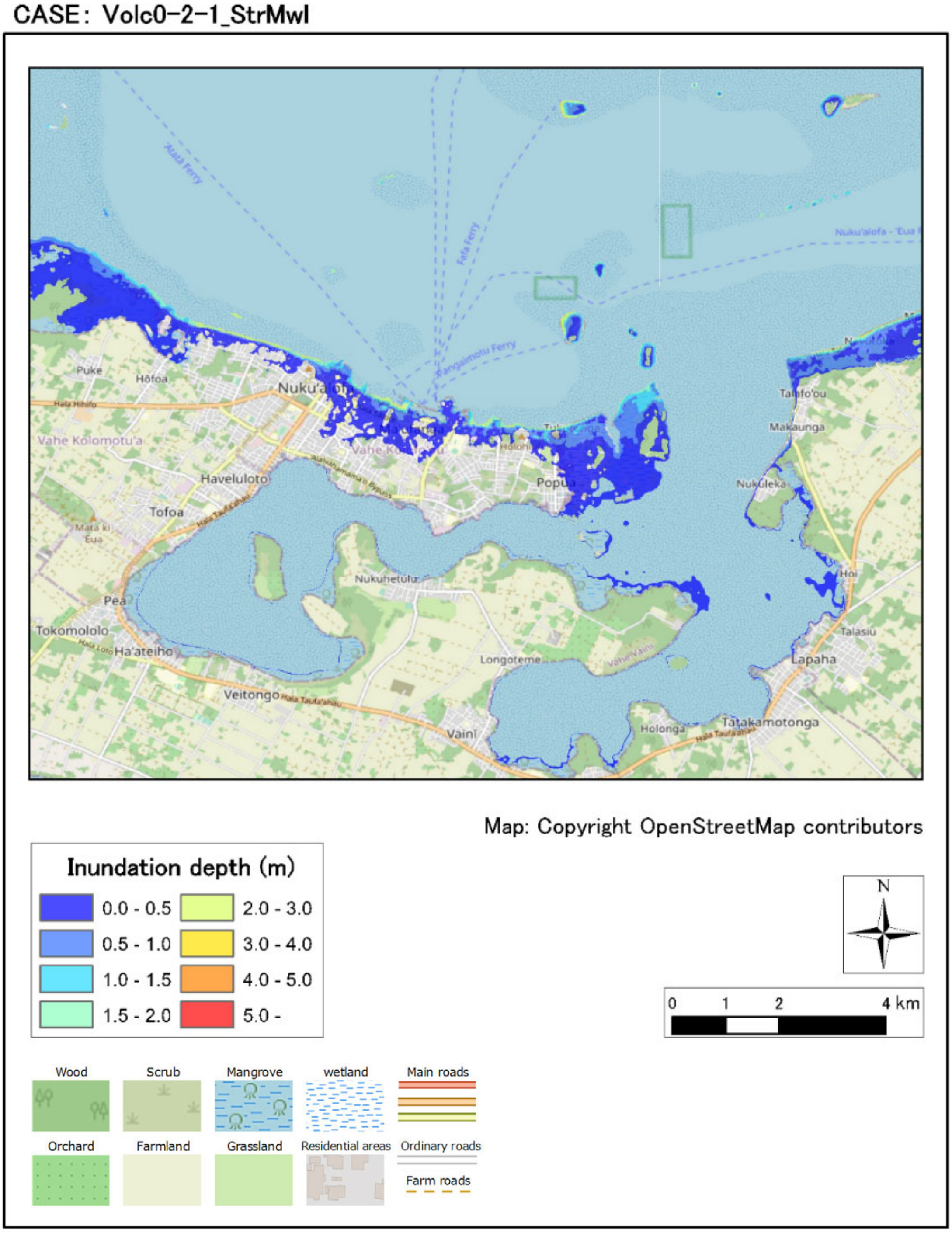
Source: JICA Study Team

Figure 2.6.57 Max inundation depth distribution (Unamed3, H=30m)



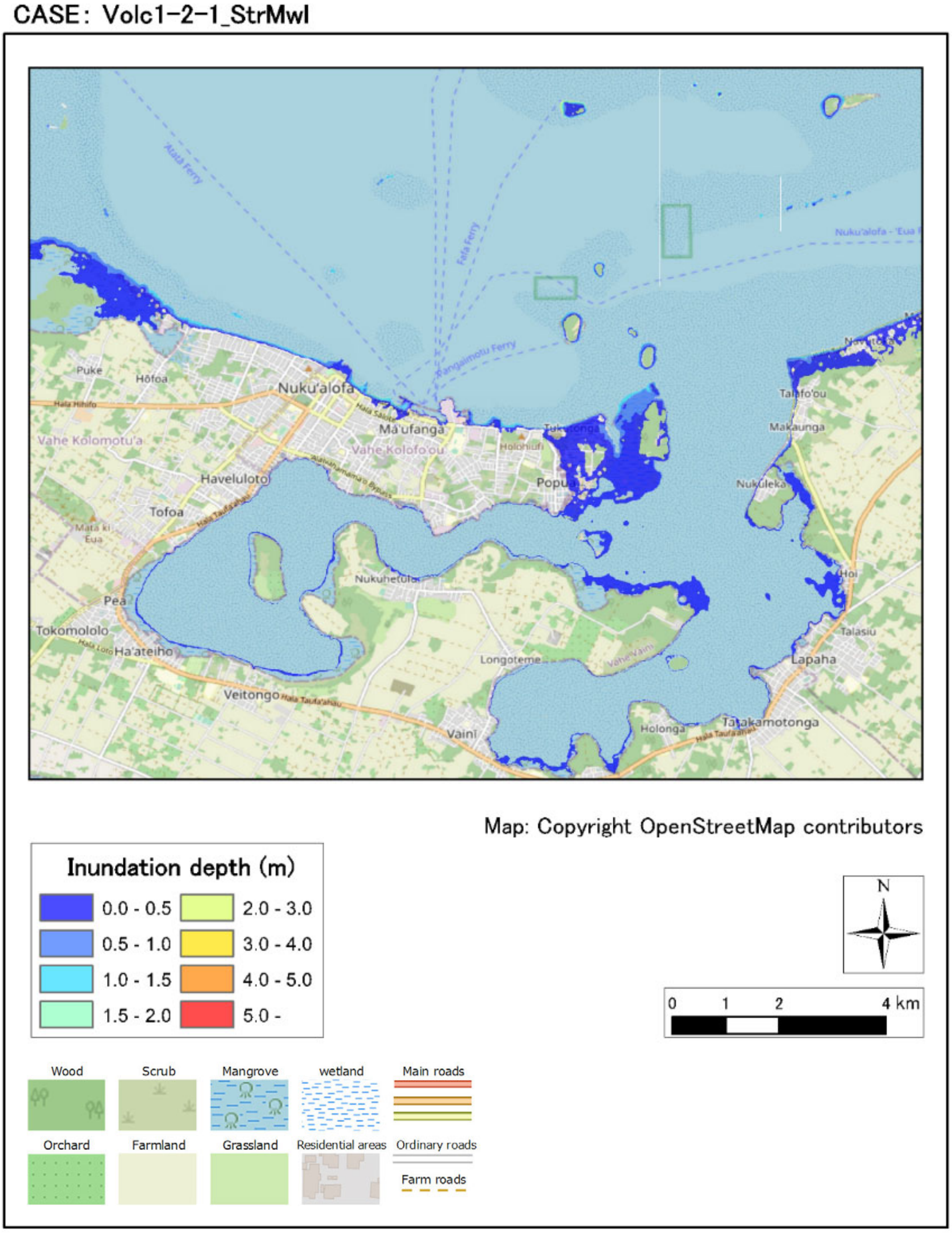
Source: JICA Study Team

Figure 2.6.58 Max inundation depth distribution (Unamed4, H=30m)



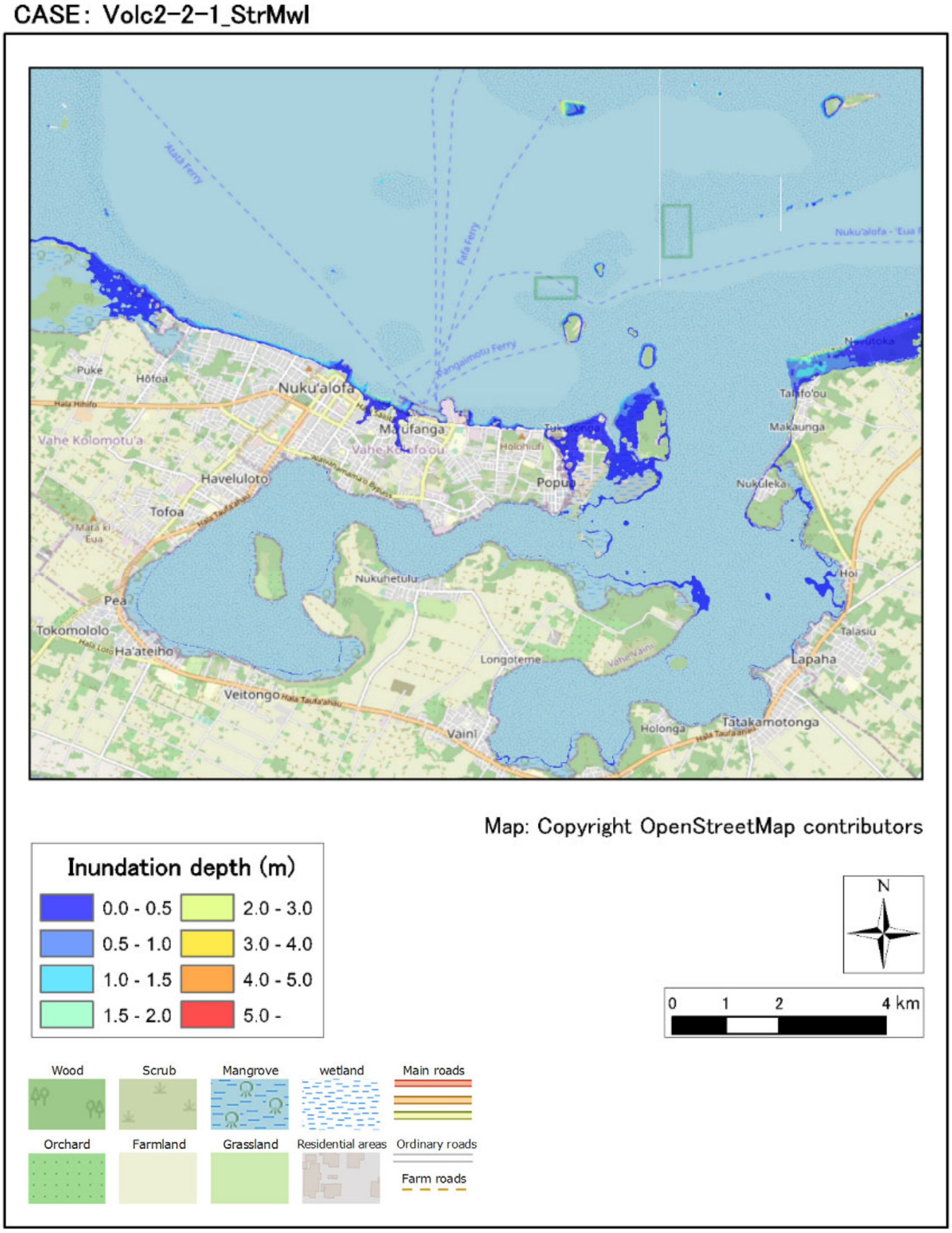
Source: JICA Study Team

Figure 2.6.59 Max inundation depth distribution (Hunga Tonga-Hunga Ha'pai, H=60m)



Source: JICA Study Team

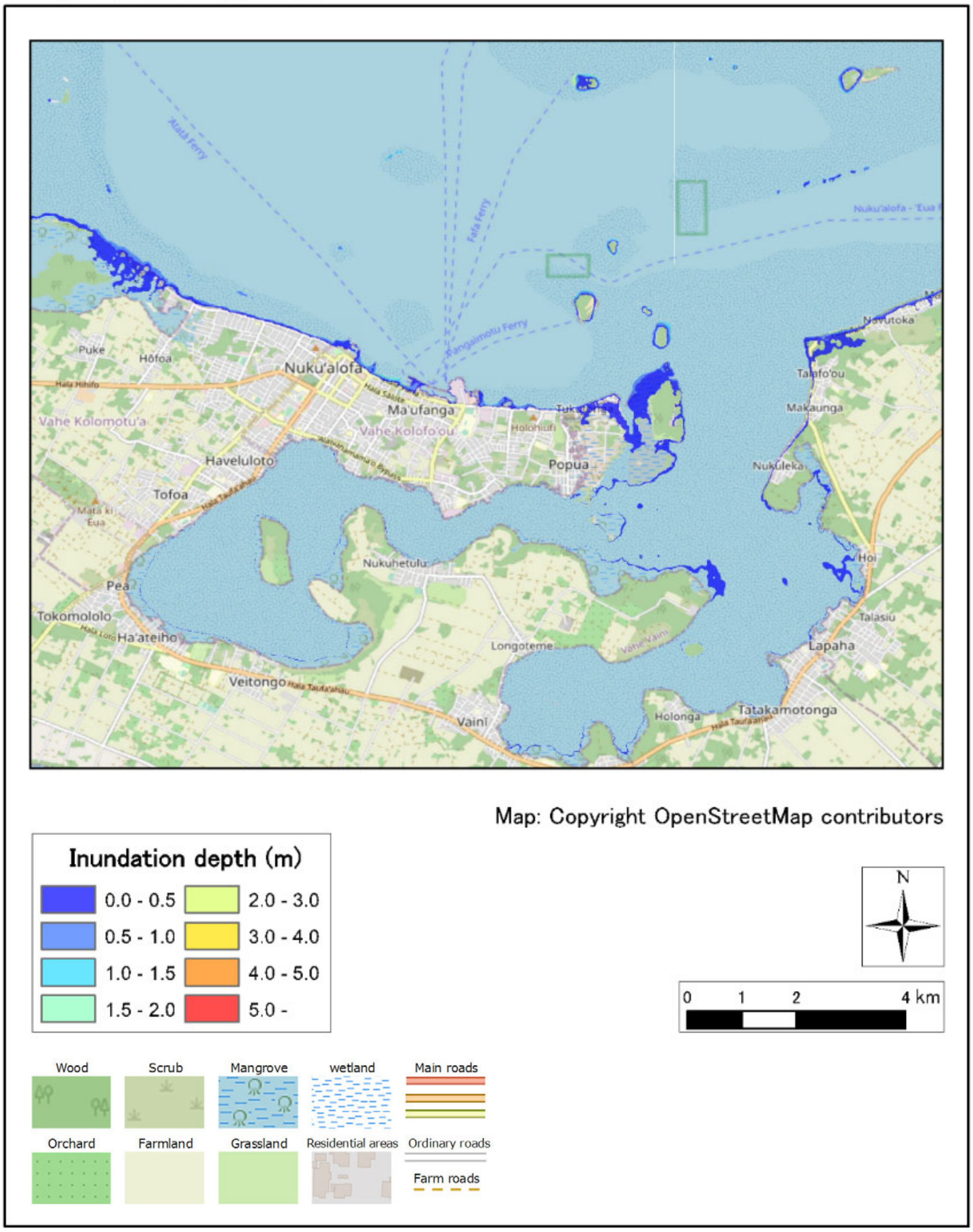
Figure 2.6.60 Max inundation depth distribution (Unnamed1, H=60m)



Source: JICA Study Team

Figure 2.6.61 Max inundation depth distribution (HomeReef, H=60m)

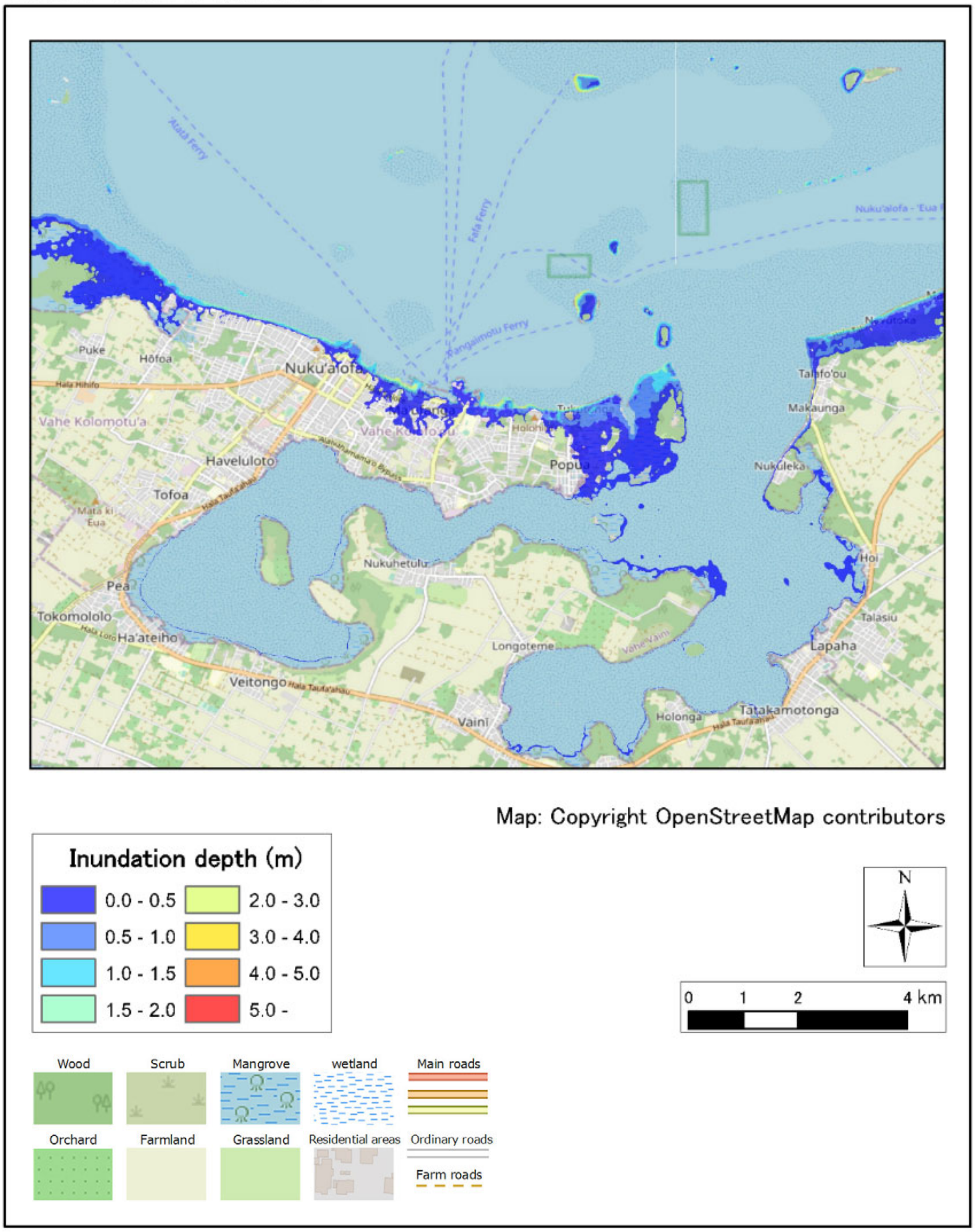
CASE：Volc3-2-1_StrMwl



Source: JICA Study Team

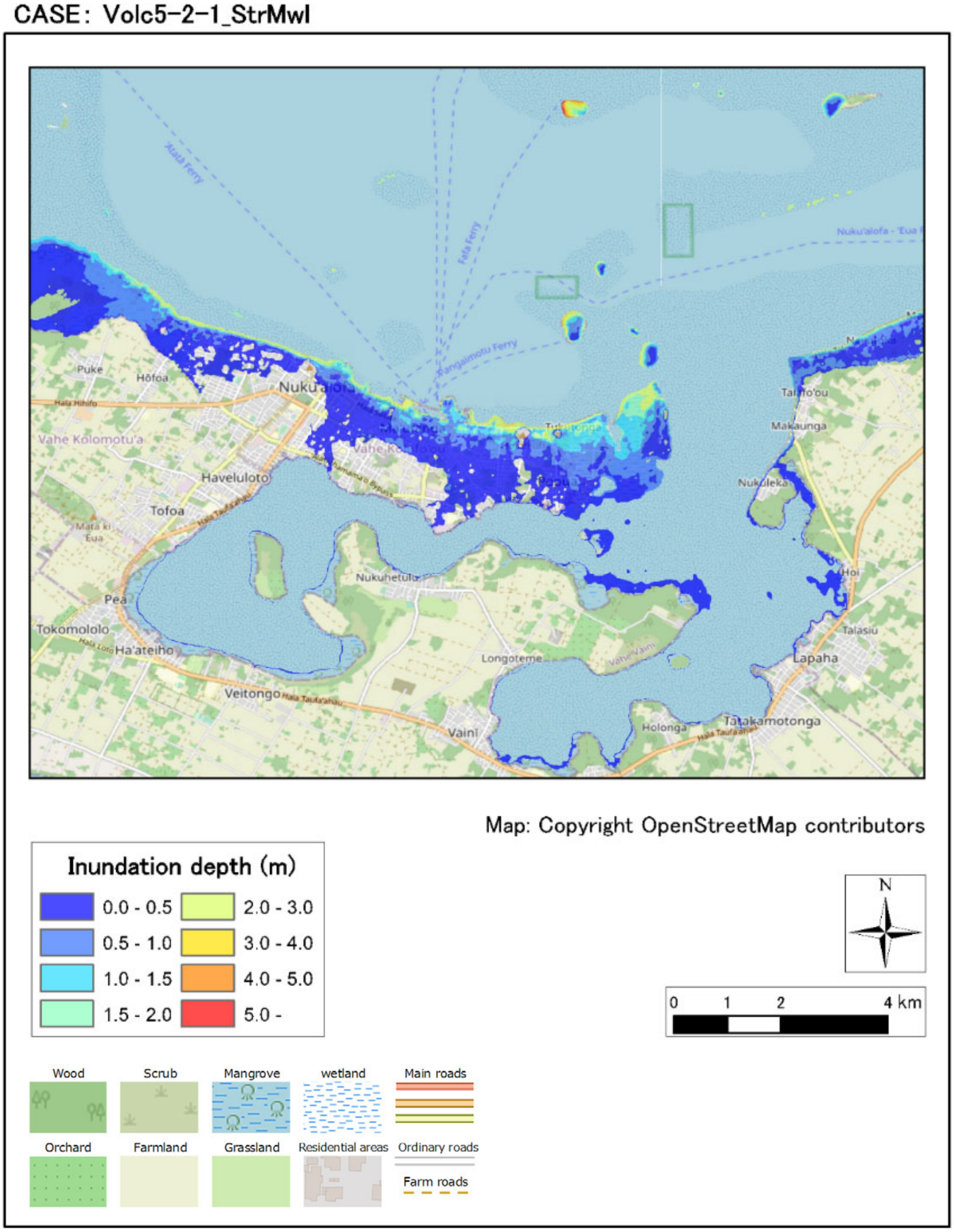
Figure 2.6.62　Max inundation depth distribution (Lateiki, H=60m)

CASE: Volc4-2-1_StrMwl



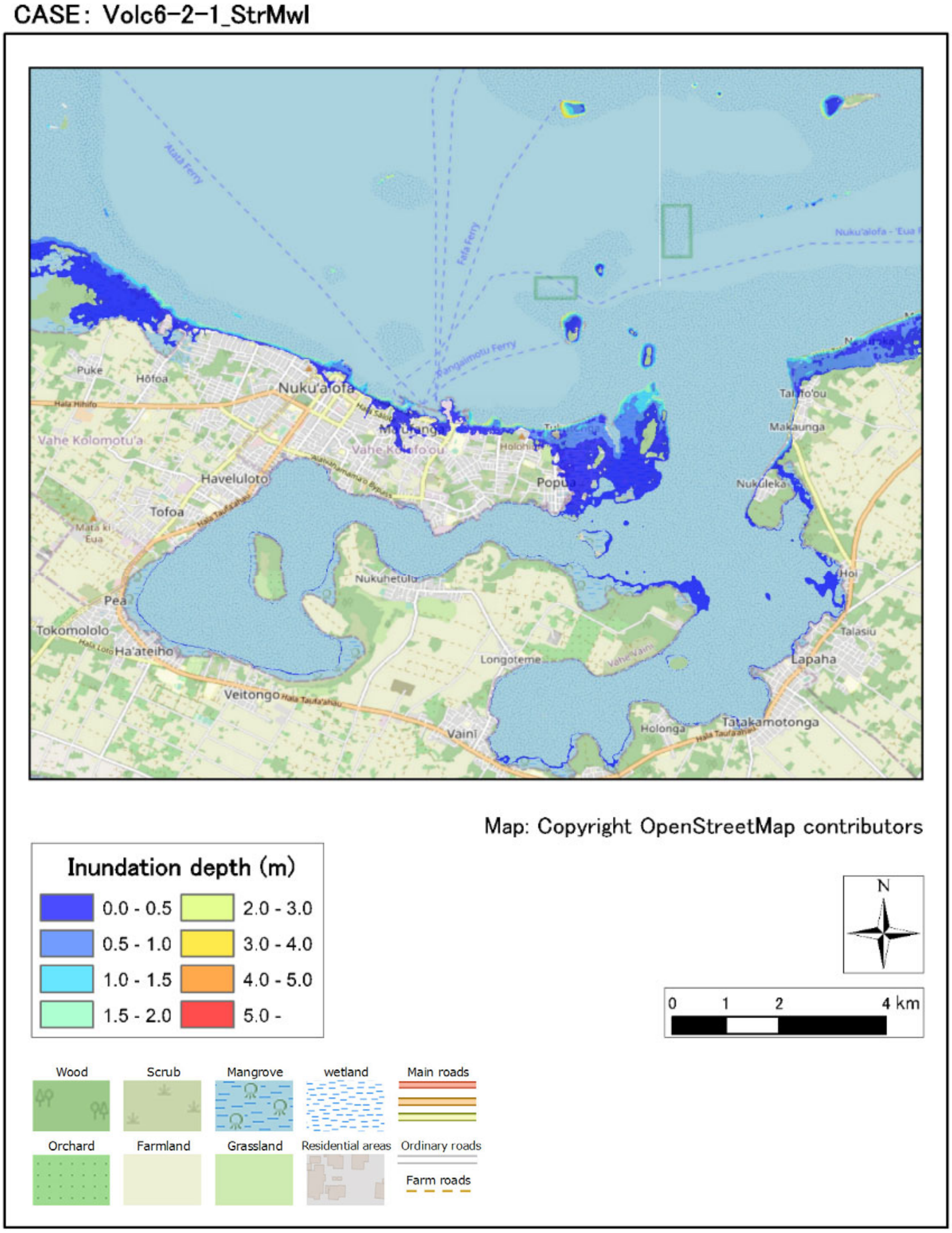
Source: JICA Study Team

Figure 2.6.63 Max inundation depth distribution (Fonuafo'ou, H=60m)



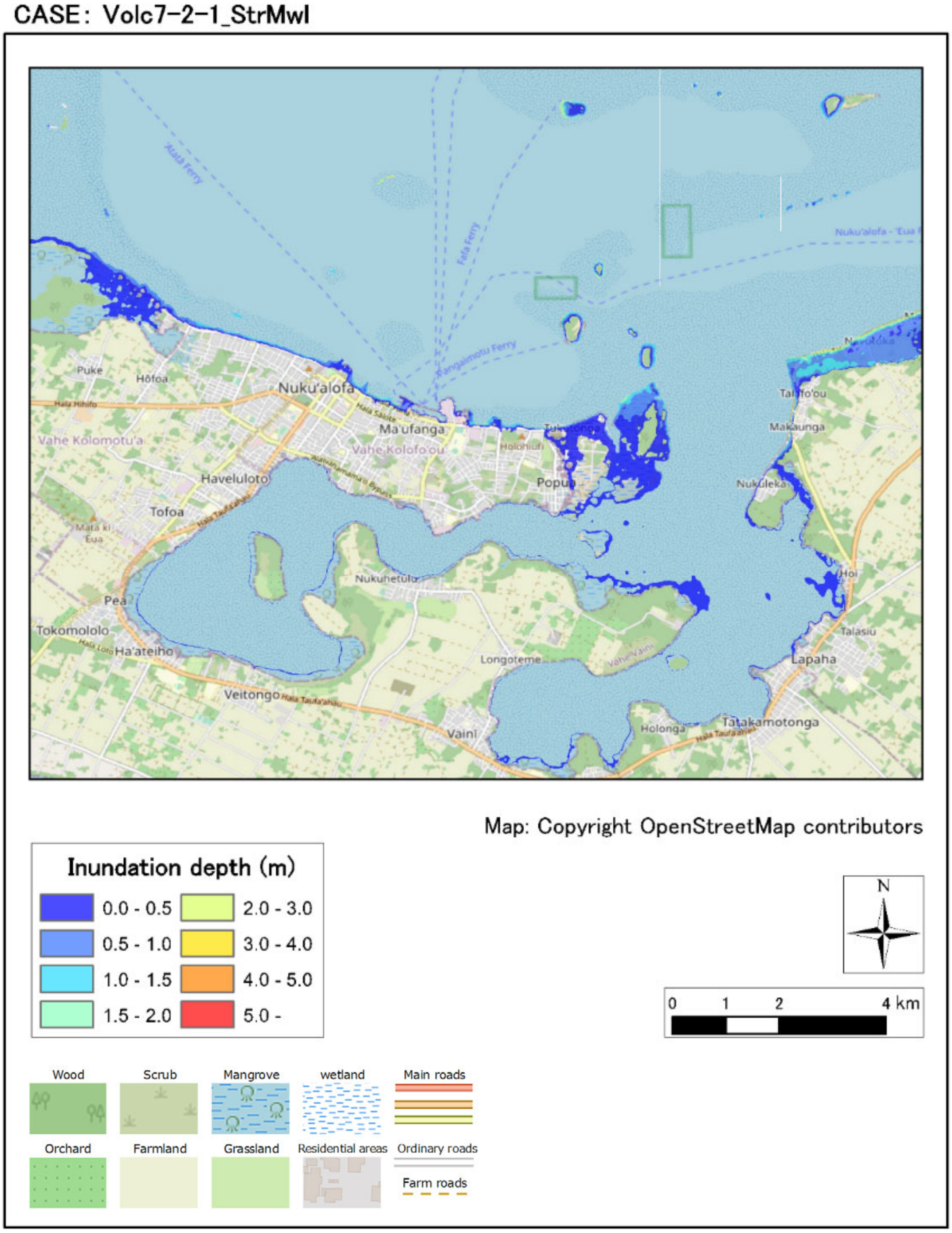
Source: JICA Study Team

Figure 2.6.64 Max inundation depth distribution (Unamed2, H=60m)



Source: JICA Study Team

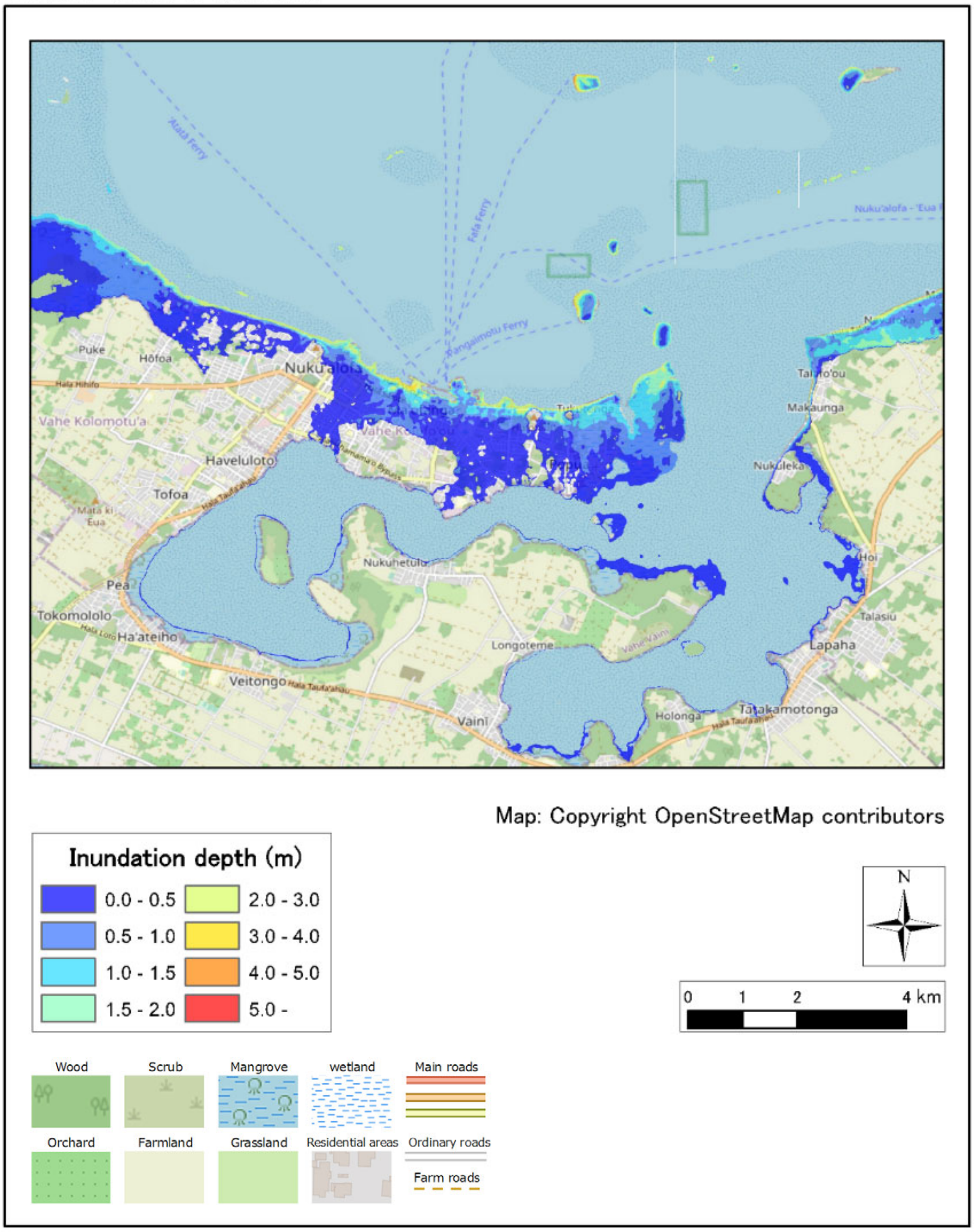
Figure 2.6.65　Max inundation depth distribution (Unamed3, H=60m)



Source: JICA Study Team

Figure 2.6.66 Max inundation depth distribution (Unamed4, H=60m)

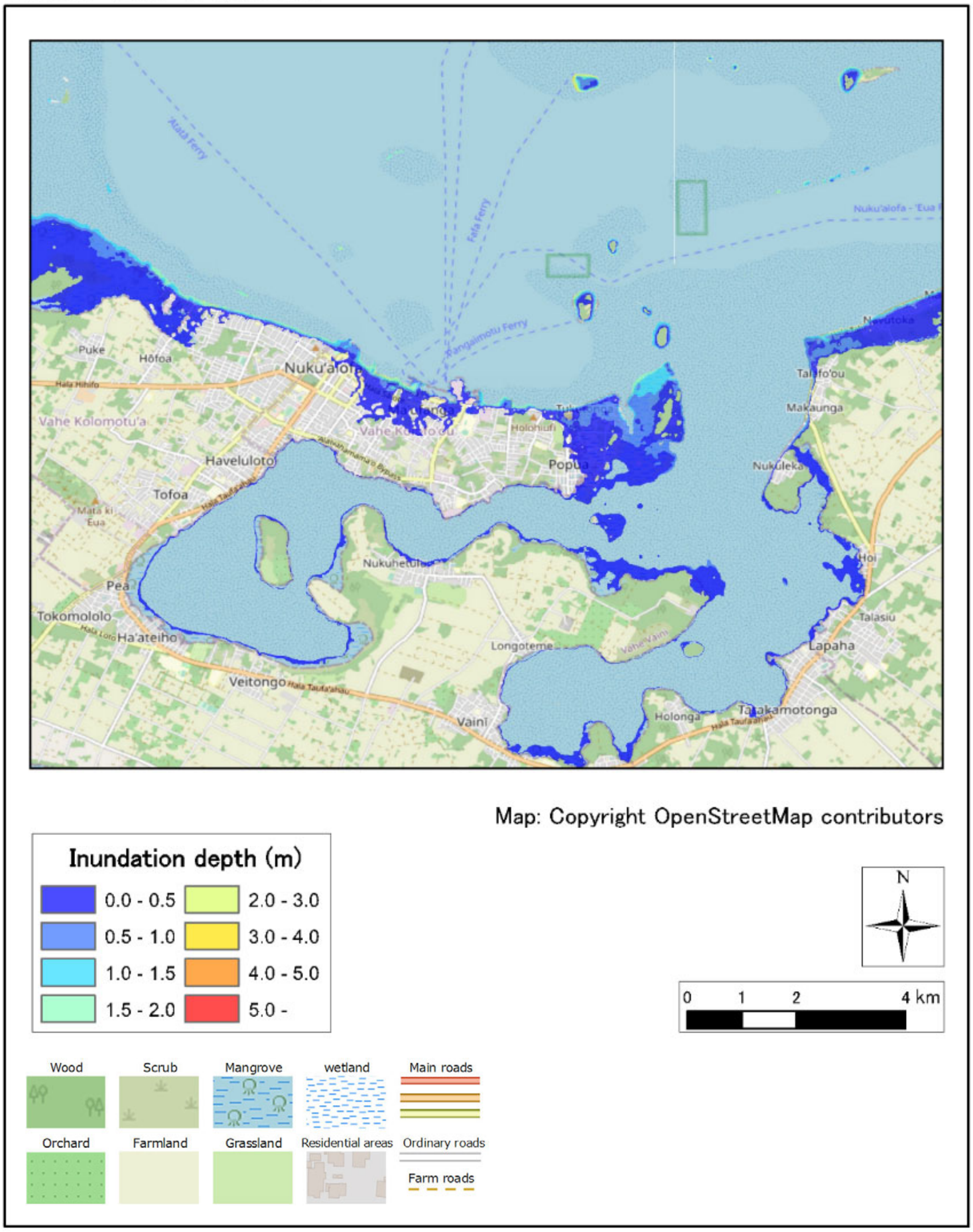
CASE: Volc0-3-1_StrMwl



Source: JICA Study Team

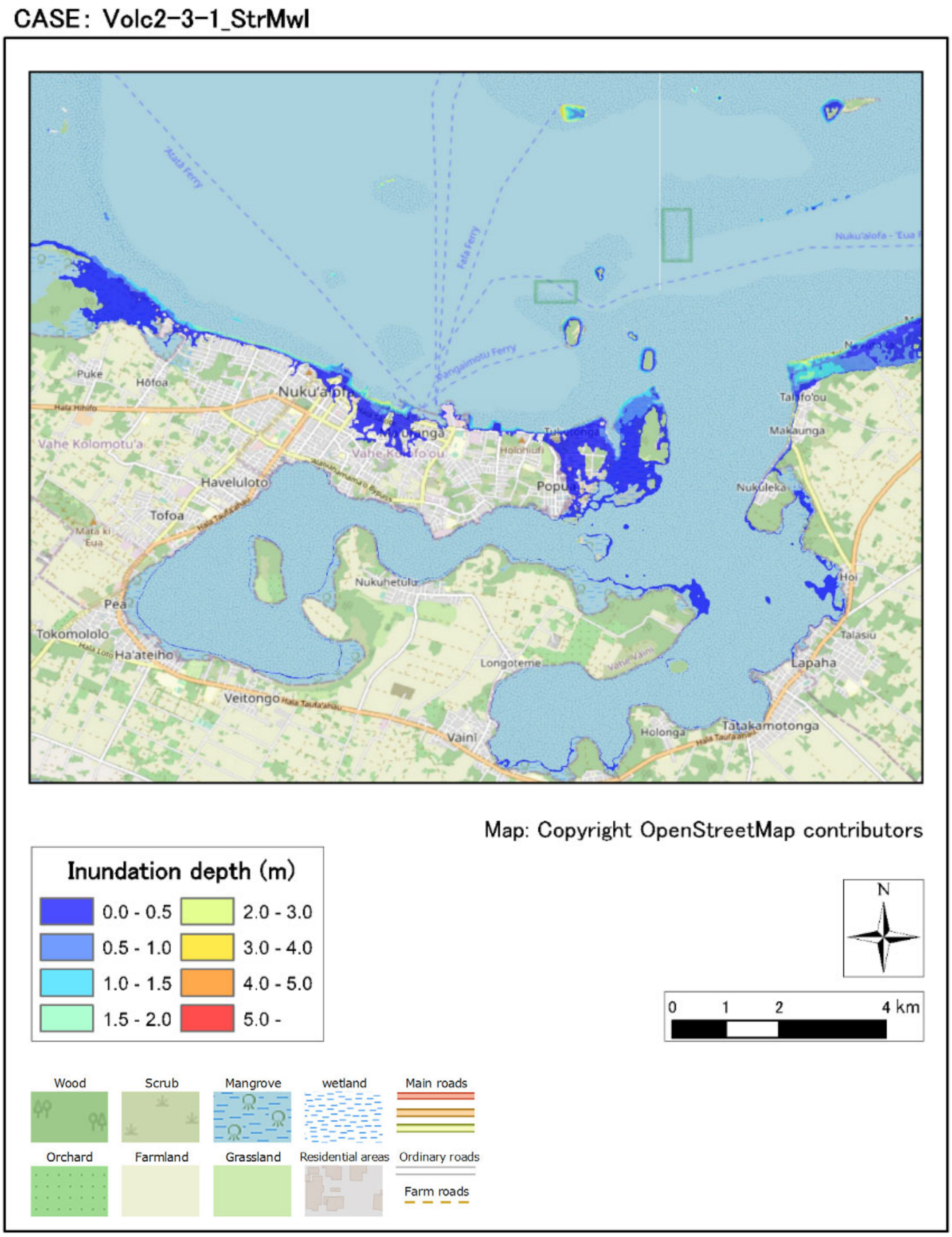
Figure 2.6.67 Max inundation depth distribution (Hunga Tonga-Hunga Ha'pai, H=90m)

CASE: Volc1-3-1_StrMwl



Source: JICA Study Team

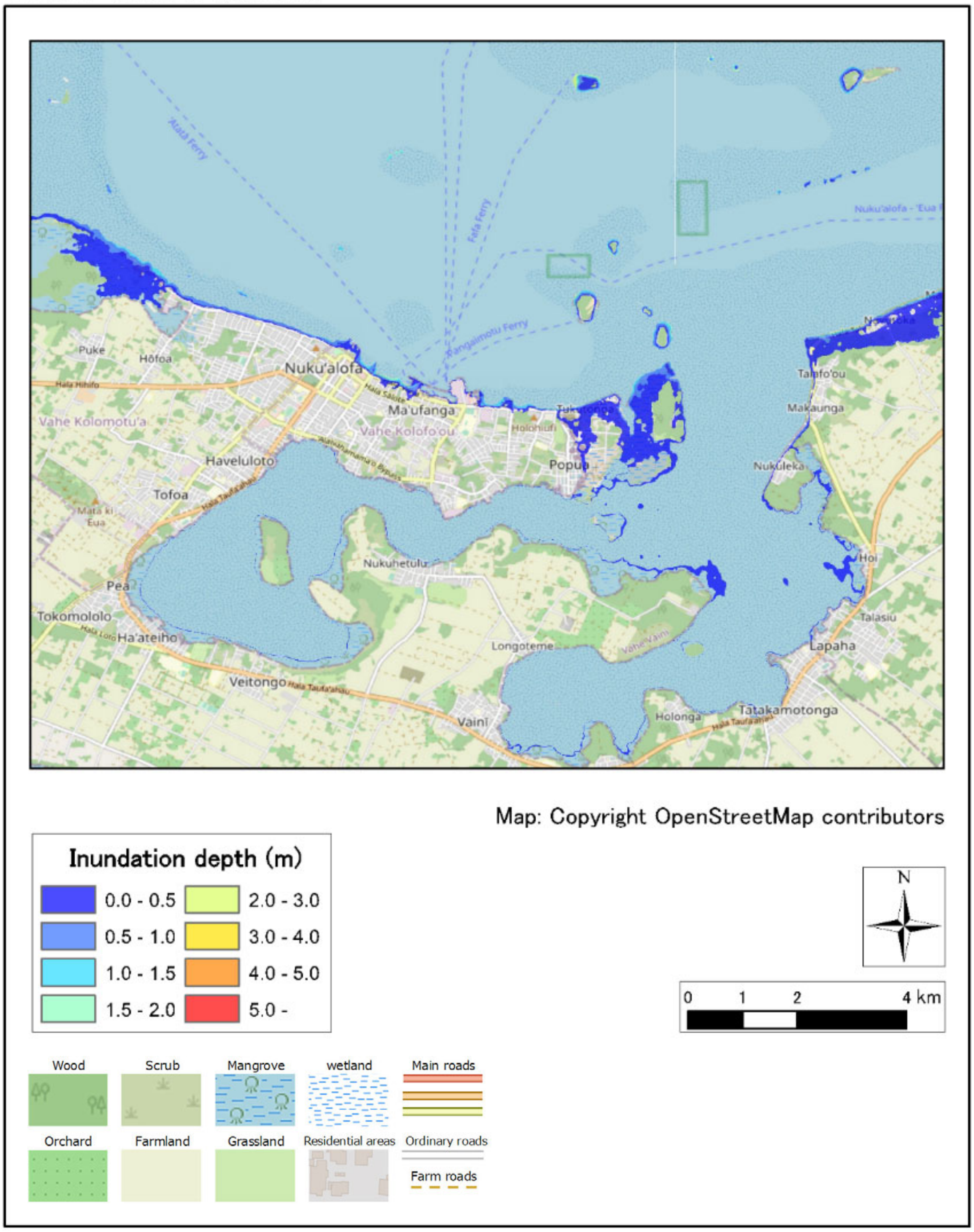
Figure 2.6.68 Max inundation depth distribution (Unnamed1, H=90m)



Source: JICA Study Team

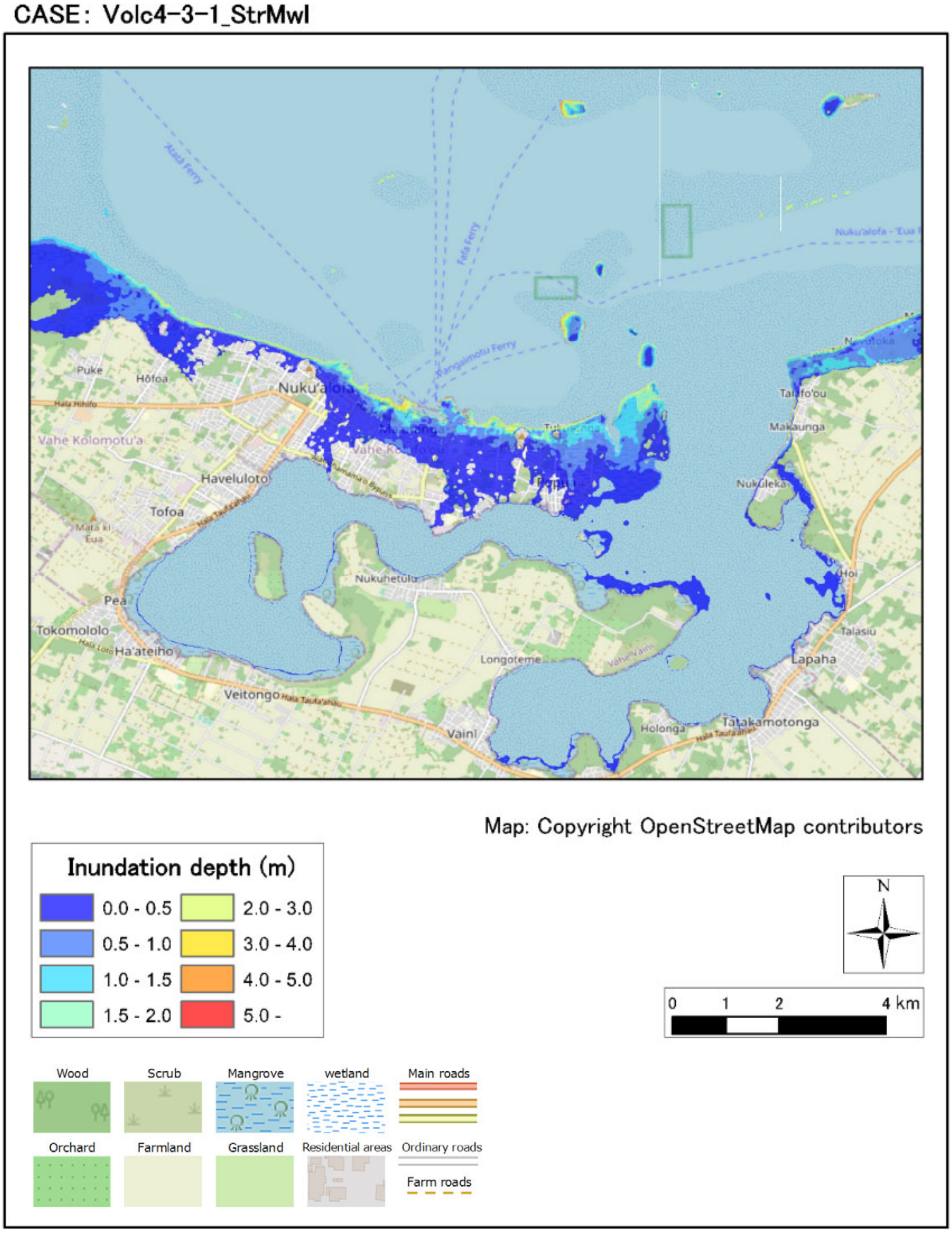
Figure 2.6.69 Max inundation depth distribution (HomeReef, H=90m)

CASE: Volc3-3-1_StrMwl



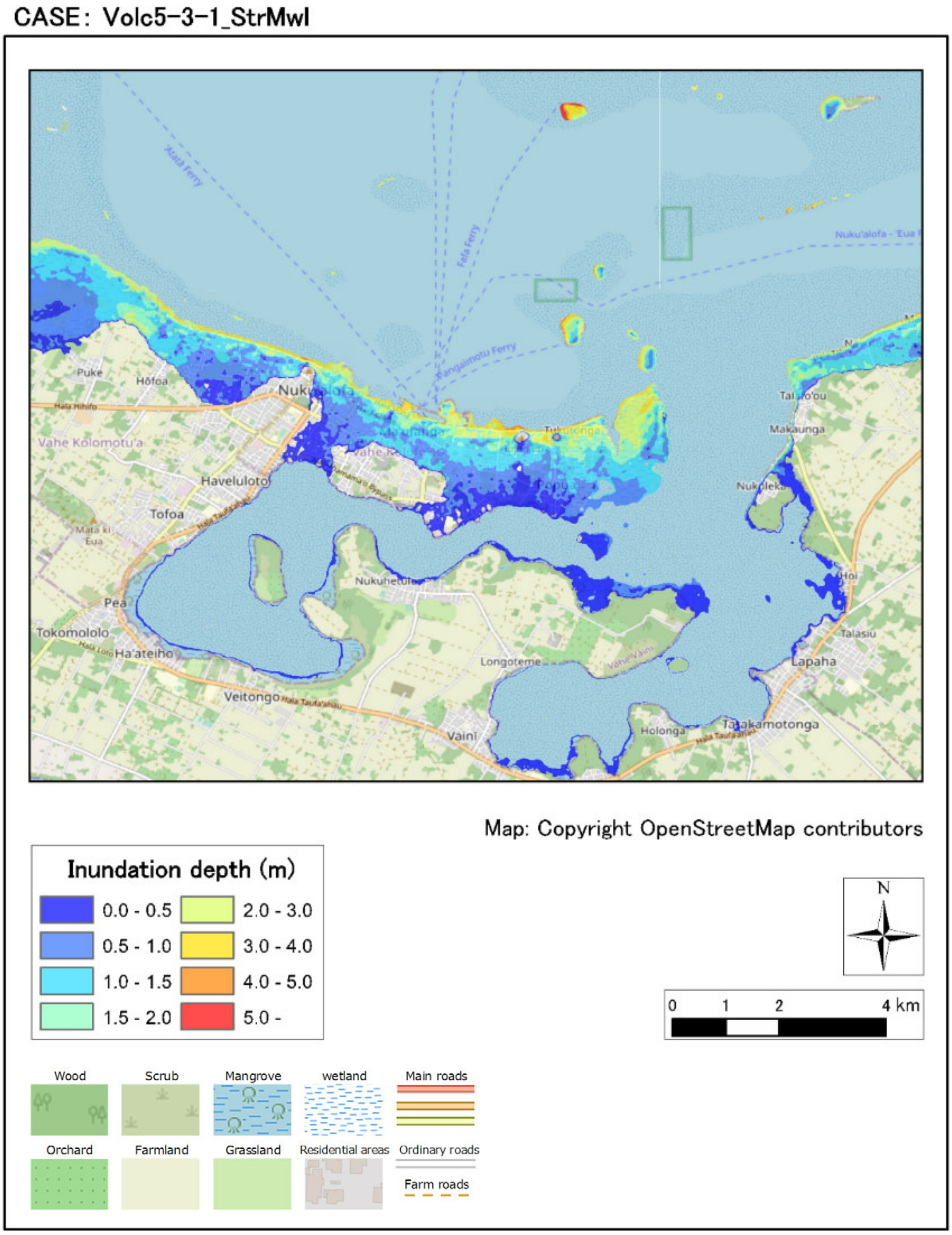
Source: JICA Study Team

Figure 2.6.70 Max inundation depth distribution (Lateiki, H=90m)



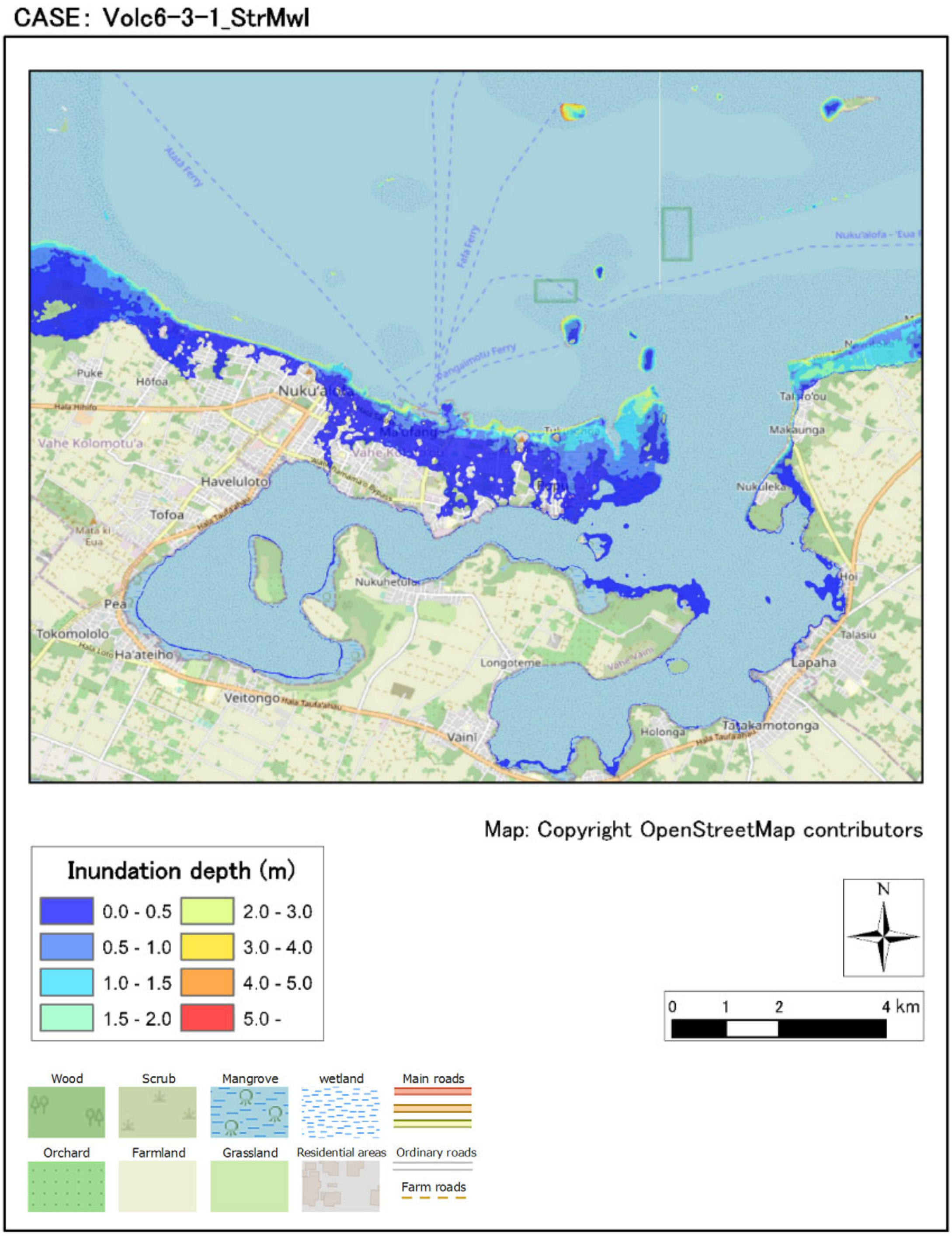
Source: JICA Study Team

Figure 2.6.71 Max inundation depth distribution (Fonuafo'ou, H=90m)



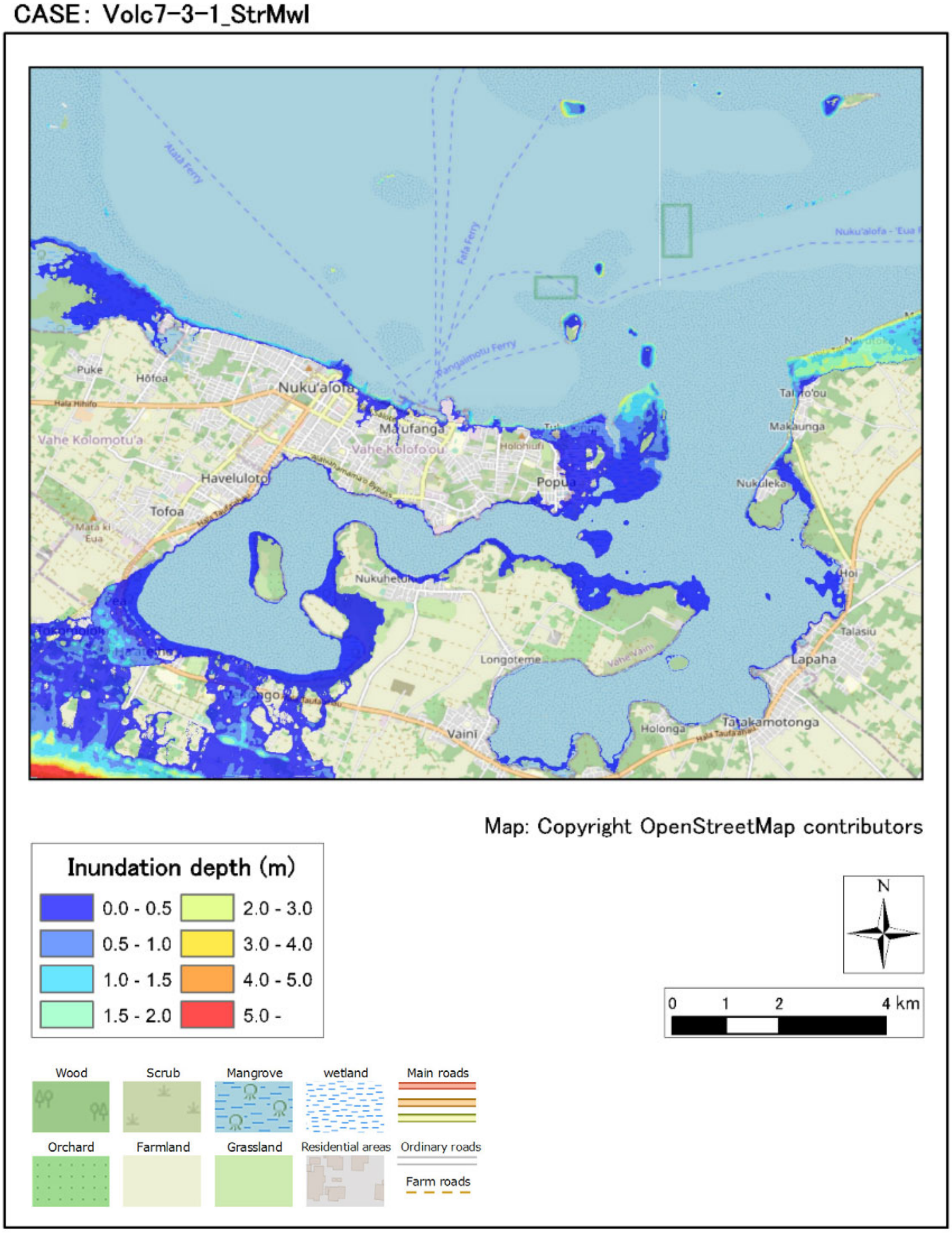
Source: JICA Study Team

Figure 2.6.72 Max inundation depth distribution (Unamed2, H=90m)



Source: JICA Study Team

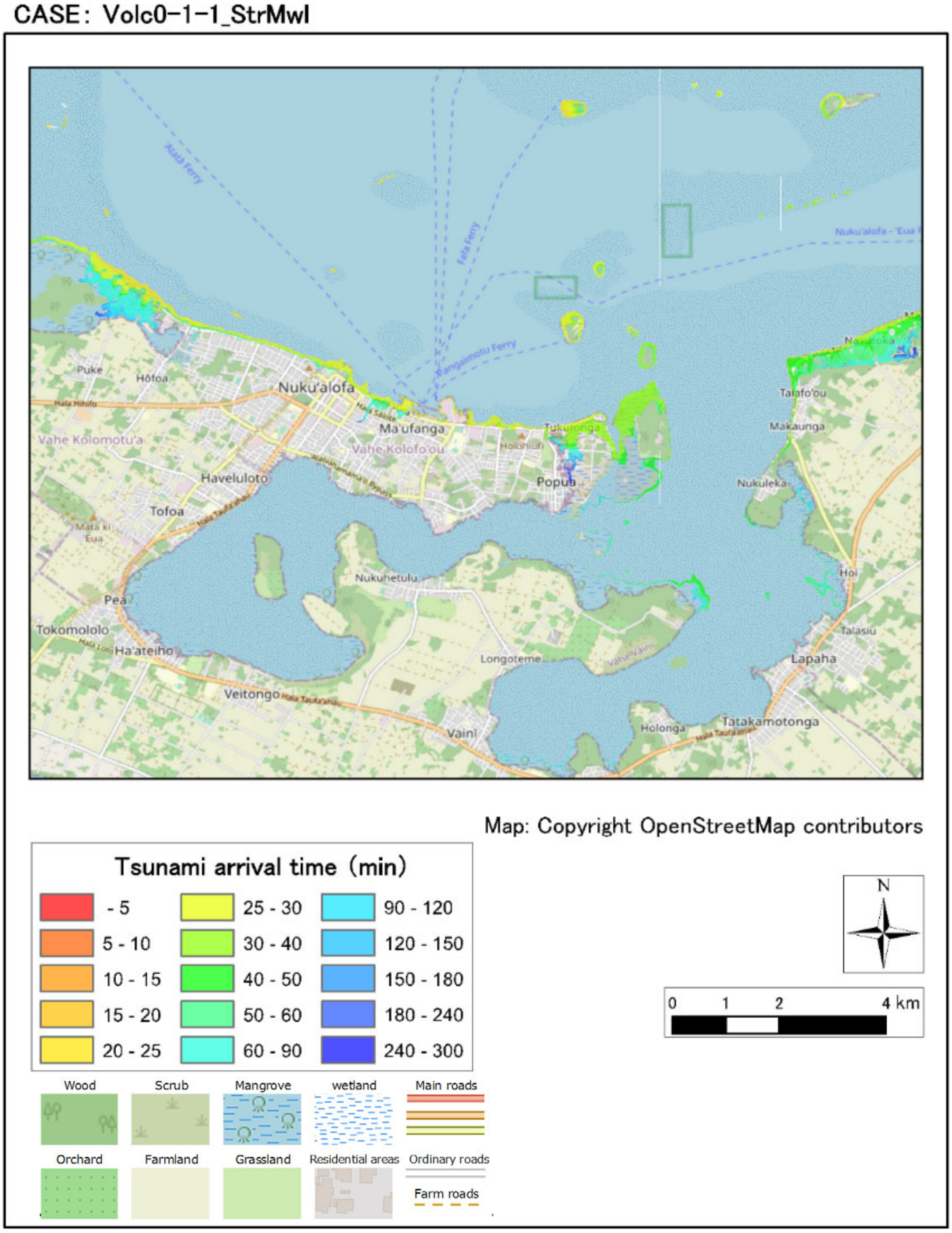
Figure 2.6.73 Max inundation depth distribution (Unamed3, H=90m)



Source: JICA Study Team

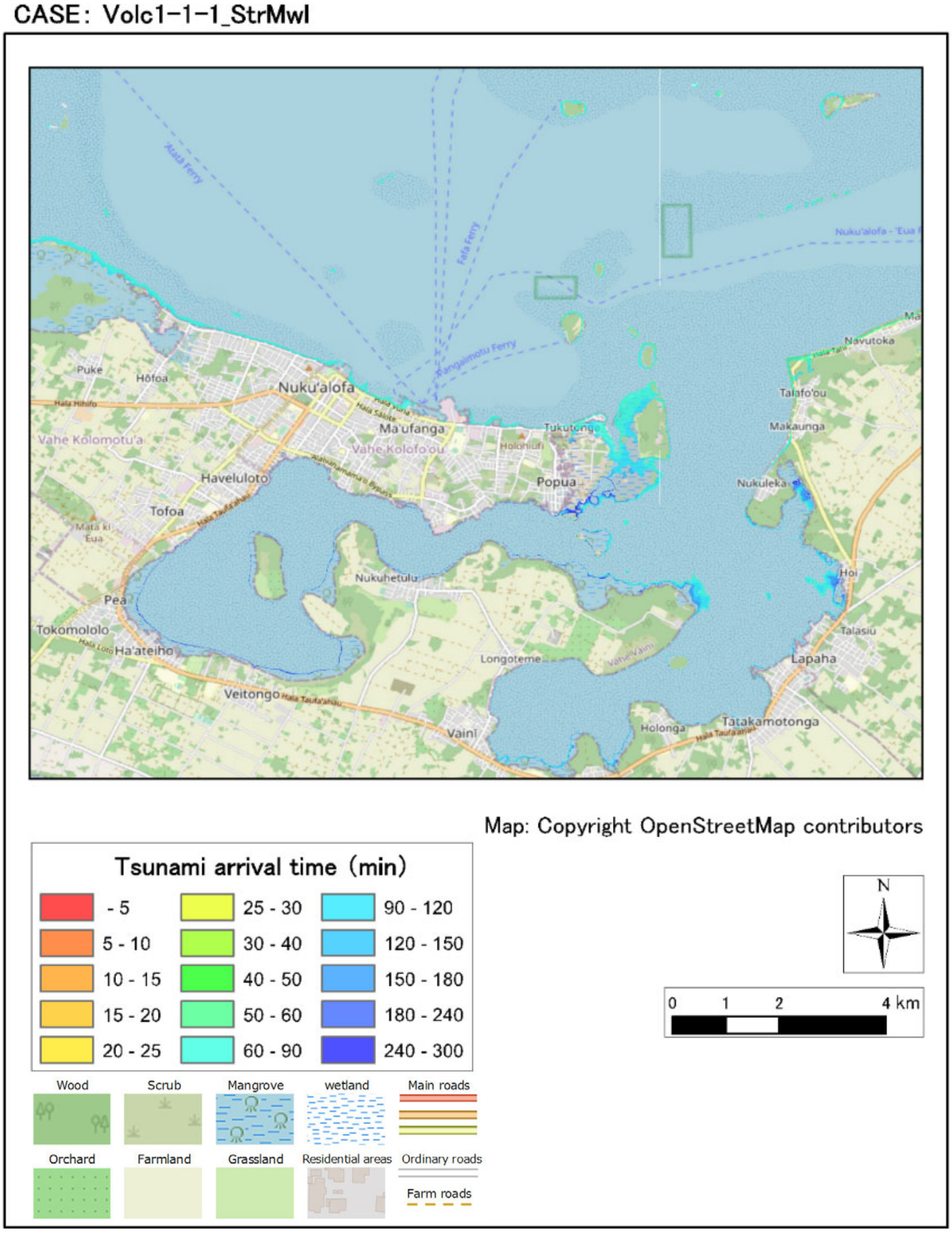
Figure 2.6.74 Max inundation depth distribution (Unamed4, H=90m)

3) Tsunami arrival time distribution map (Nuku'alofa, Tongatapu Island)



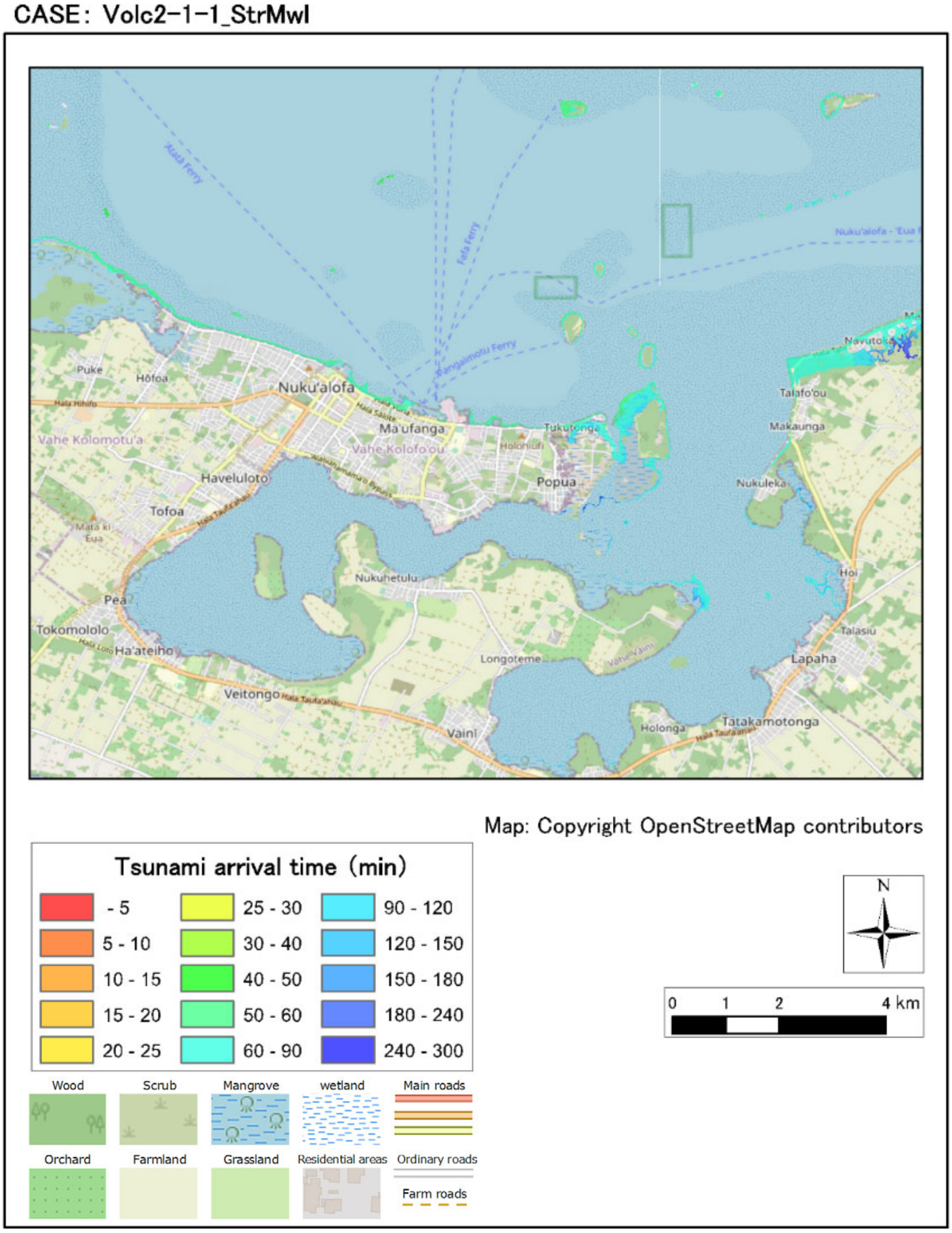
Source: JICA Study Team

Figure 2.6.75 Tsunami Arraival Time Distribution (Hunga Tonga-Hunga Ha'pai, H=30m)



Source: JICA Study Team

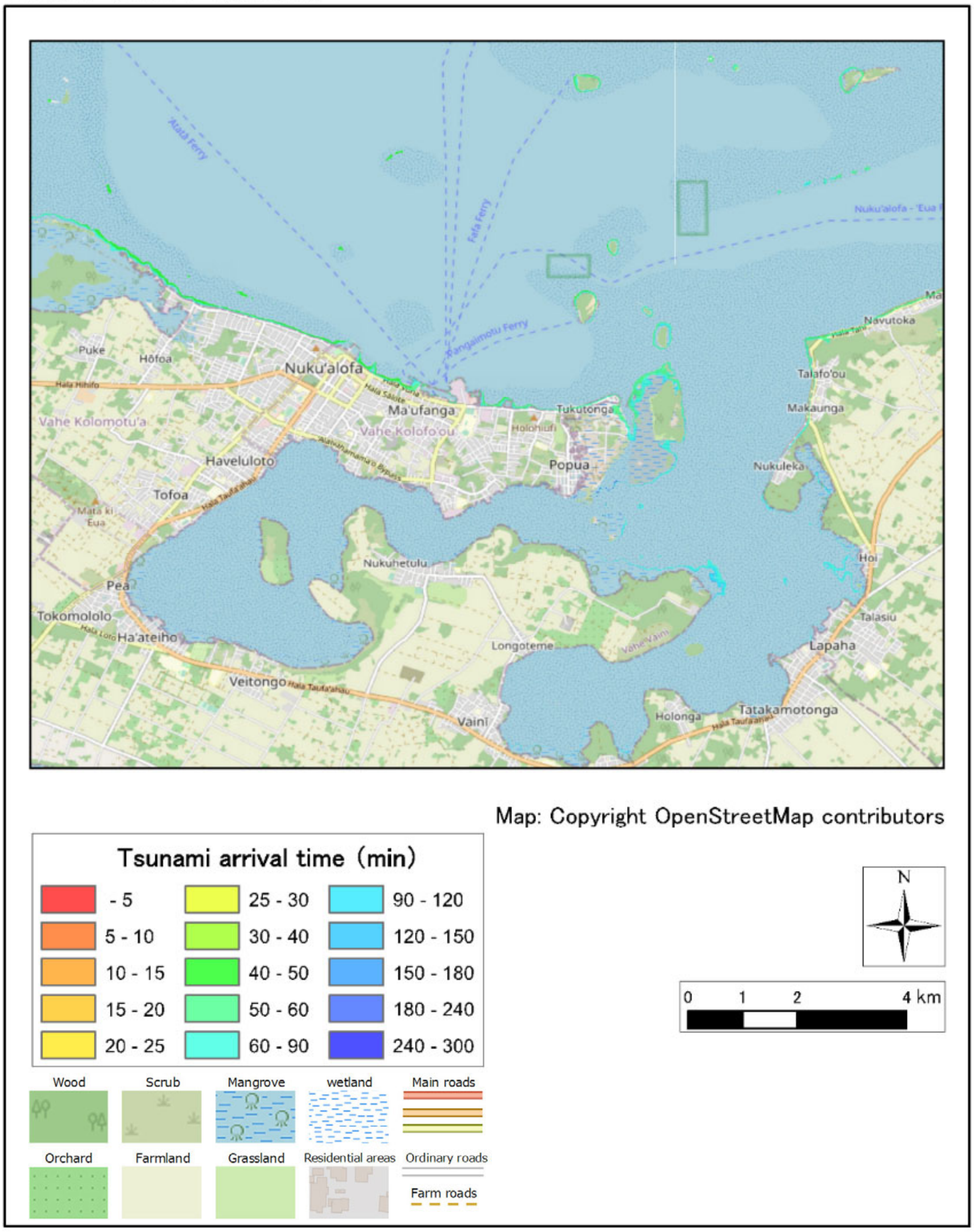
Figure 2.6.76 Tsunami Arraival Time Distribution (Unnamed1, H=30m)



Source: JICA Study Team

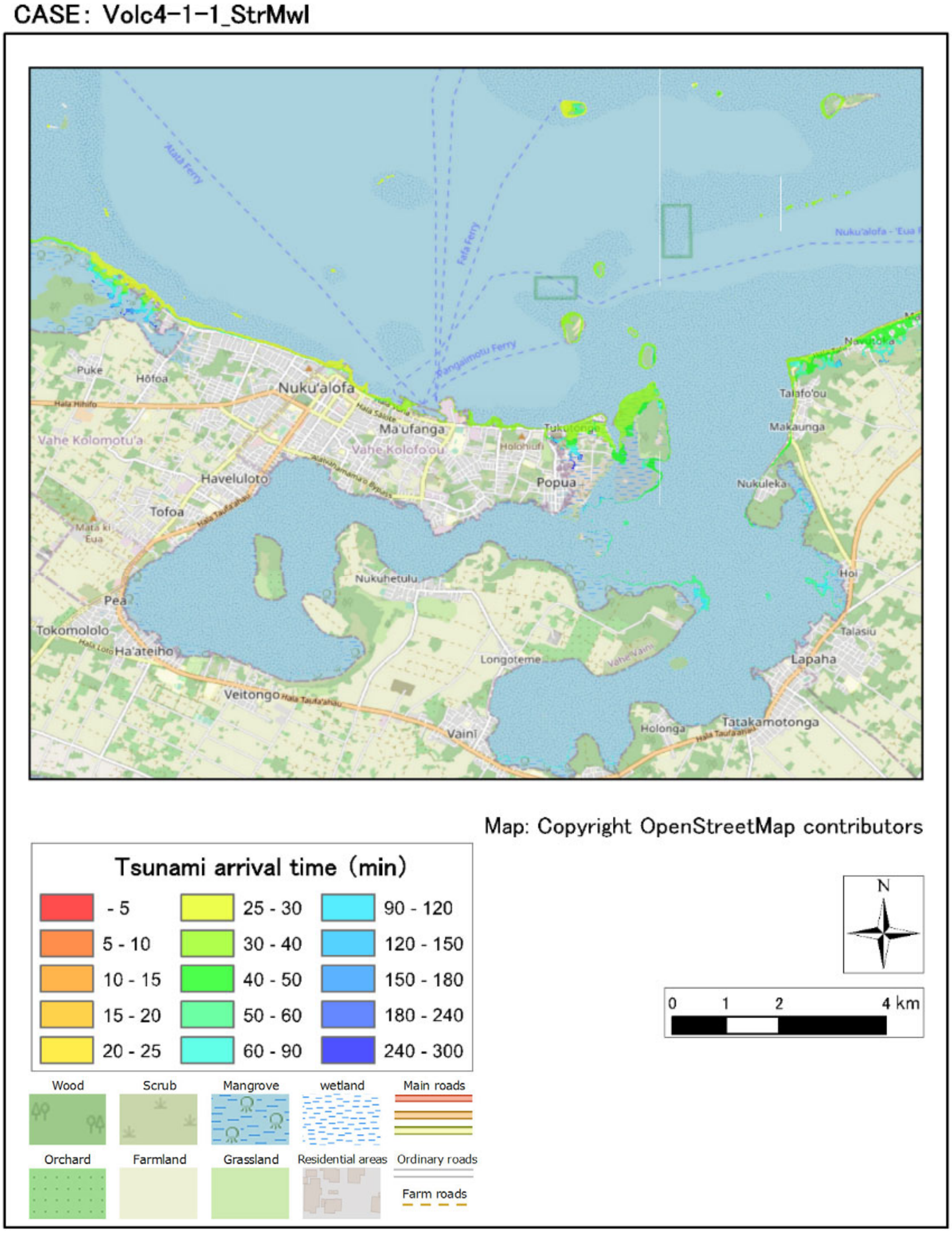
Figure 2.6.77 Tsunami Arraival Time Distribution (HomeReef, H=30m)

CASE: Volc3-1-1_StrMwl



Source: JICA Study Team

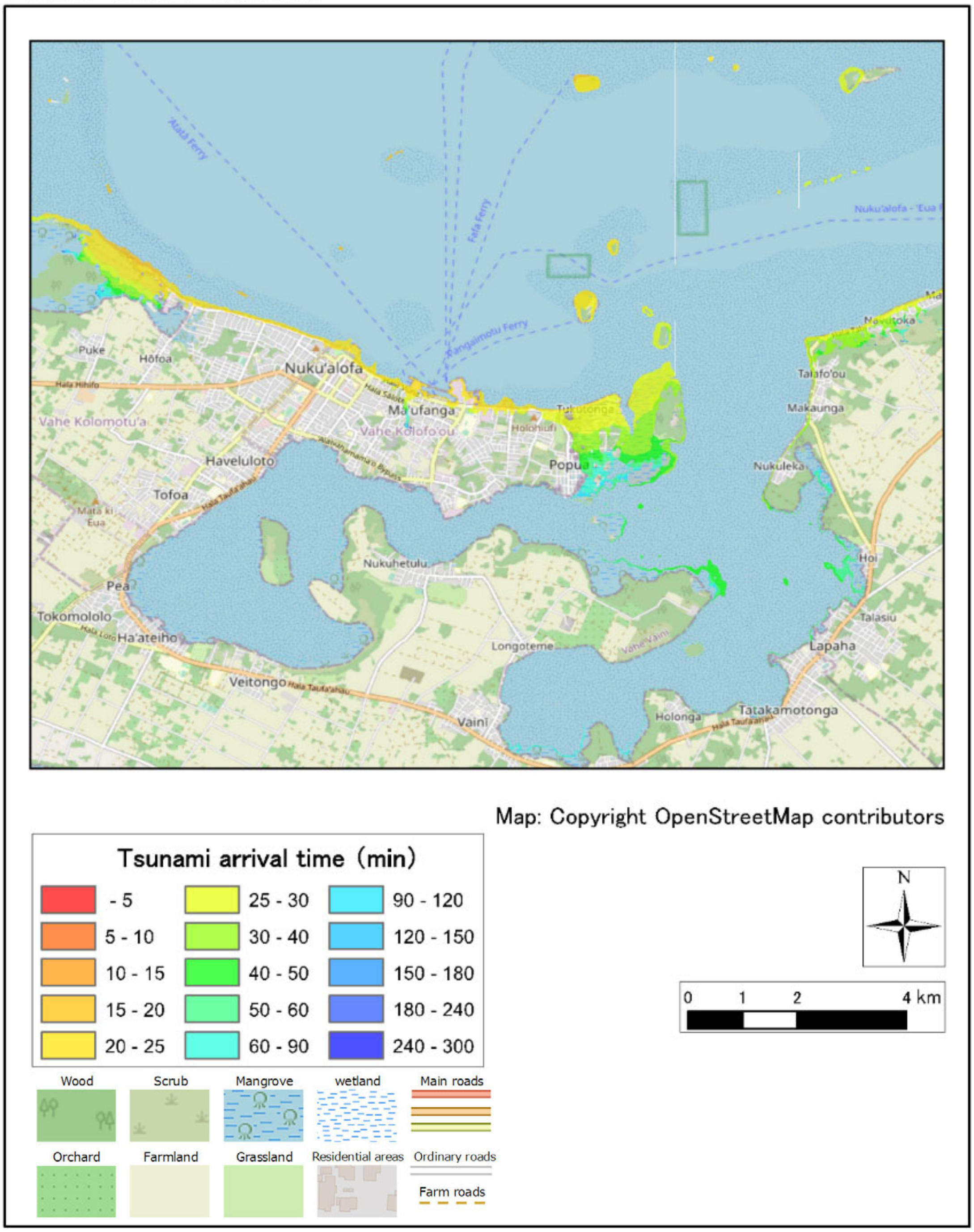
Figure 2.6.78 Tsunami Arraival Time Distribution (Lateiki, H=30m)



Source: JICA Study Team

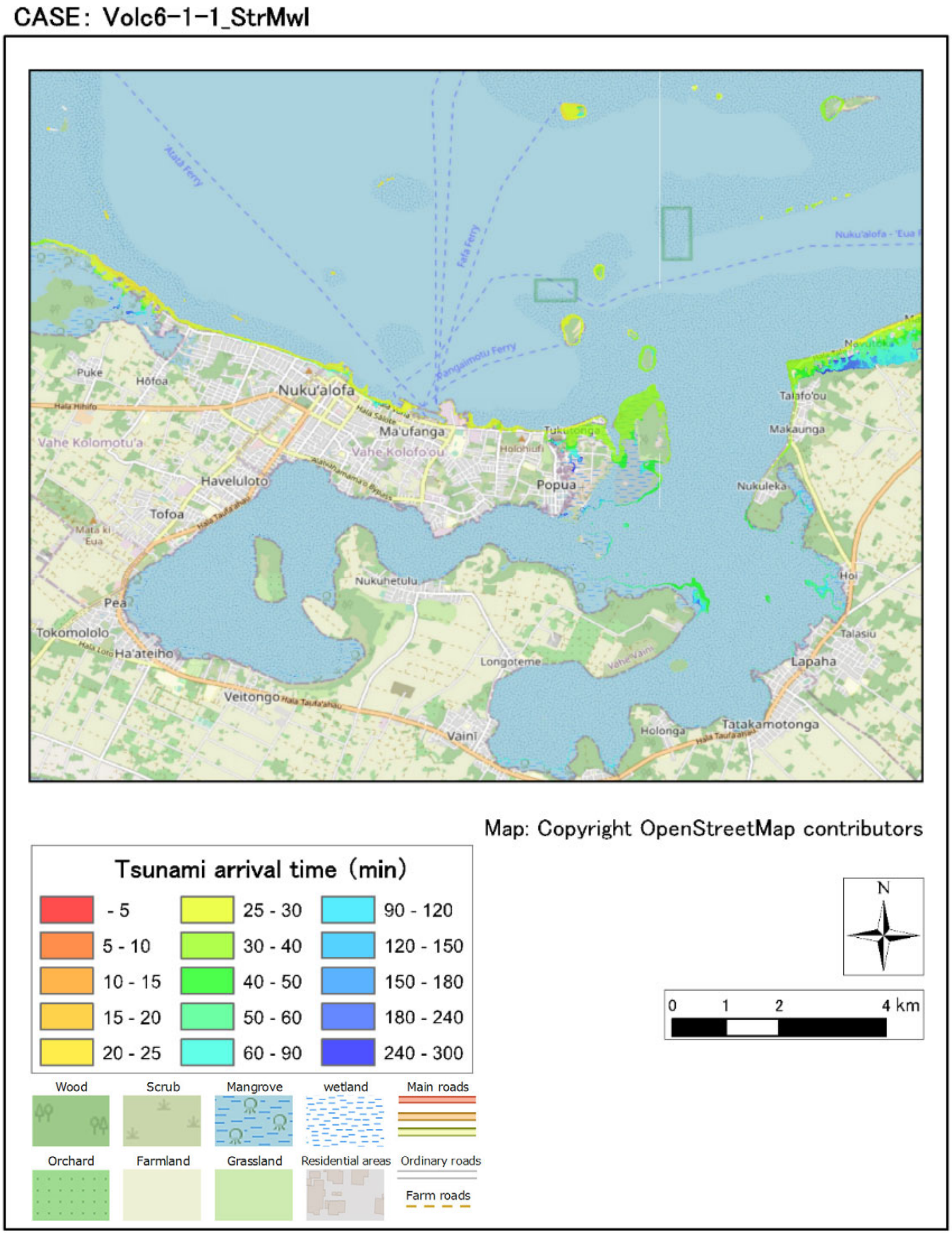
Figure 2.6.79 Tsunami Arraival Time Distribution (Fonuafo'ou H=30m)

CASE：Volc5-1-1_StrMwl



Source: JICA Study Team

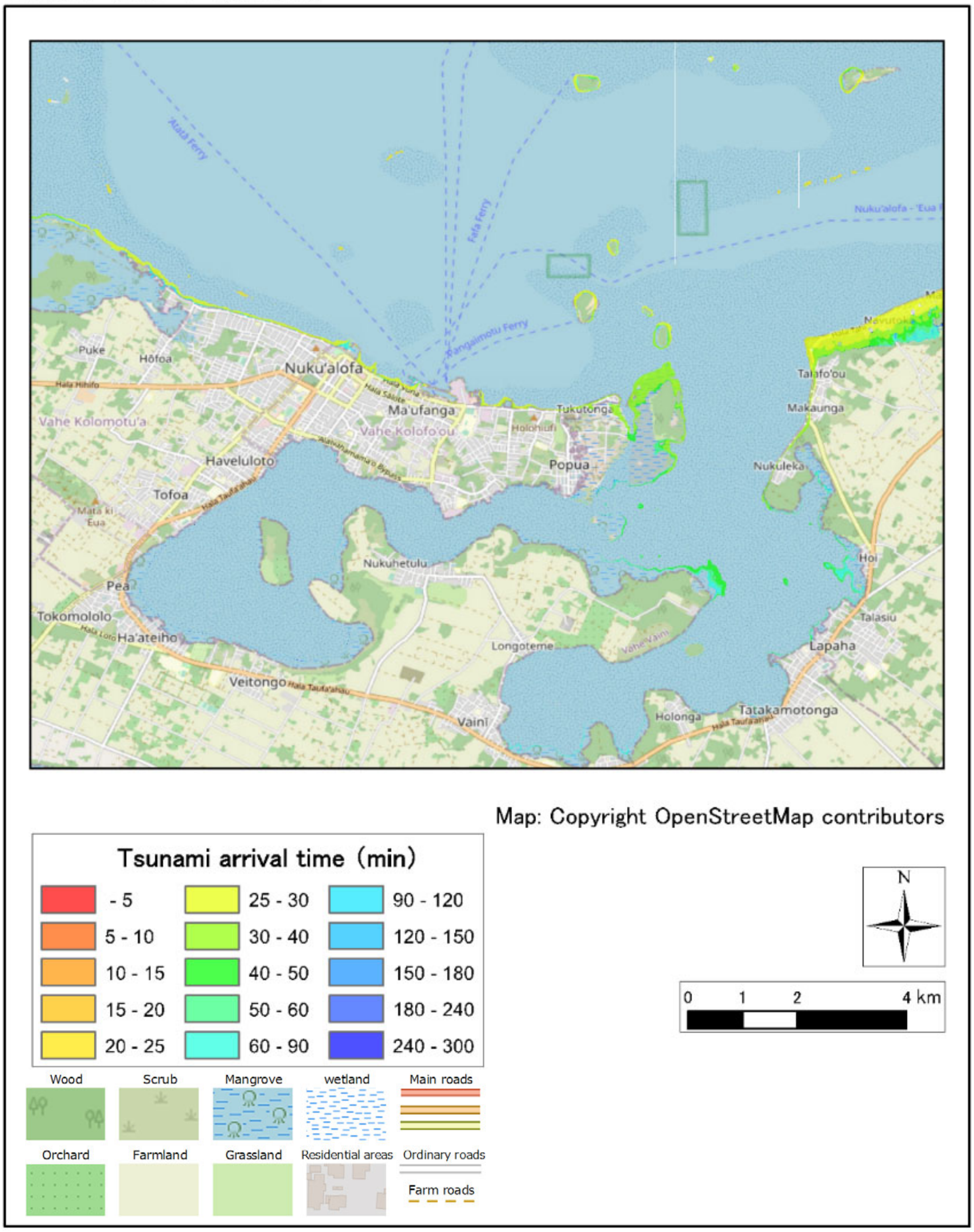
Figure 2.6.80　Tsunami Arraival Time Distribution (Unamed2, H=30m)



Source: JICA Study Team

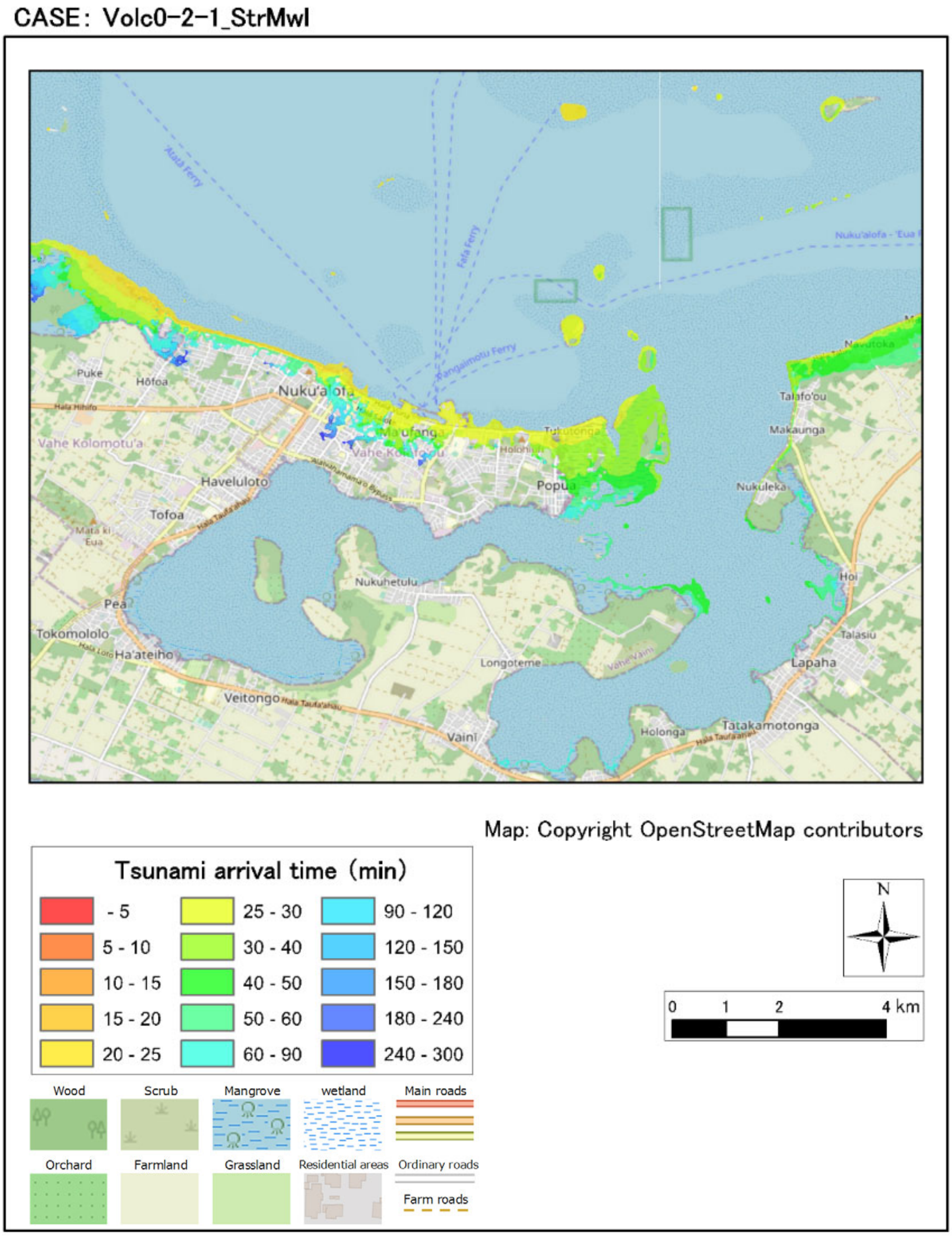
Figure 2.6.81 Tsunami Arraival Time Distribution (Unamed3, H=30m)

CASE: Volc7-1-1_StrMwl



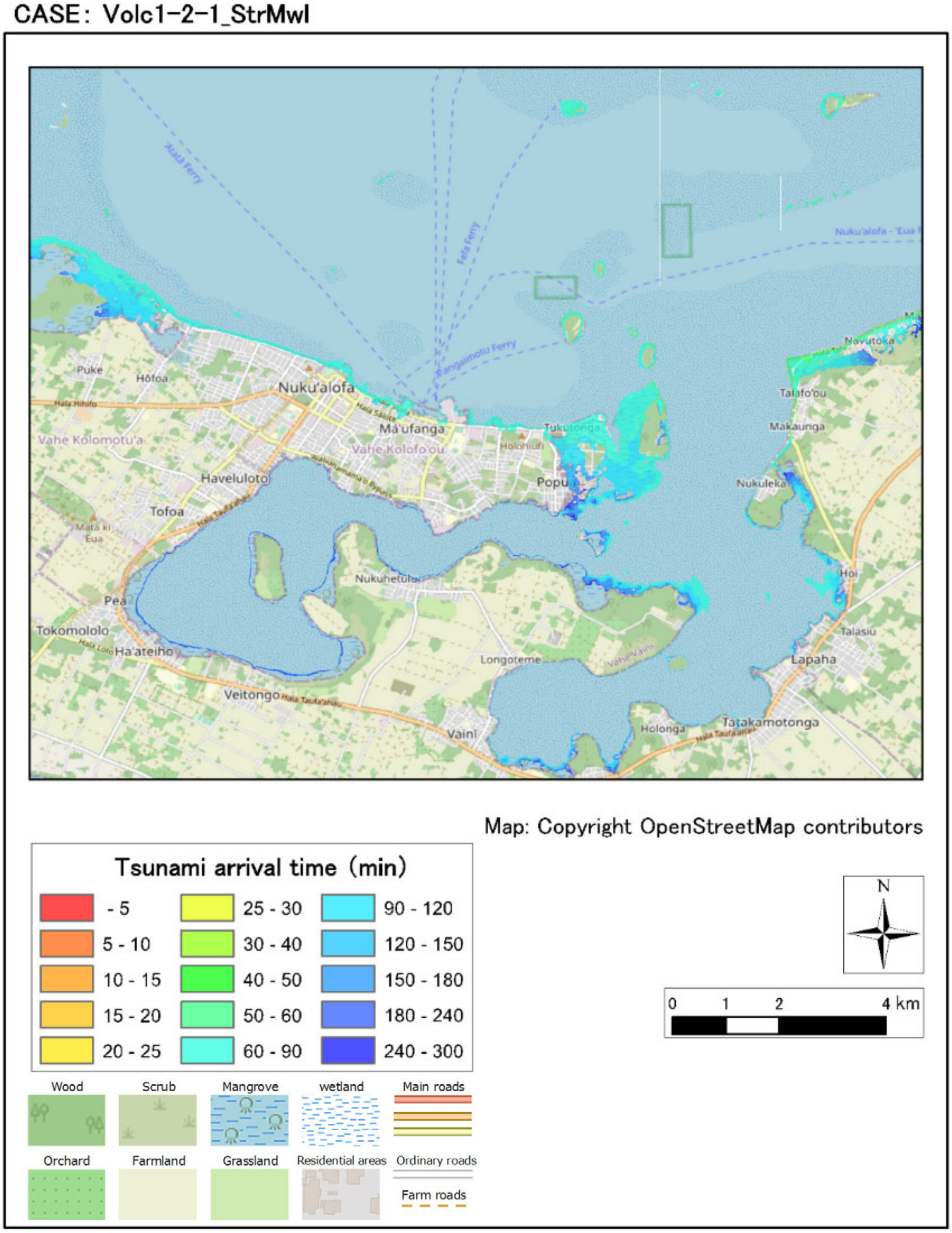
Source: JICA Study Team

Figure 2.6.82 Tsunami Arraival Time Distribution (Unamed4, H=30m)



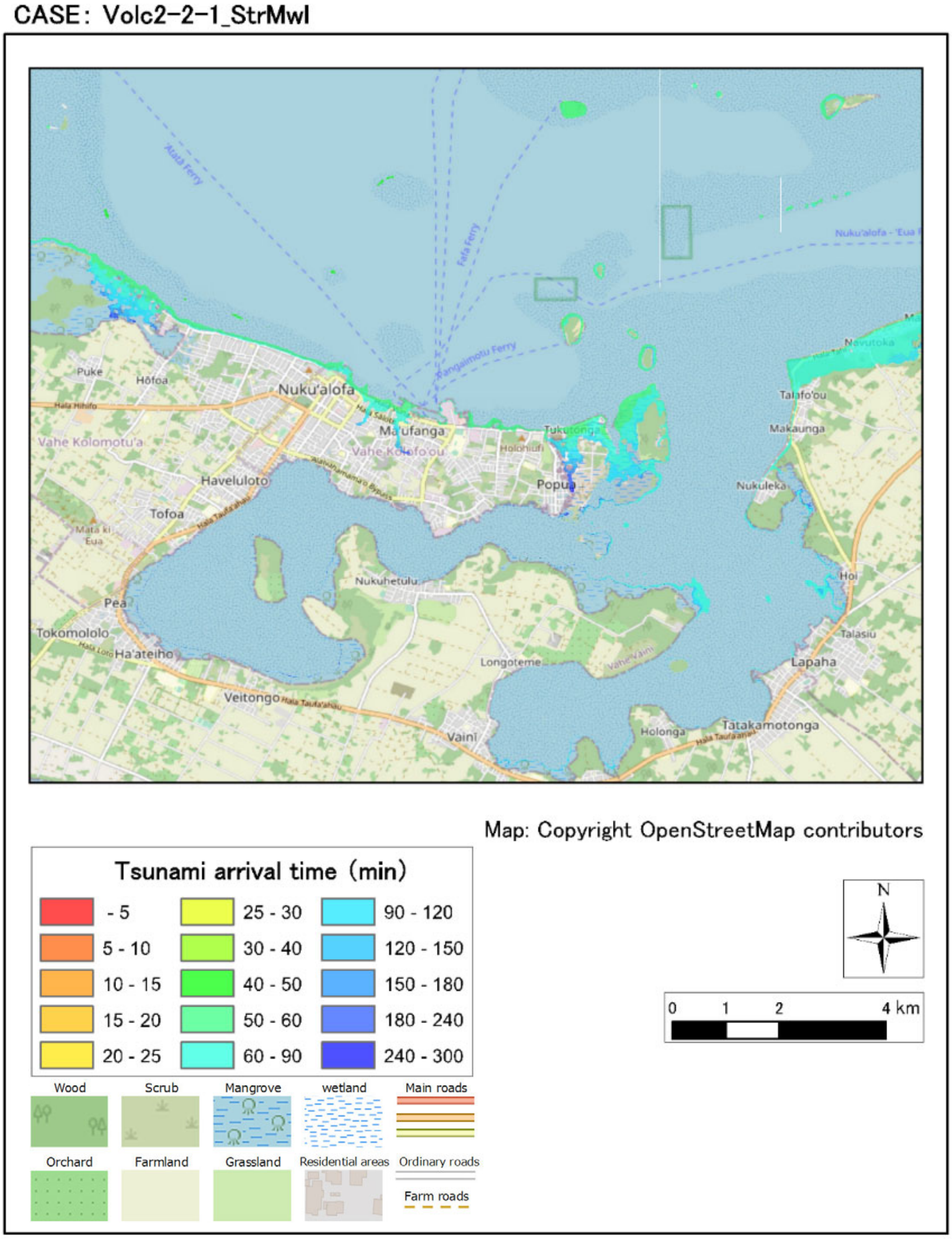
Source: JICA Study Team

Figure 2.6.83 Tsunami Arraival Time Distribution (Hunga Tonga-Hunga Ha'pai, H=60m)



Source: JICA Study Team

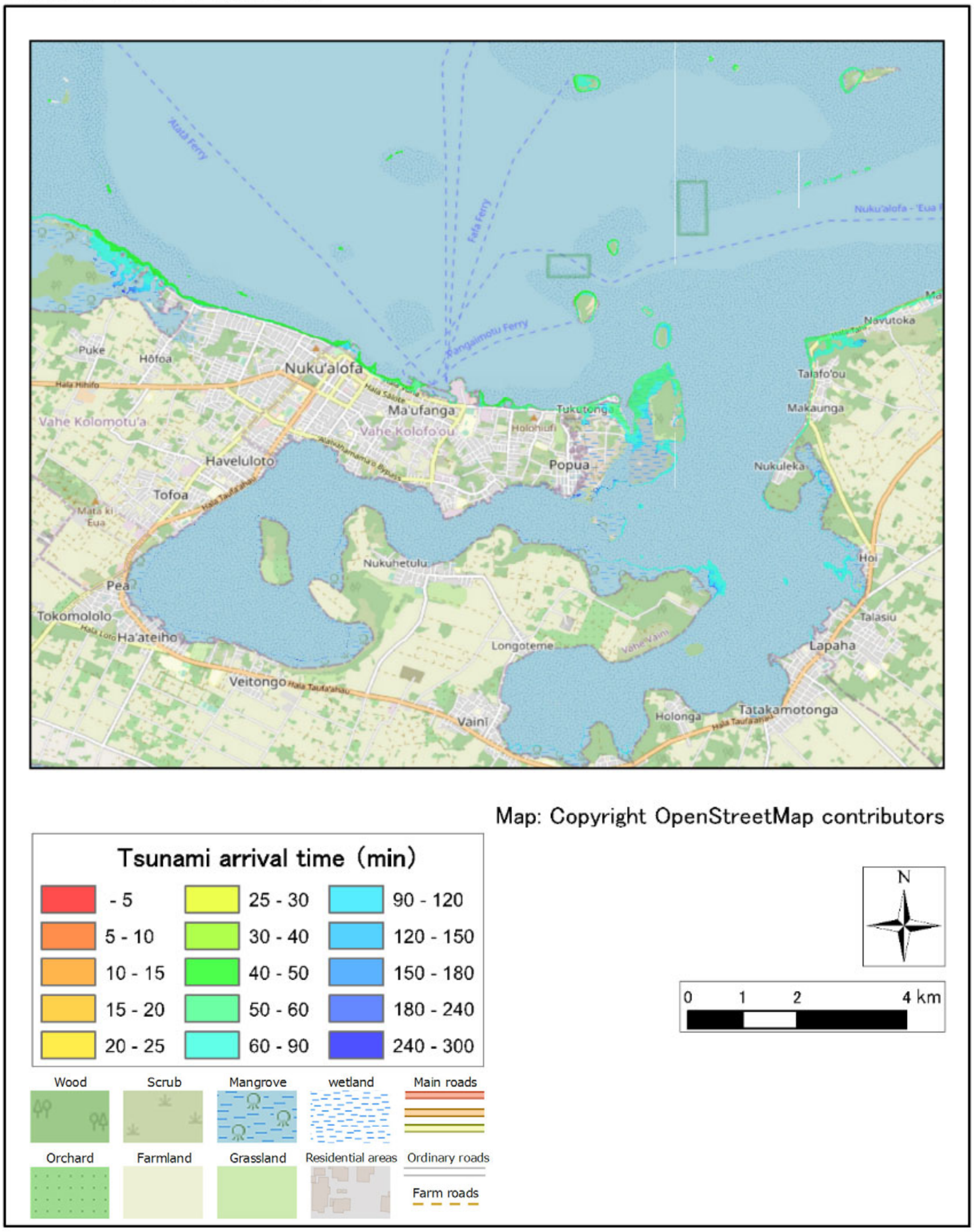
Figure 2.6.84 Tsunami Arraival Time Distribution (Unnamed1, H=60m)



Source: JICA Study Team

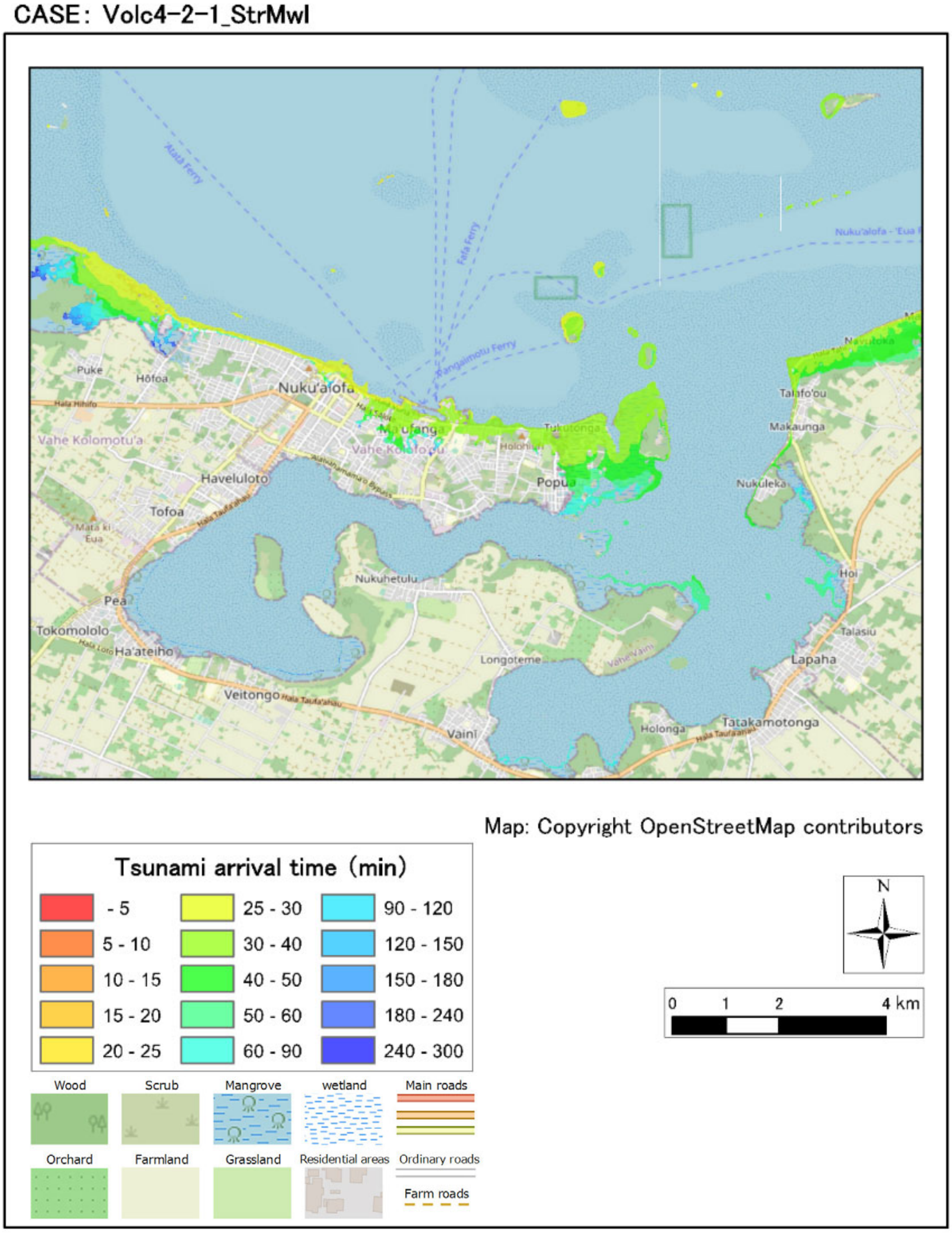
Figure 2.6.85 Tsunami Arraival Time Distribution (HomeReef, H=60m)

CASE：Volc3-2-1_StrMwl



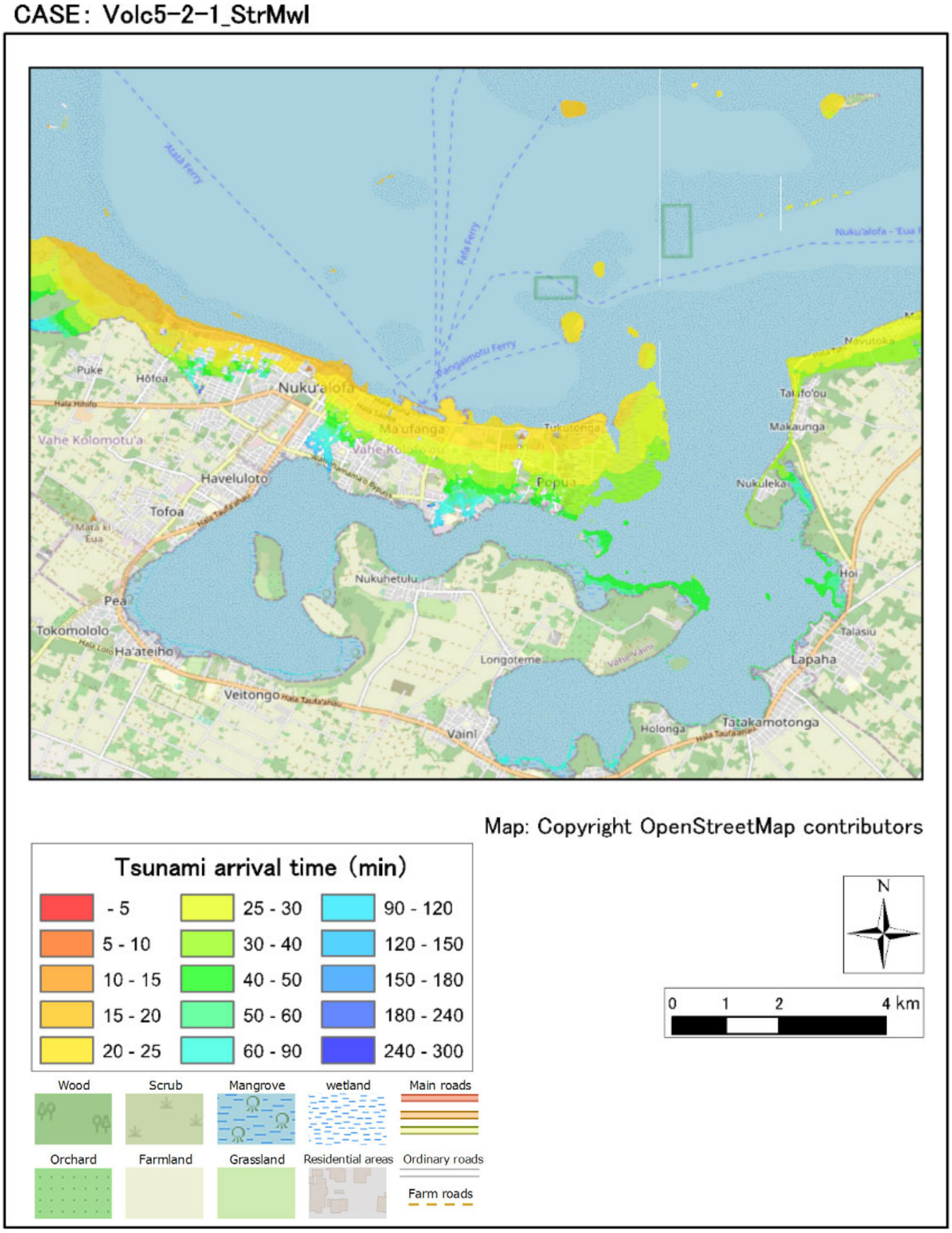
Source: JICA Study Team

Figure 2.6.86 Tsunami Arraival Time Distribution (Lateiki, H=60m)



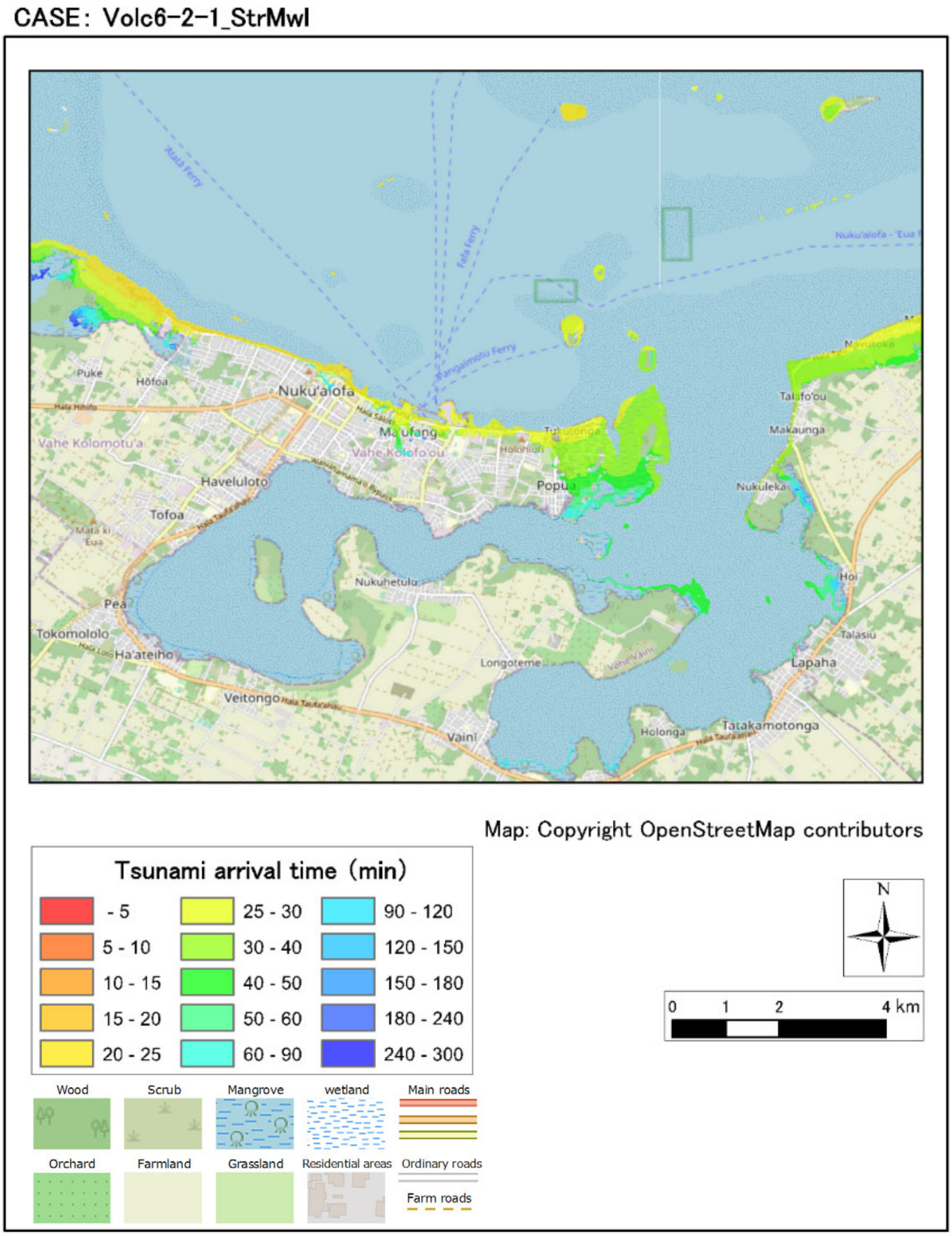
Source: JICA Study Team

Figure 2.6.87 Tsunami Arraival Time Distribution (Fonuafo'ou, H=60m)



Source: JICA Study Team

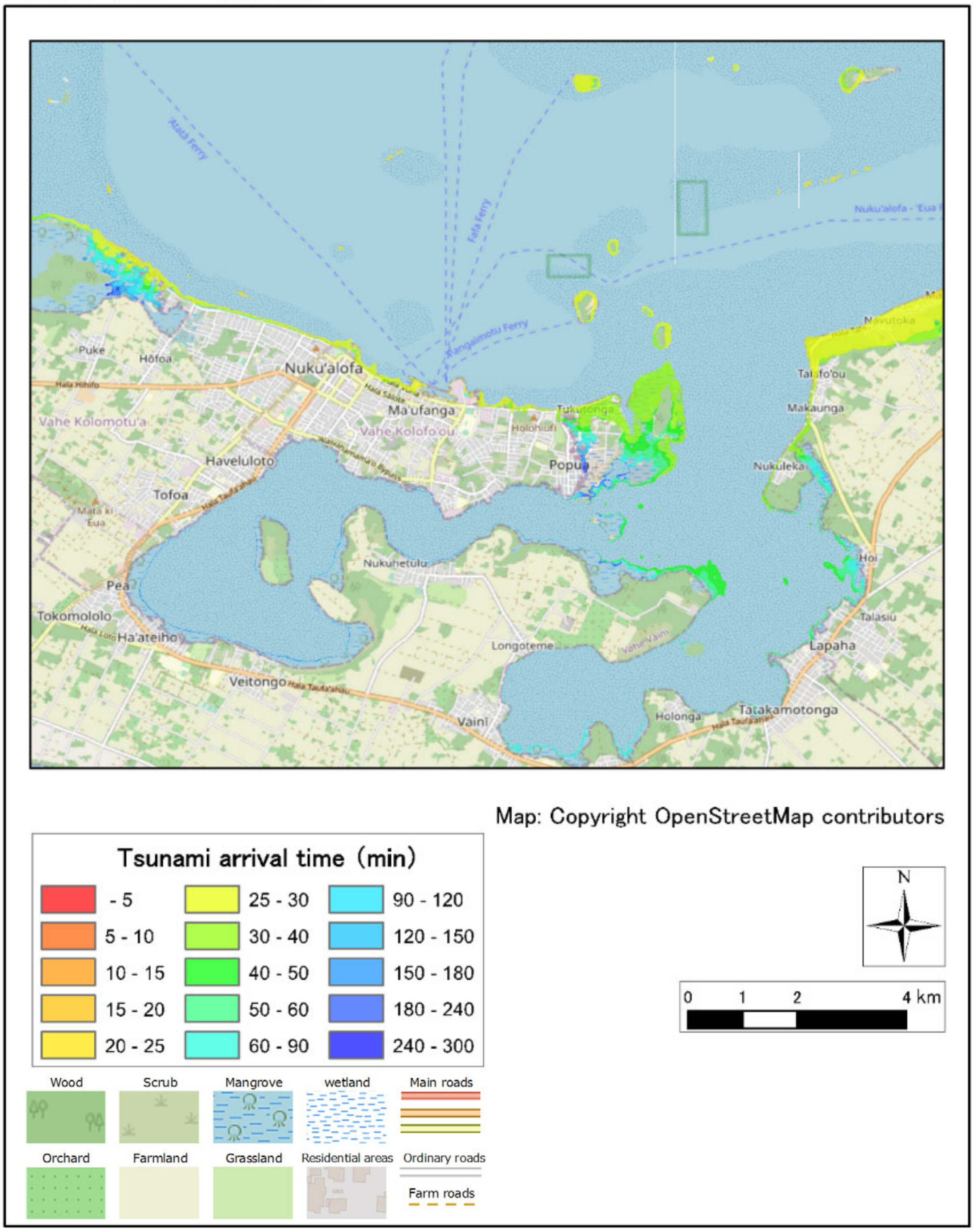
Figure 2.6.88 Tsunami Arraival Time Distribution (Unamed2, H=60m)



Source: JICA Study Team

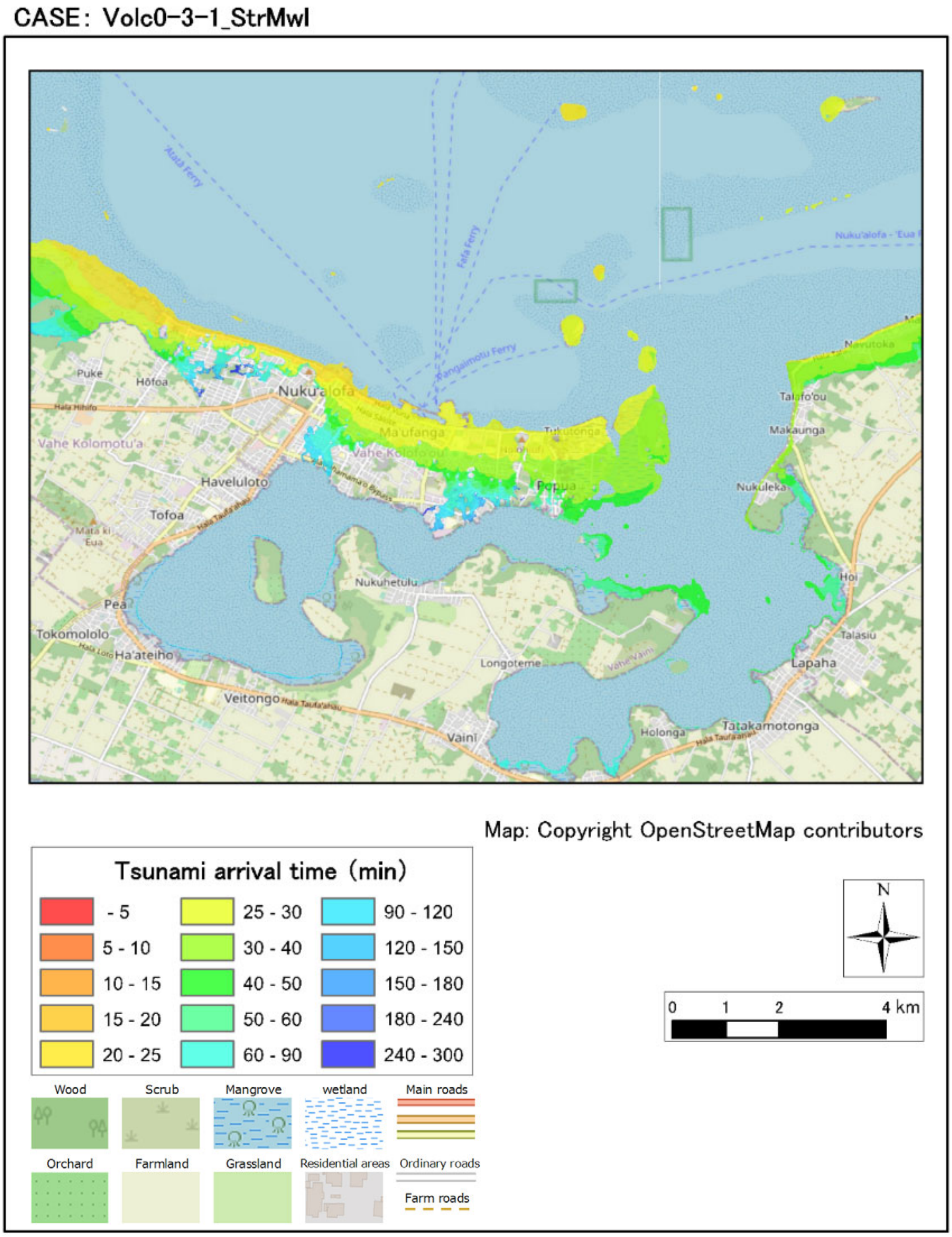
Figure 2.6.89 Tsunami Arraival Time Distribution (Unamed3, H=60m)

CASE: Volc7-2-1_StrMwl



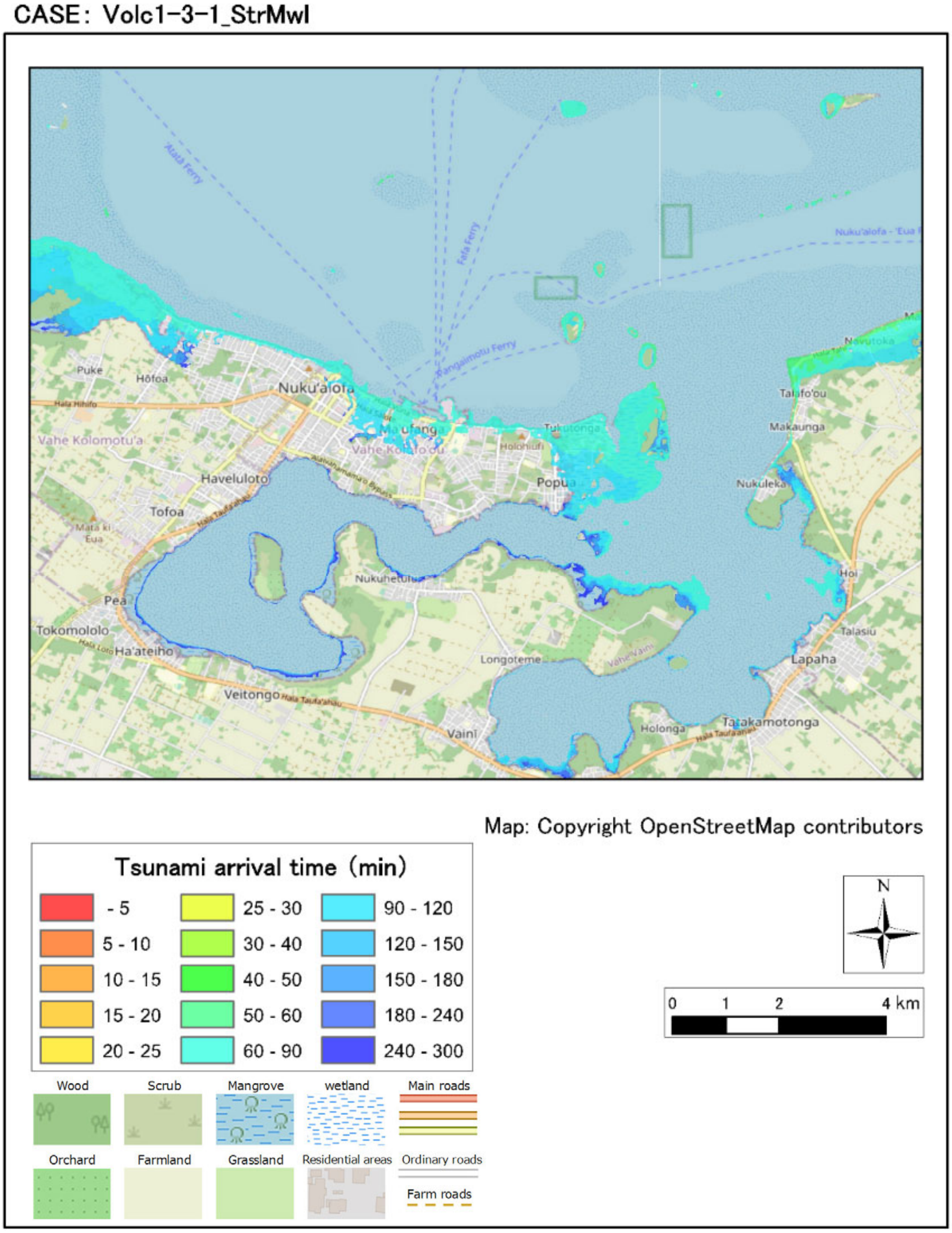
Source: JICA Study Team

Figure 2.6.90 Tsunami Arraival Time Distribution (Unamed4, H=60m)



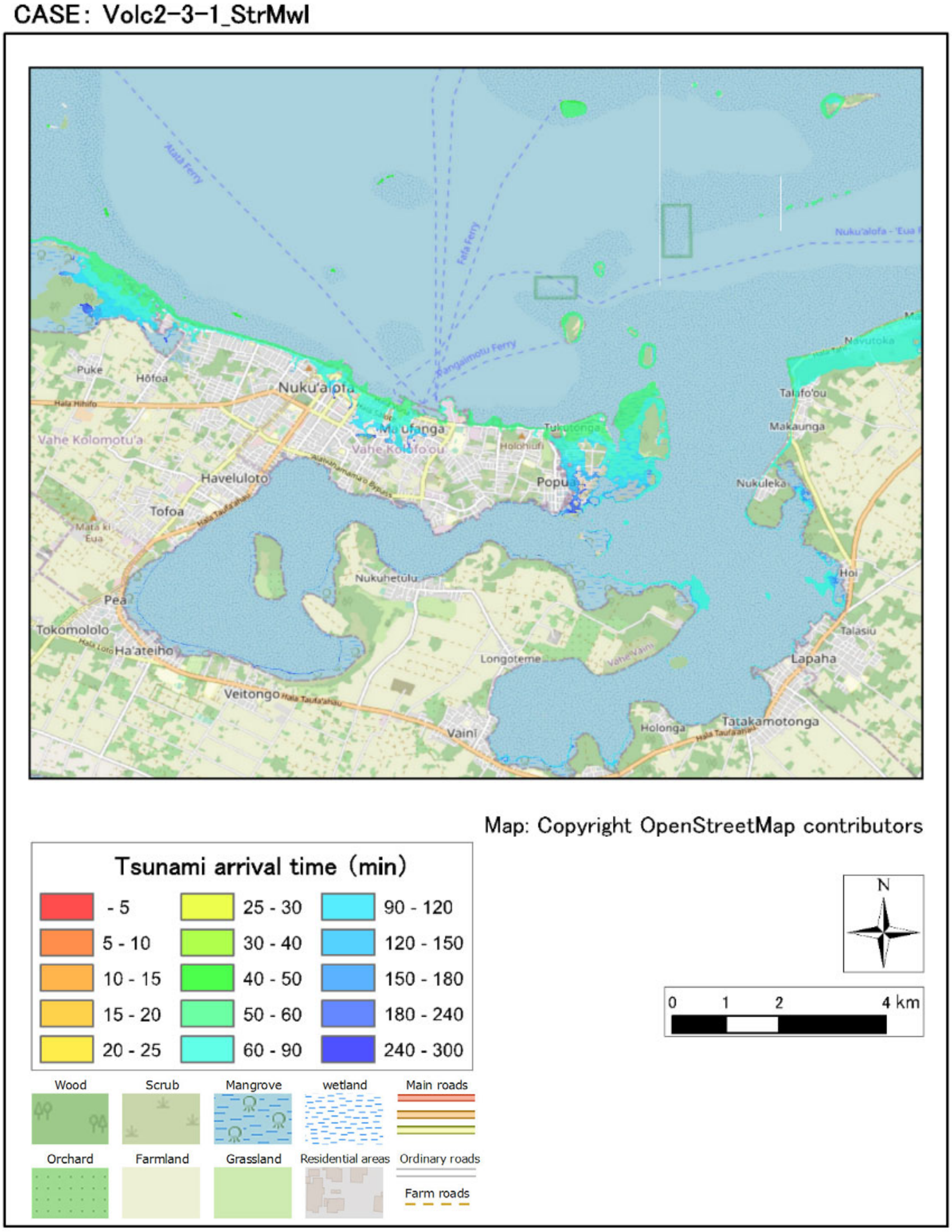
Source: JICA Study Team

Figure 2.6.91 Tsunami Arraival Time Distribution (Hunga Tonga-Hunga Ha'pai, H=90m)



Source: JICA Study Team

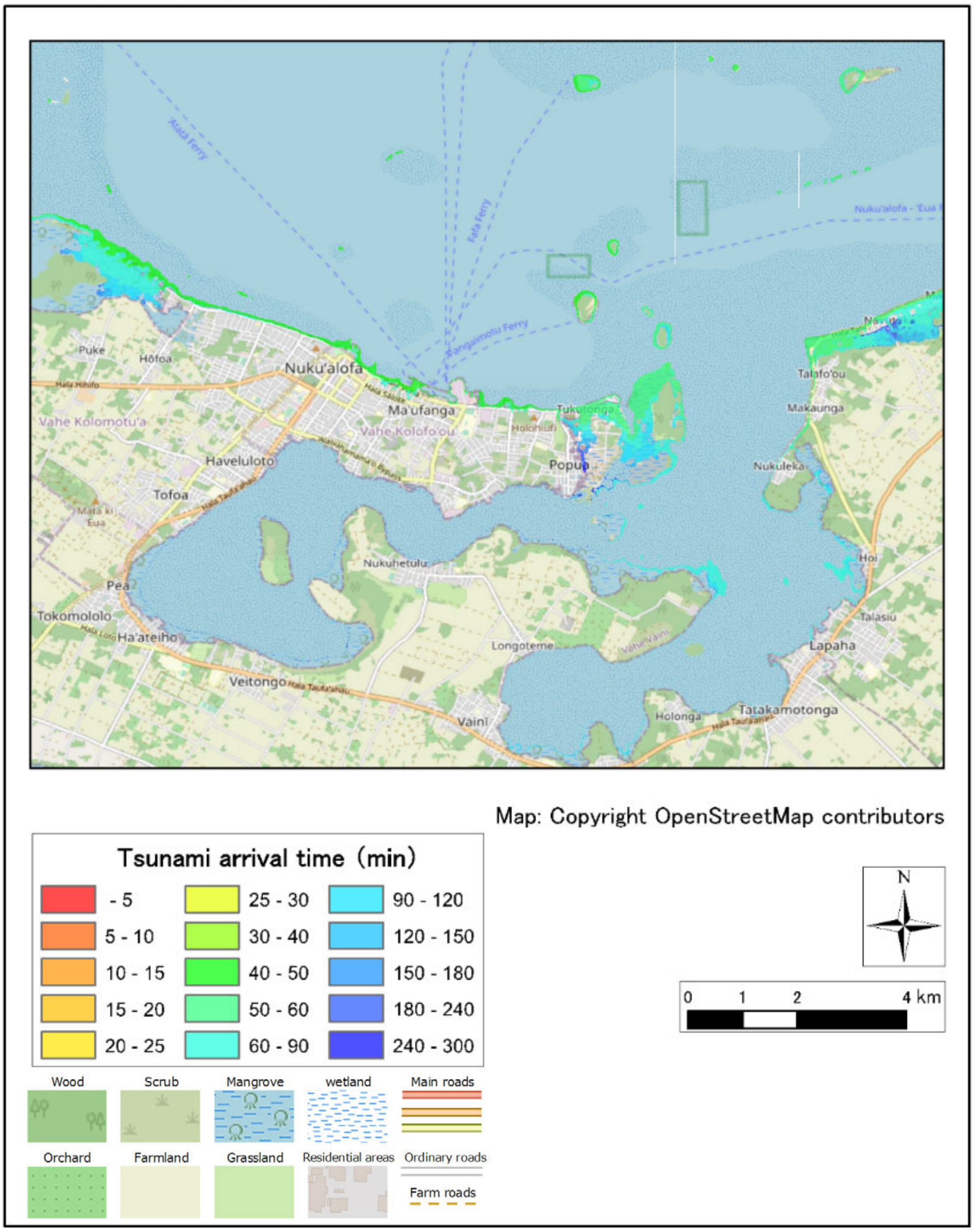
Figure 2.6.92 Tsunami Arraival Time Distribution (Unnamed1, H=90m)



Source: JICA Study Team

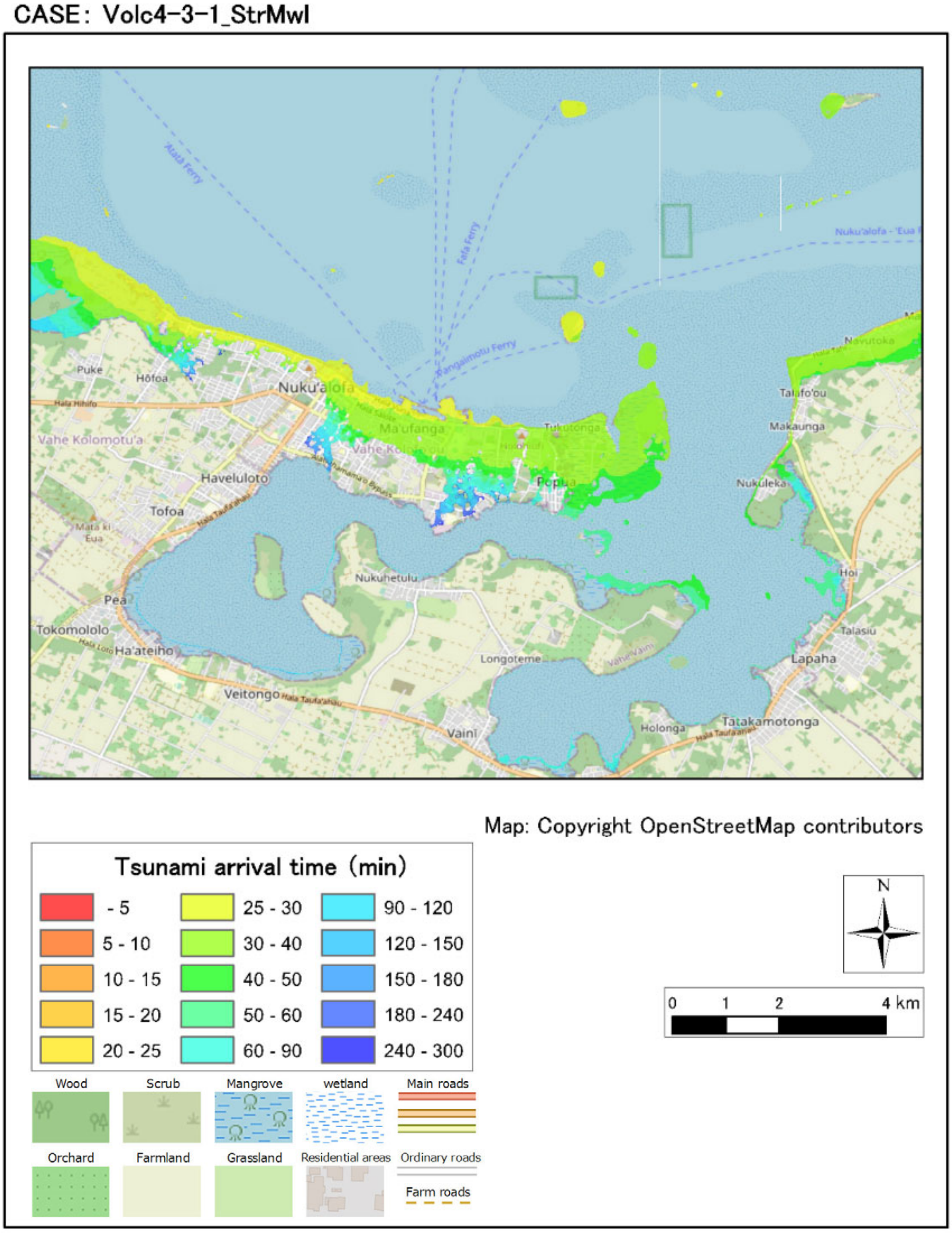
Figure 2.6.93 Tsunami Arraival Time Distribution (HomeReef, H=90m)

CASE: Volc3-3-1_StrMwl



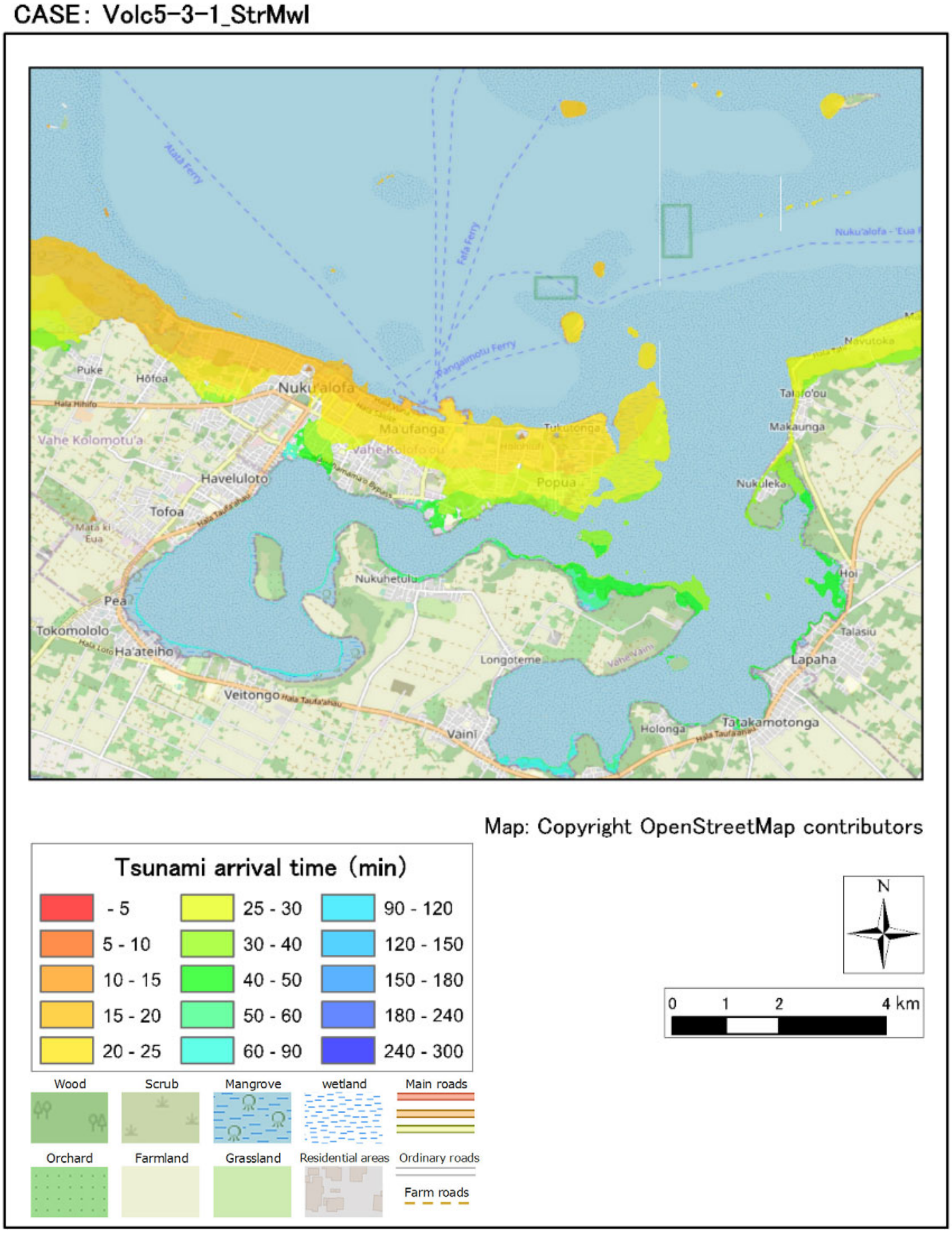
Source: JICA Study Team

Figure 2.6.94 Tsunami Arraival Time Distribution (Lateiki, H=90m)



Source: JICA Study Team

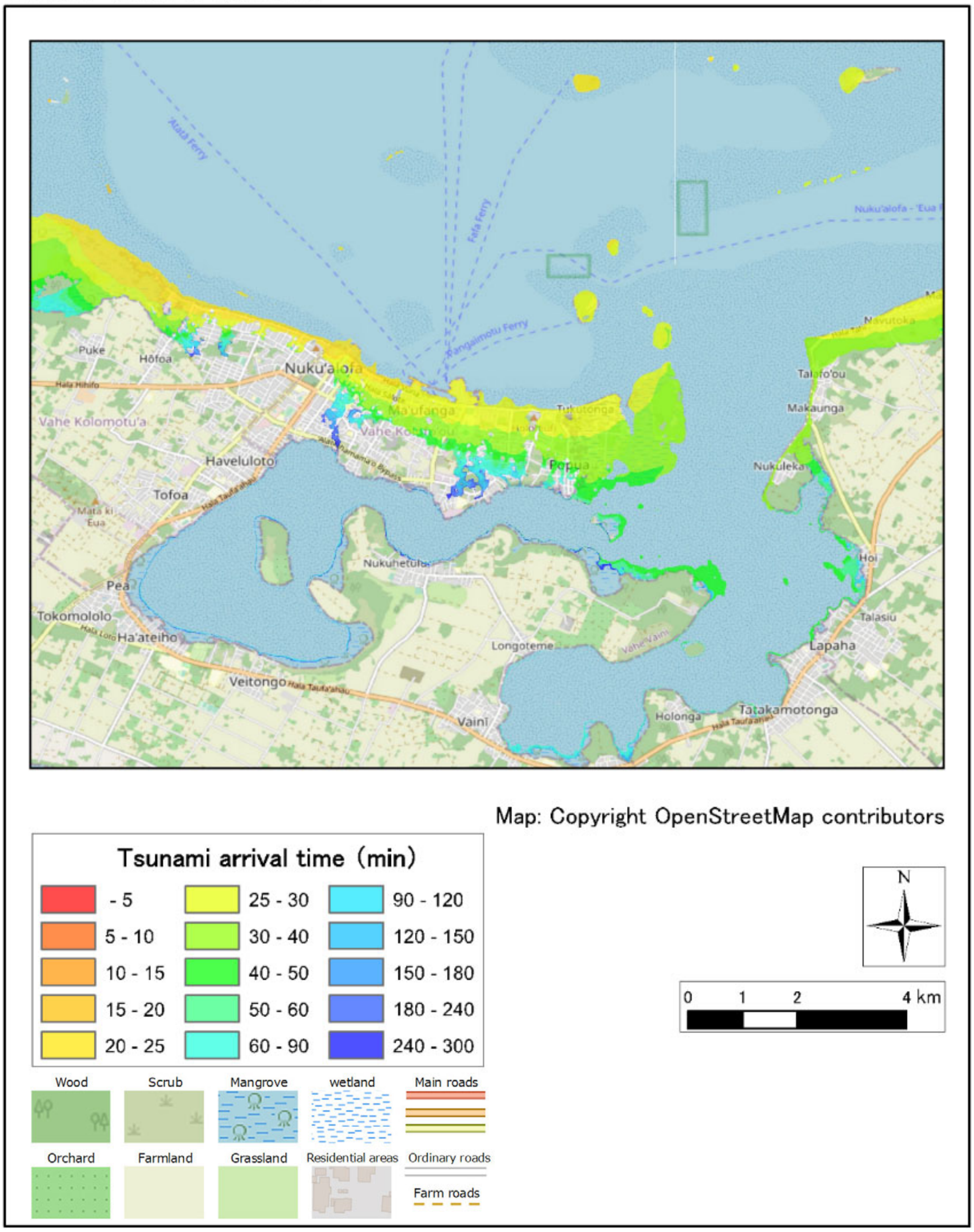
Figure 2.6.95 Tsunami Arraival Time Distribution (Fonuafo'ou, H=90m)



Source: JICA Study Team

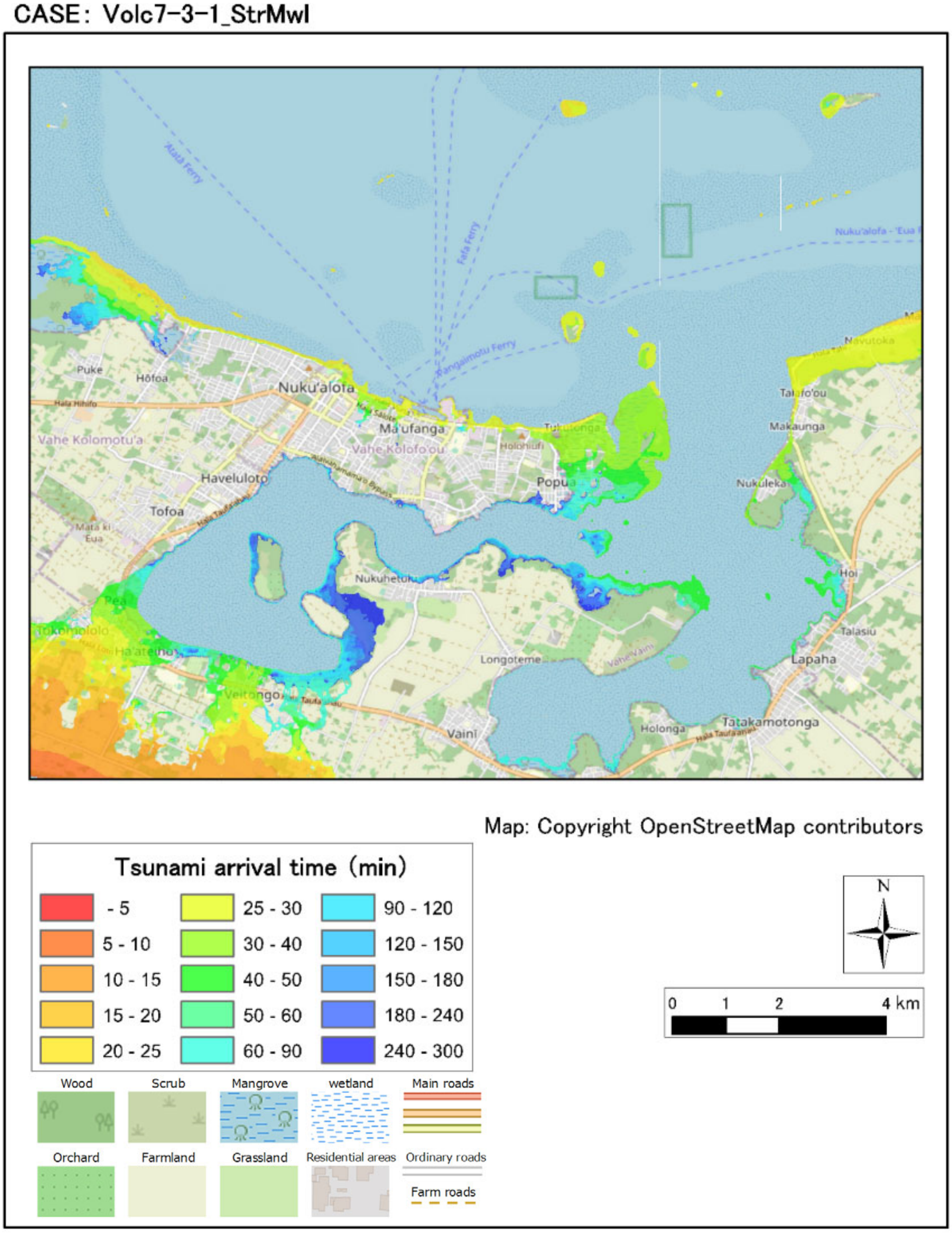
Figure 2.6.96 Tsunami Arraival Time Distribution (Unamed2, H=90m)

CASE：Volc6-3-1_StrMwl



Source: JICA Study Team

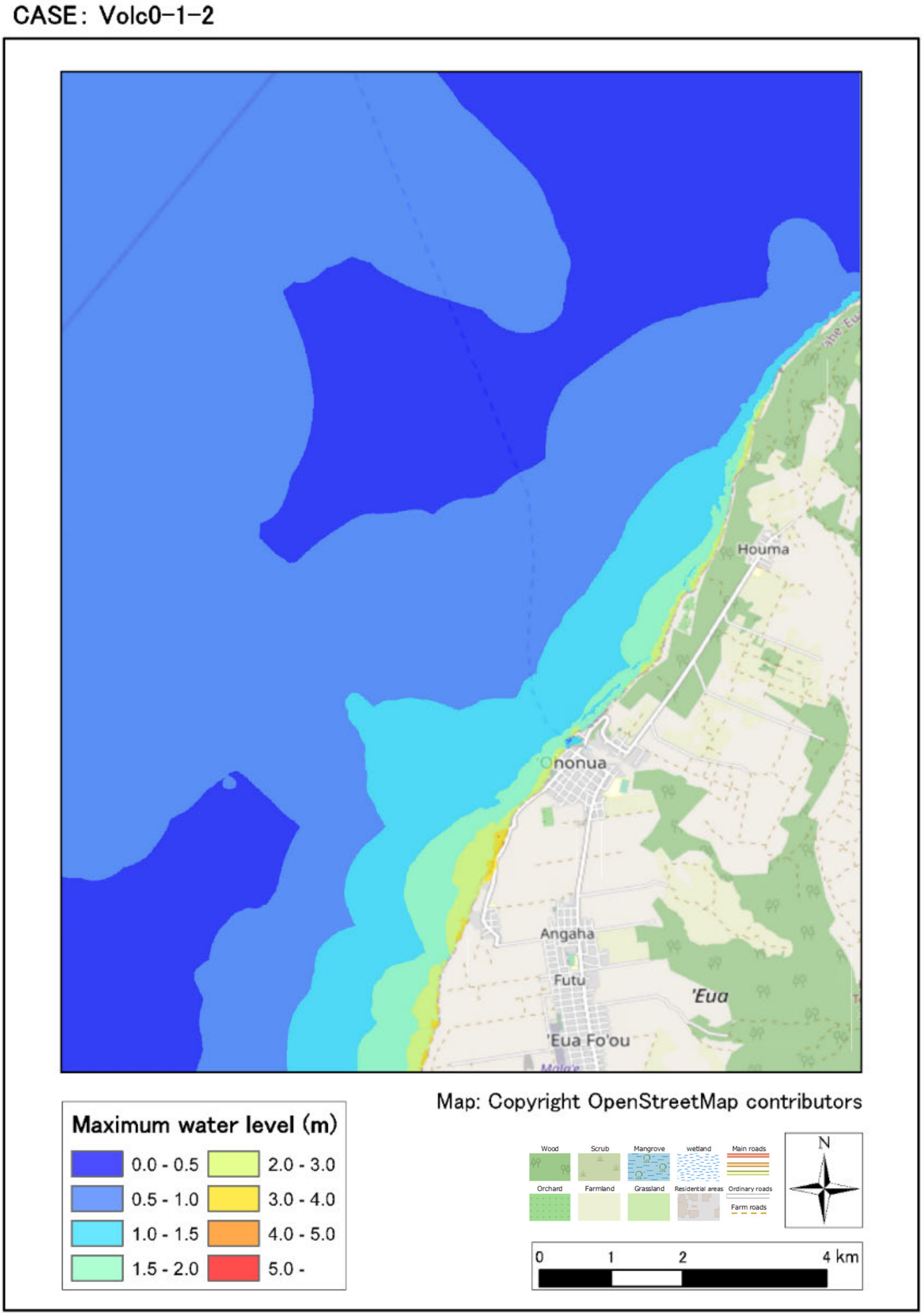
Figure 2.6.97 Tsunami Arraival Time Distribution (Unamed3, H=90m)



Source: JICA Study Team

Figure 2.6.98 Tsunami Arraival Time Distribution (Unamed4, H=90m)

4) Max Water Level Distribution (Ohonua, Eua Island.)



Source: JICA Study Team

Figure 2.6.99 Max Water Level Distribution (Hunga Tonga-Hunga Ha'pai, H=30m)

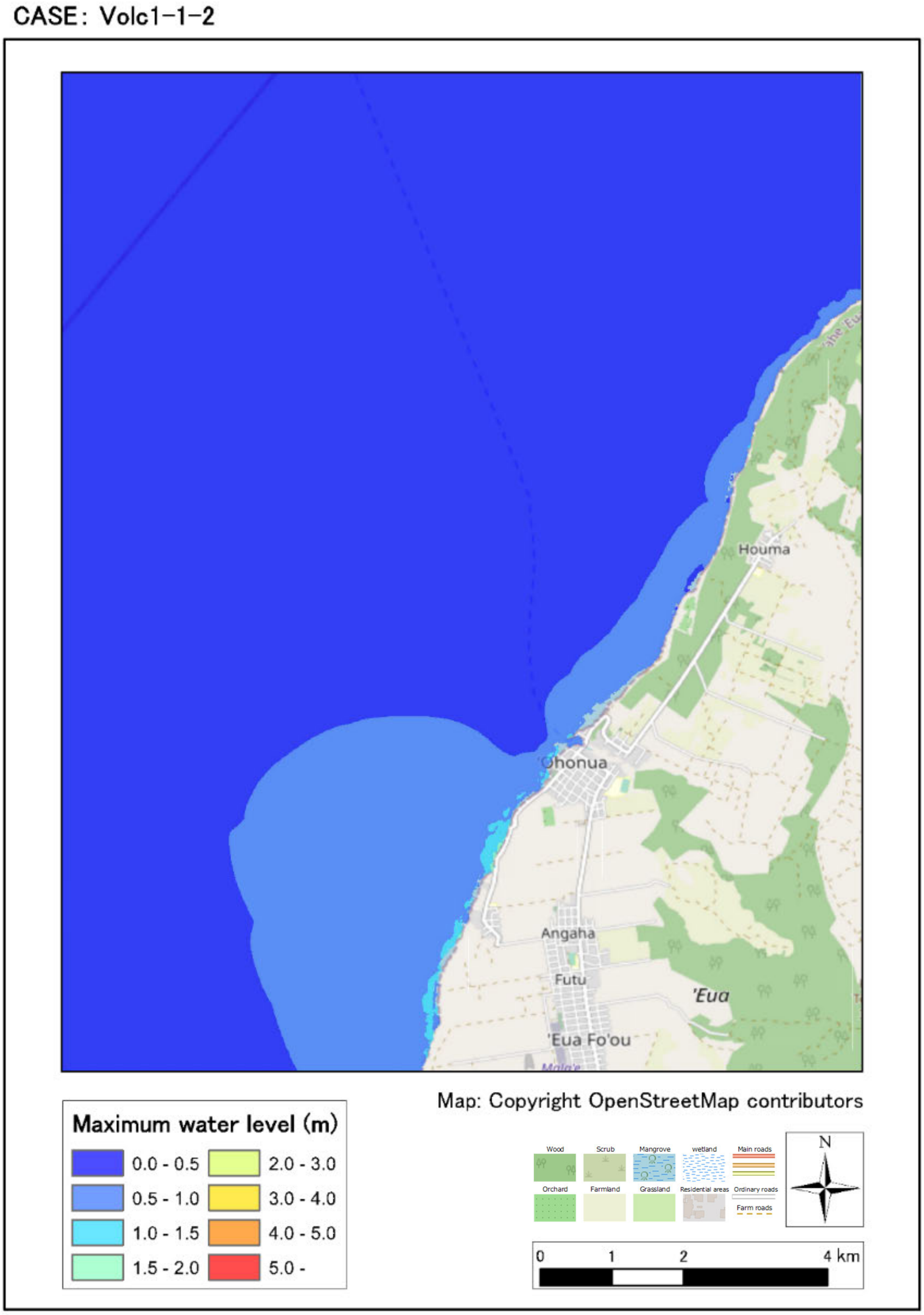
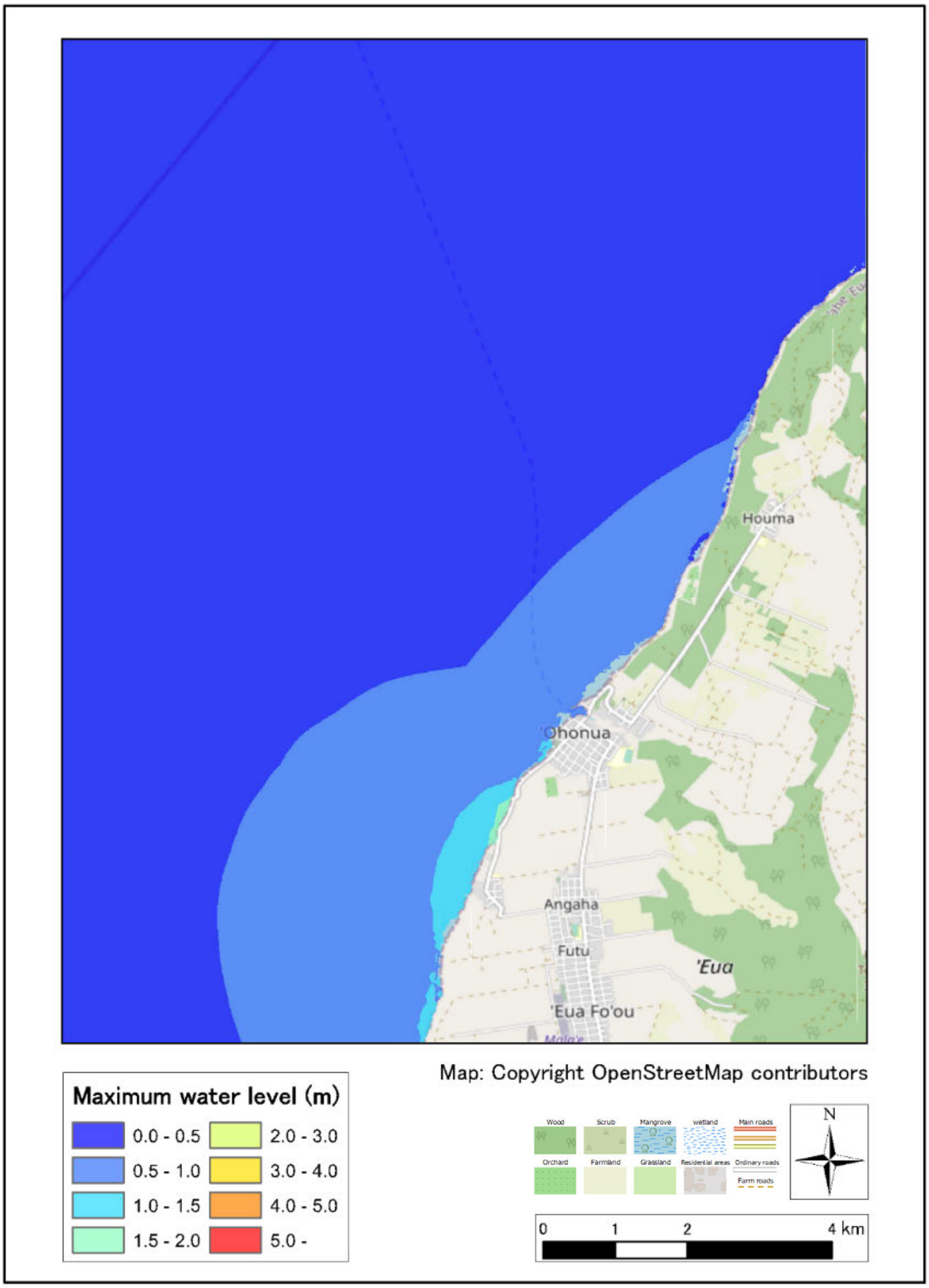


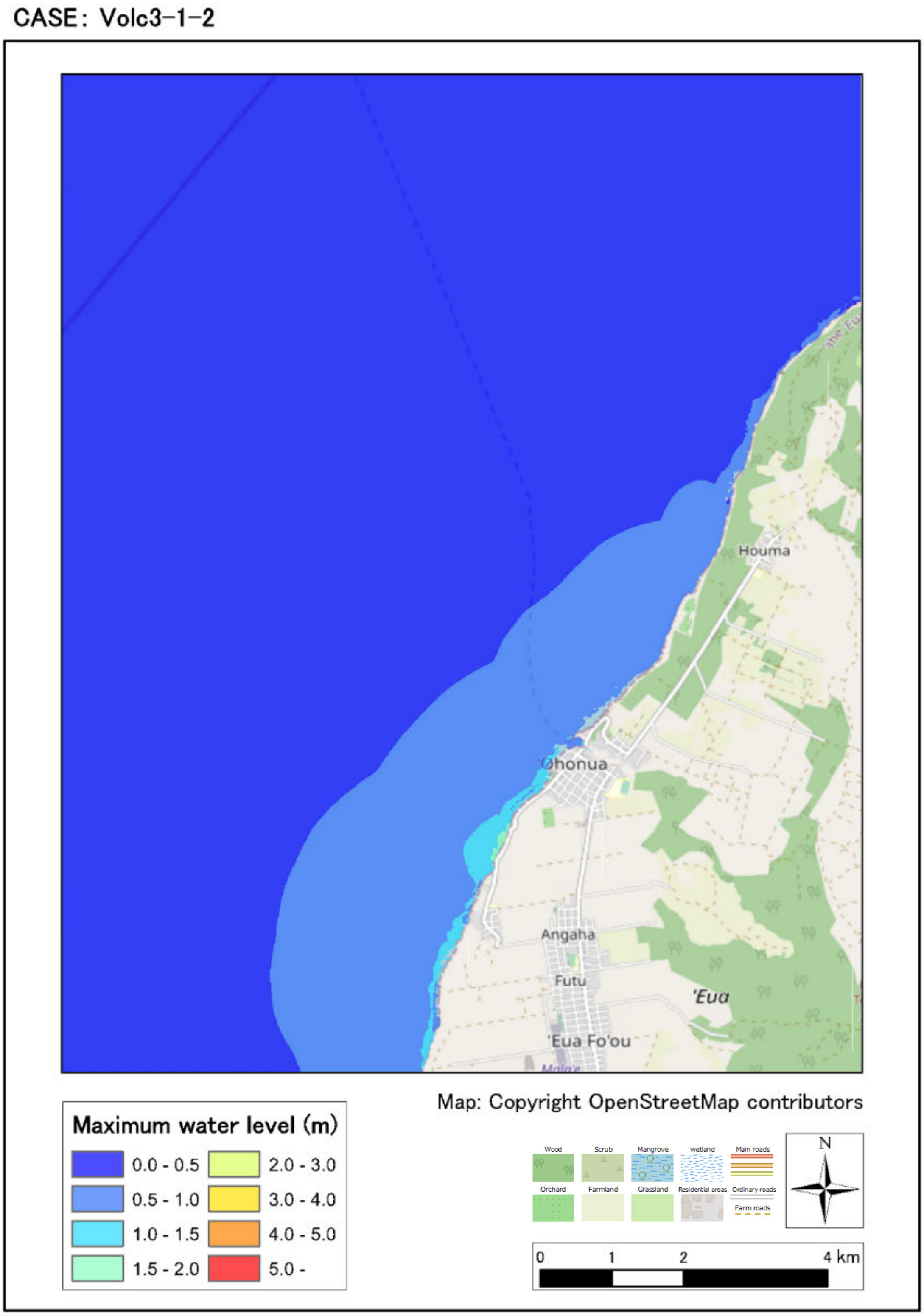
Figure 2.6.100 Max Water Level Distribution (Unnamed1, H=30m)

CASE：Volc2-1-2



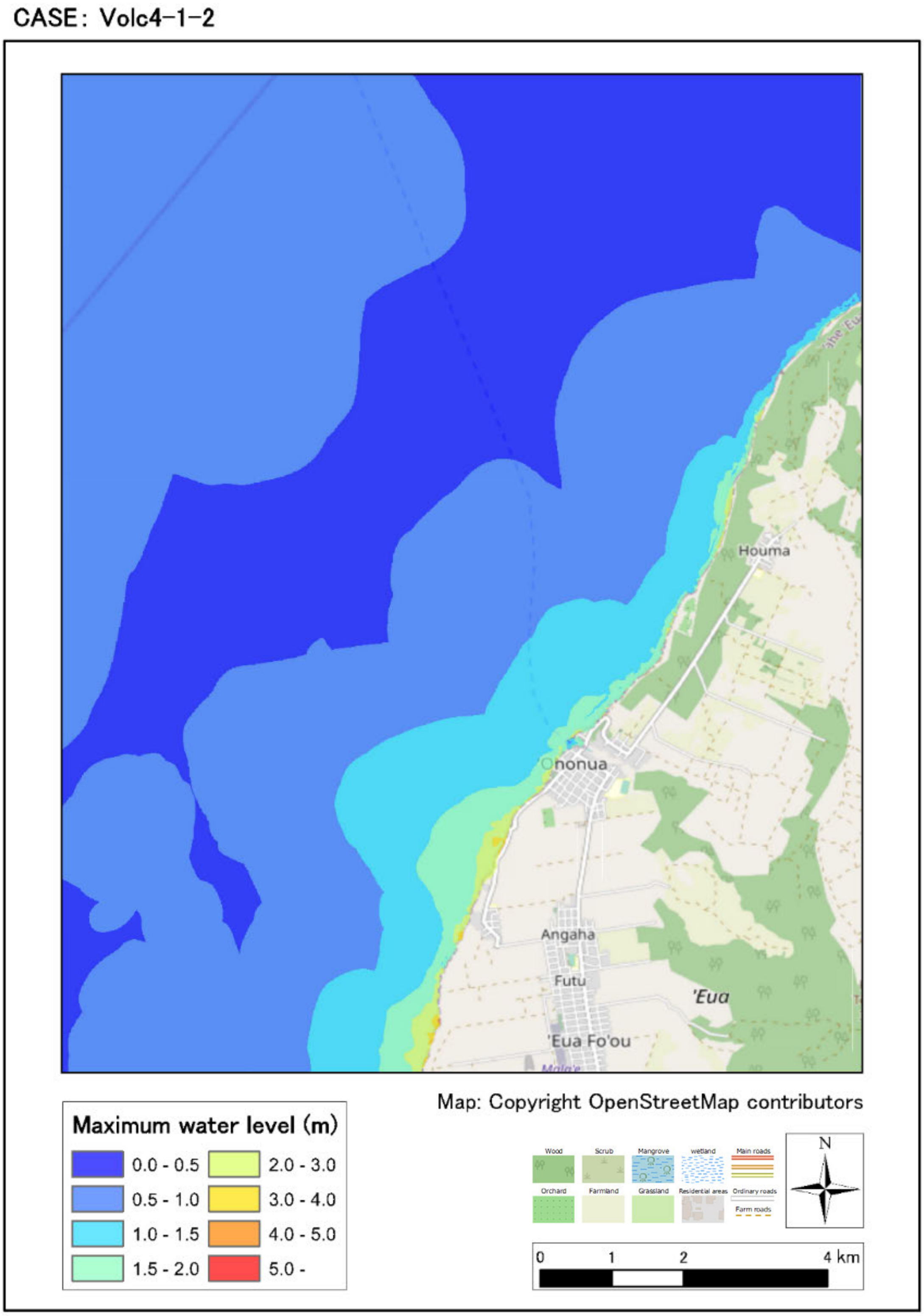
Source: JICA Study Team

Figure 2.6.101 Max Water Level Distribution (HomeReef, H=30m)



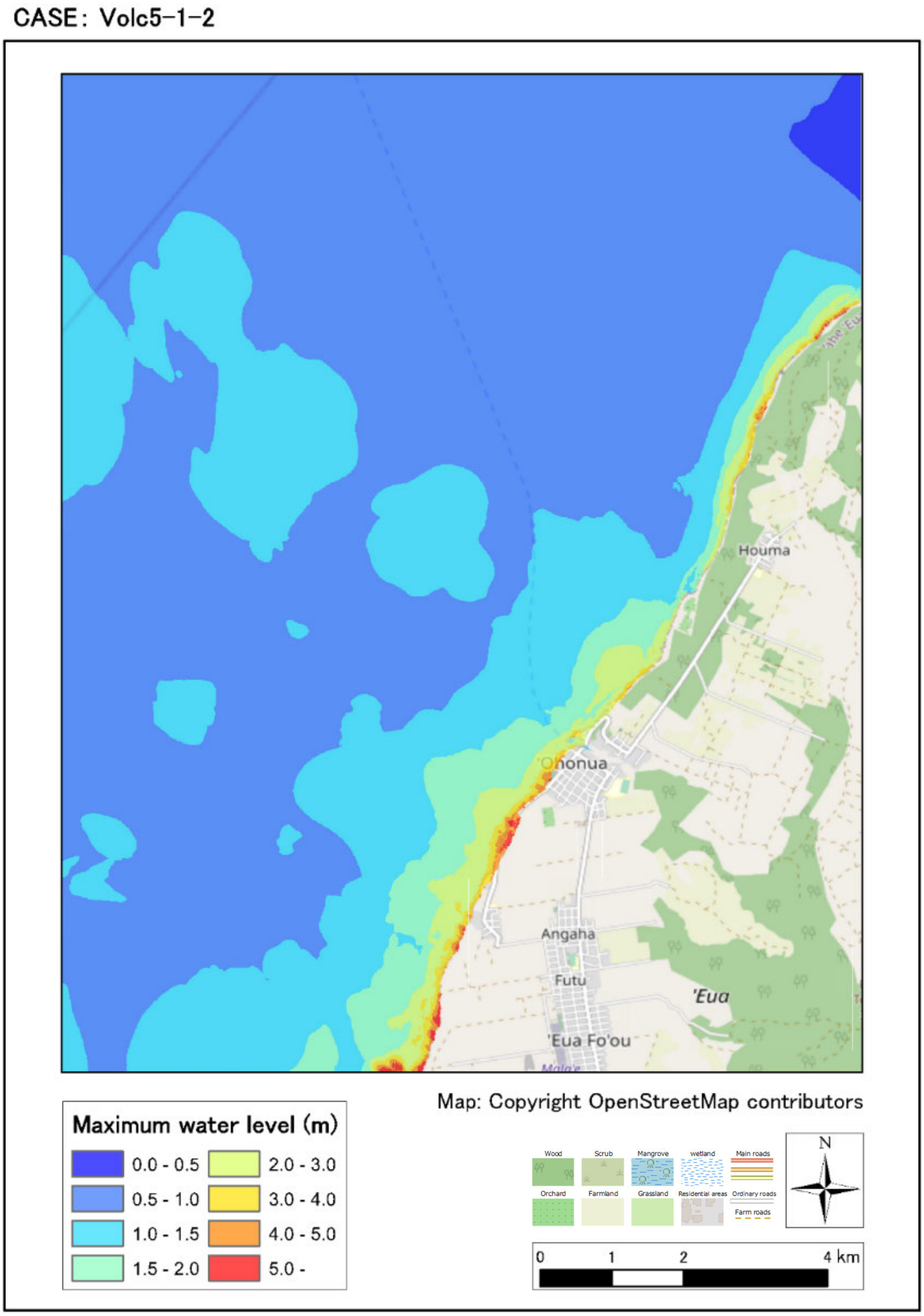
Source: JICA Study Team

Figure 2.6.102 Max Water Level Distribution (Lateiki, H=30m)



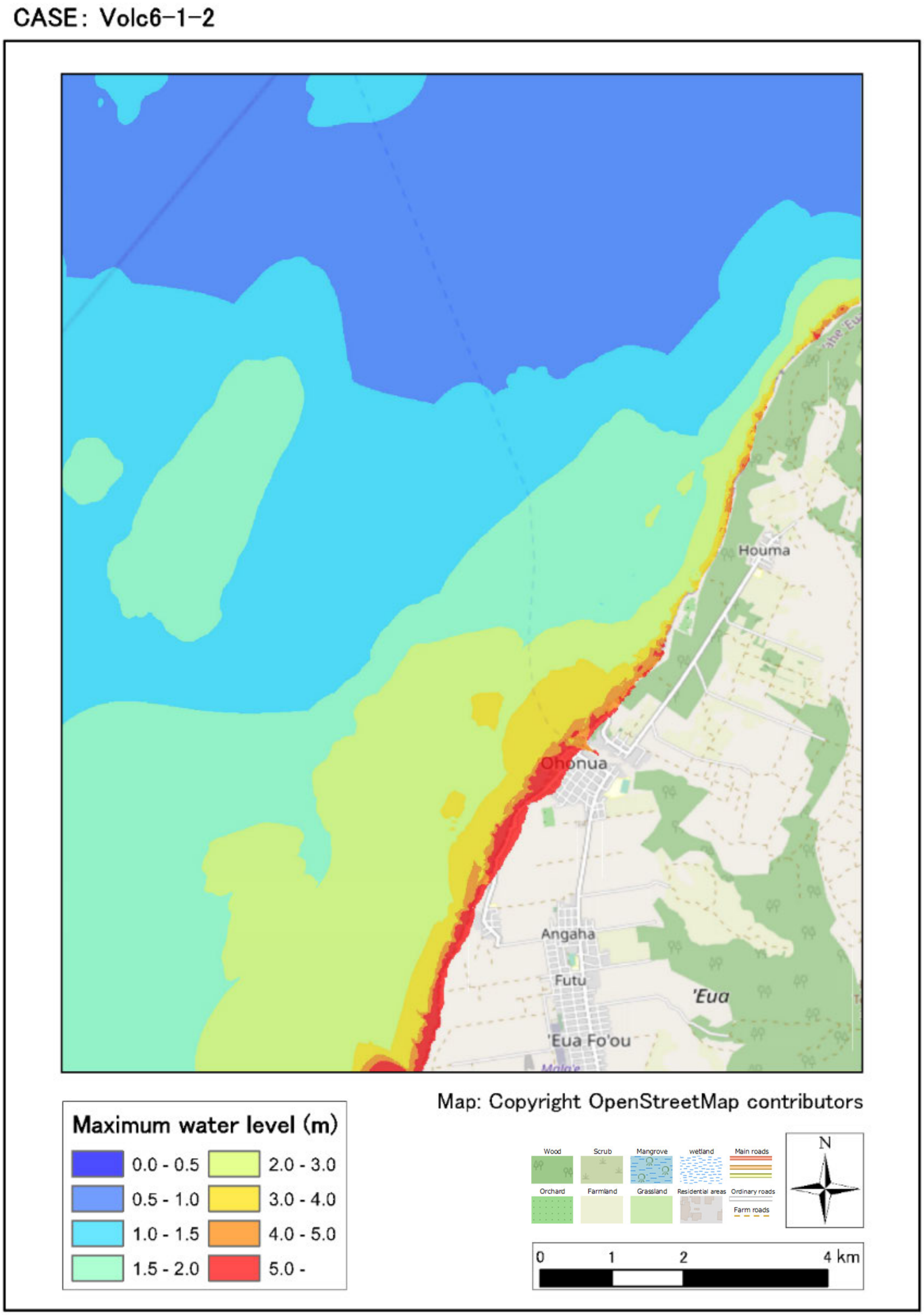
Source: JICA Study Team

Figure 2.6.103 Max Water Level Distribution (Fonuafo'ou H=30m)



Source: JICA Study Team

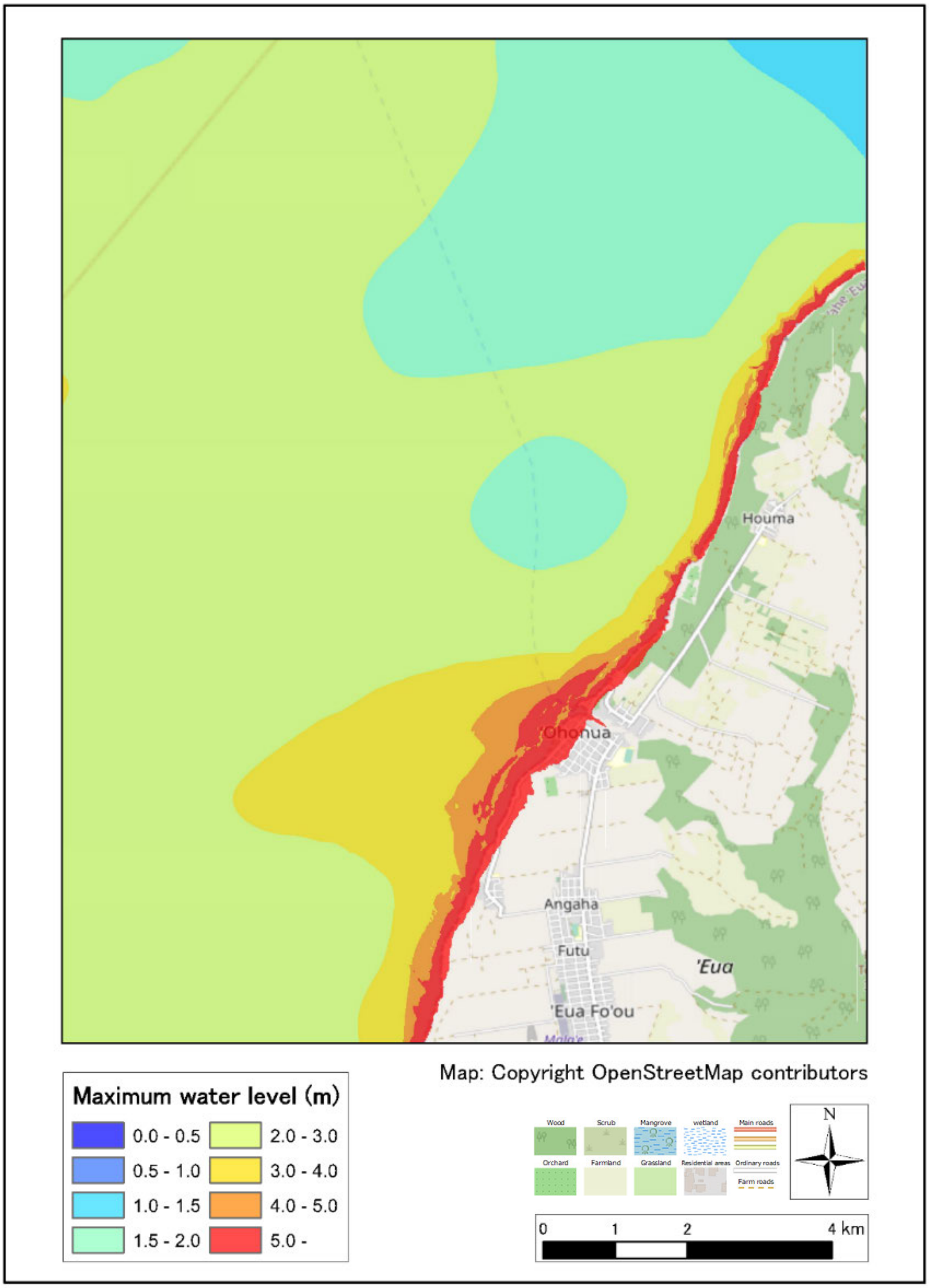
Figure 2.6.104 Max Water Level Distribution (Unamed2, H=30m)



Source: JICA Study Team

Figure 2.6.105 Max Water Level Distribution (Unamed3, H=30m)

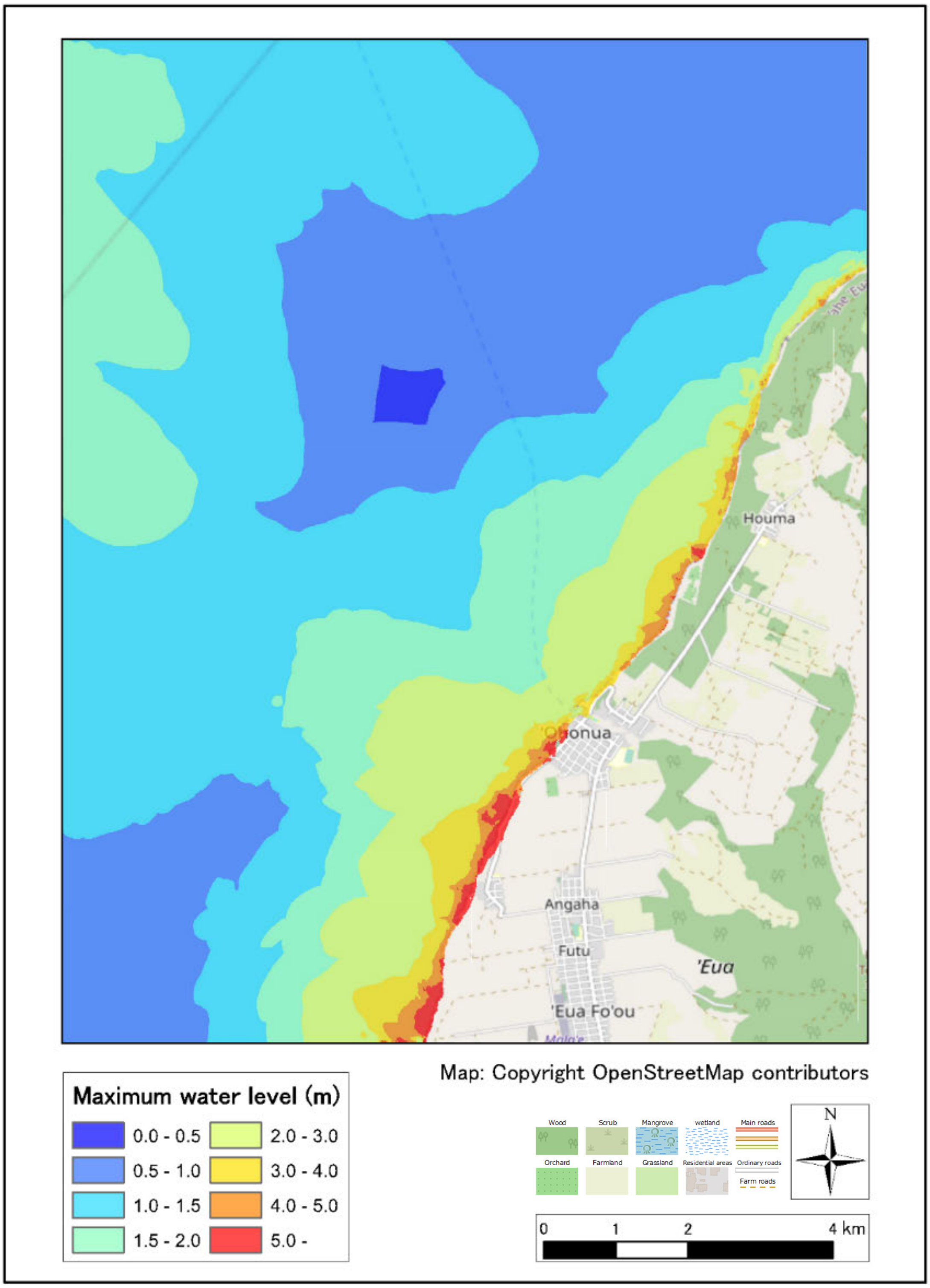
CASE: Volc7-1-2



Source: JICA Study Team

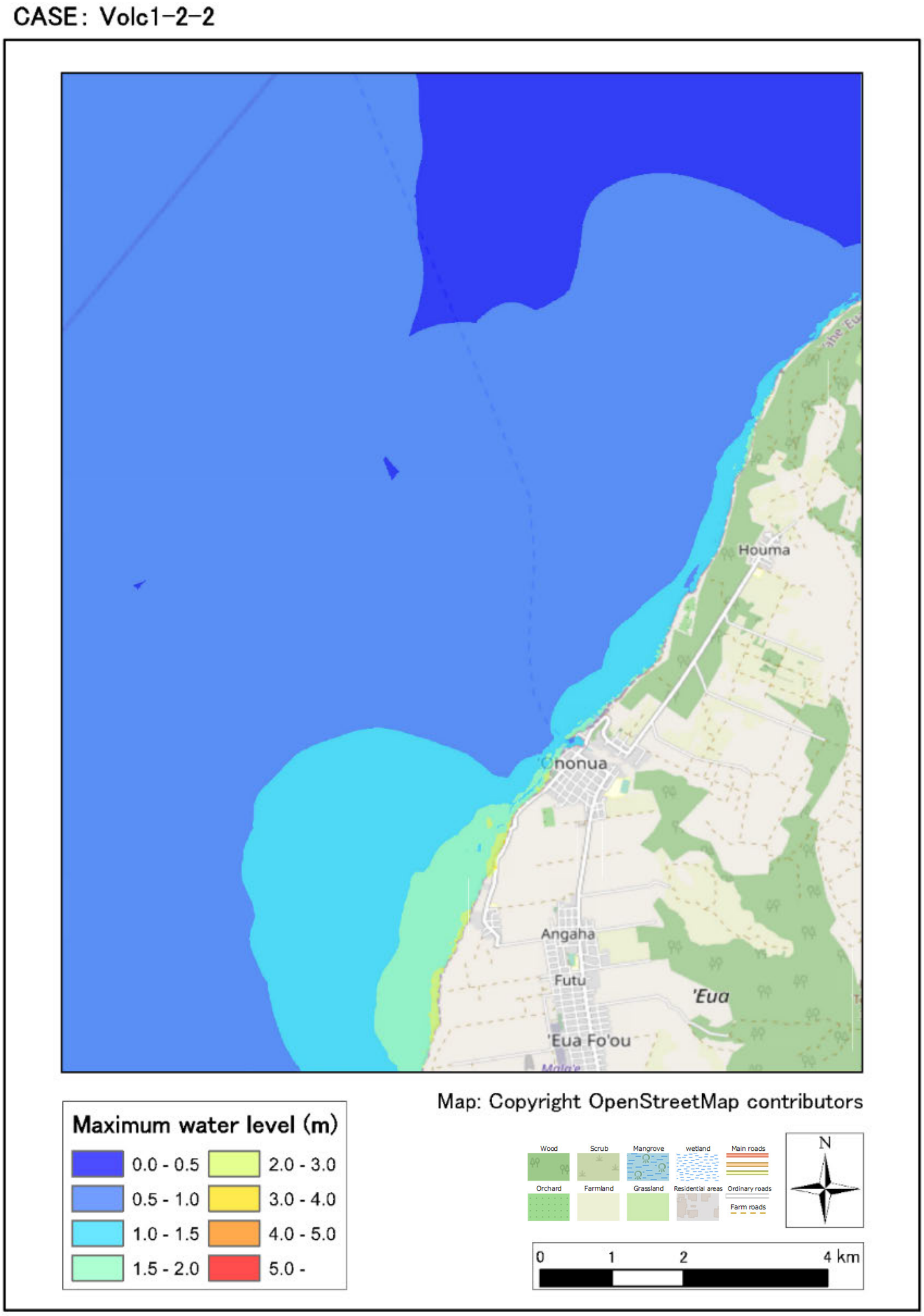
Figure 2.6.106 Max Water Level Distribution (Unamed4, H=30m)

CASE: Volc0-2-2



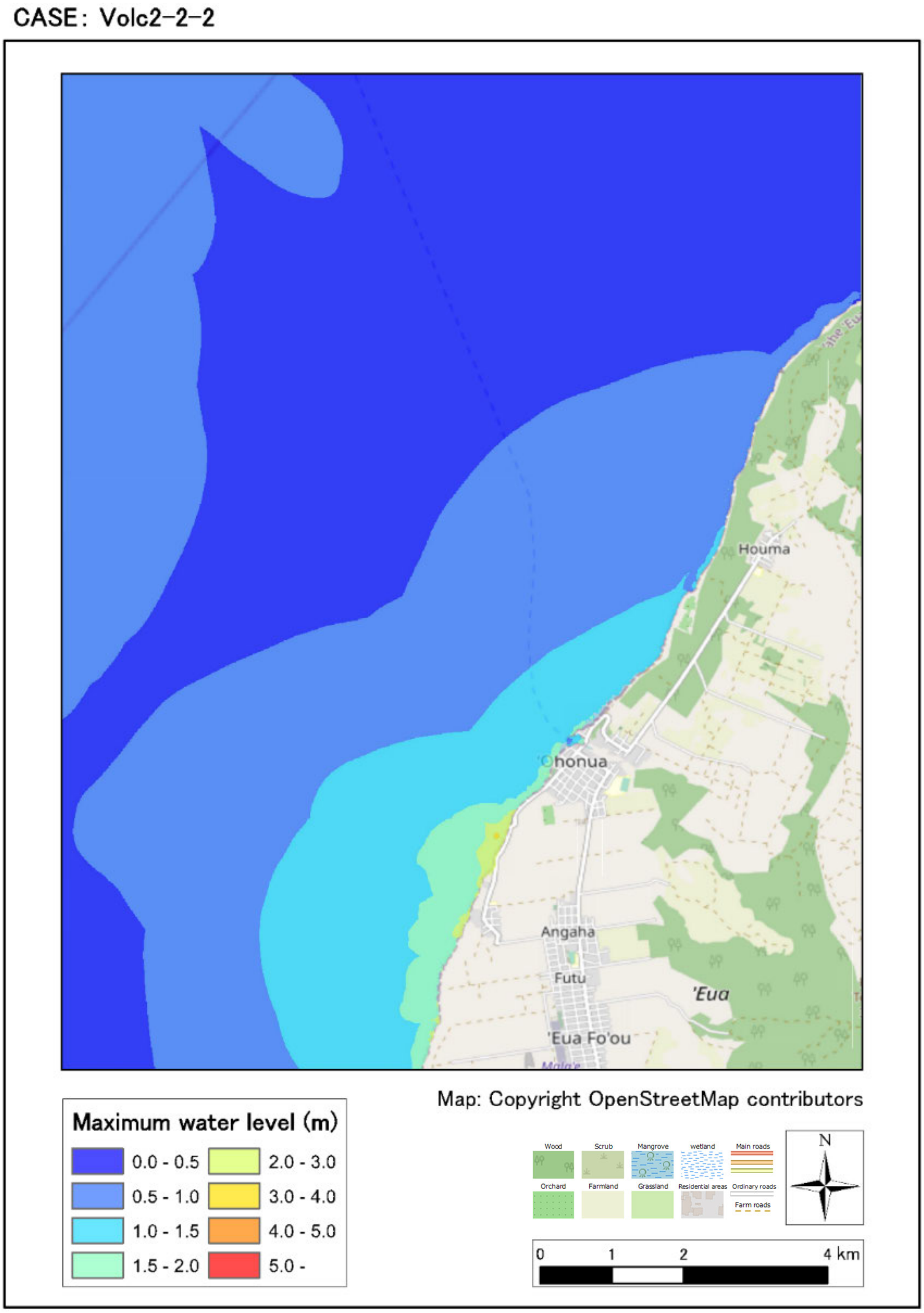
Source: JICA Study Team

Figure 2.6.107 Max Water Level Distribution (Hunga Tonga-Hunga Ha'pai, H=60m)



Source: JICA Study Team

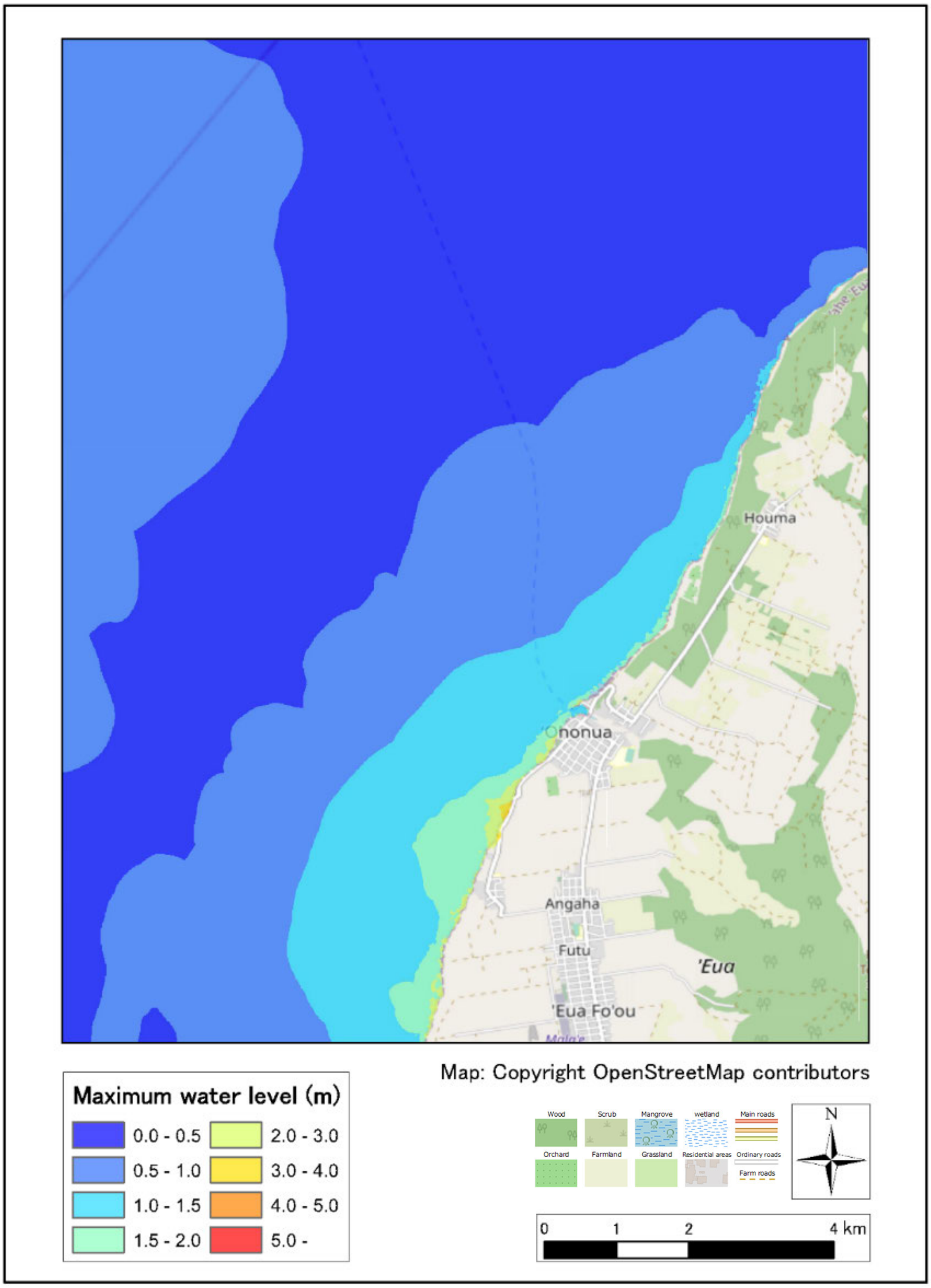
Figure 2.6.108 Max Water Level Distribution (Unnamed1, H=60m)



Source: JICA Study Team

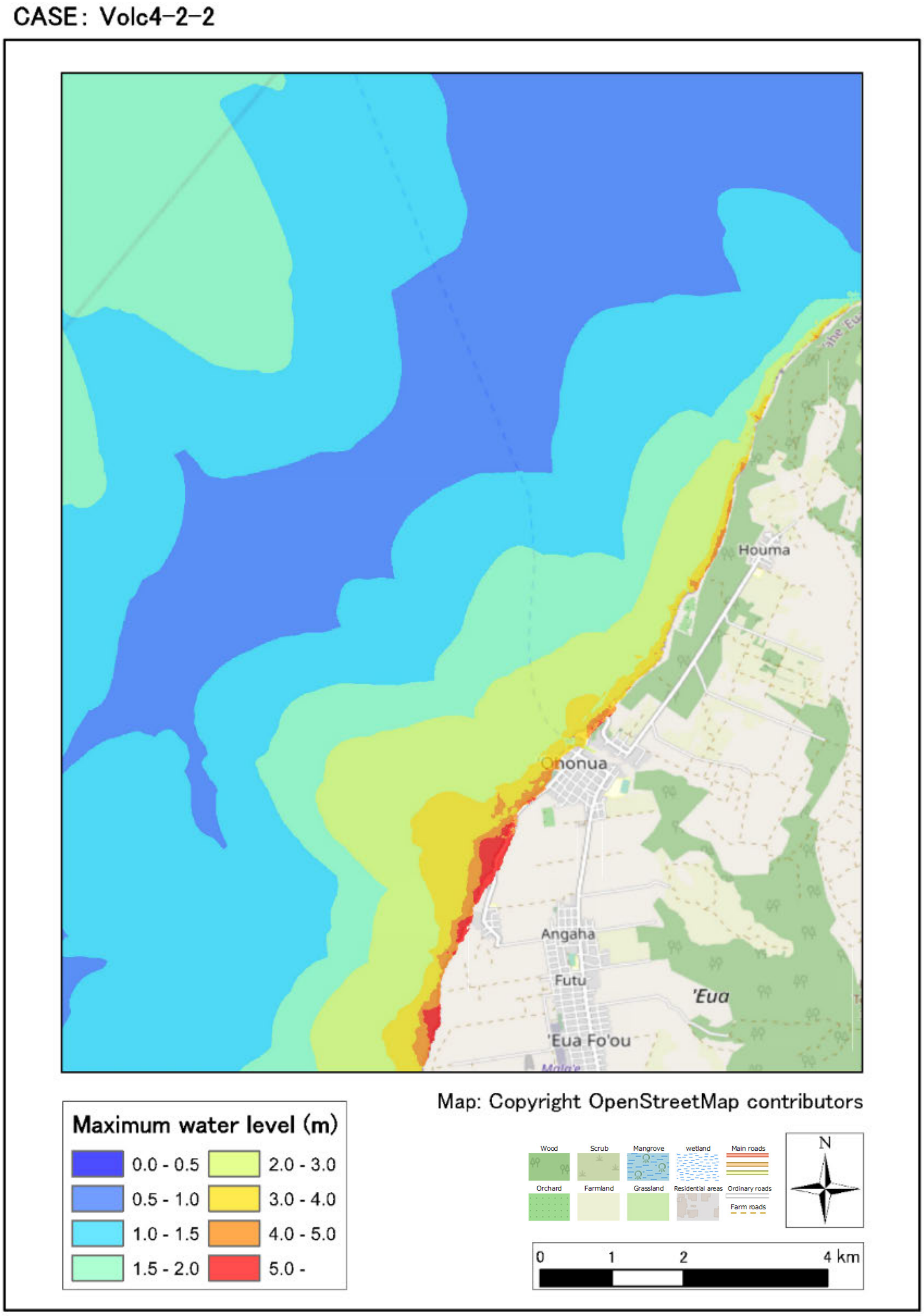
Figure 2.6.109 Max Water Level Distribution (HomeReef, H=60m)

CASE: Volc3-2-2



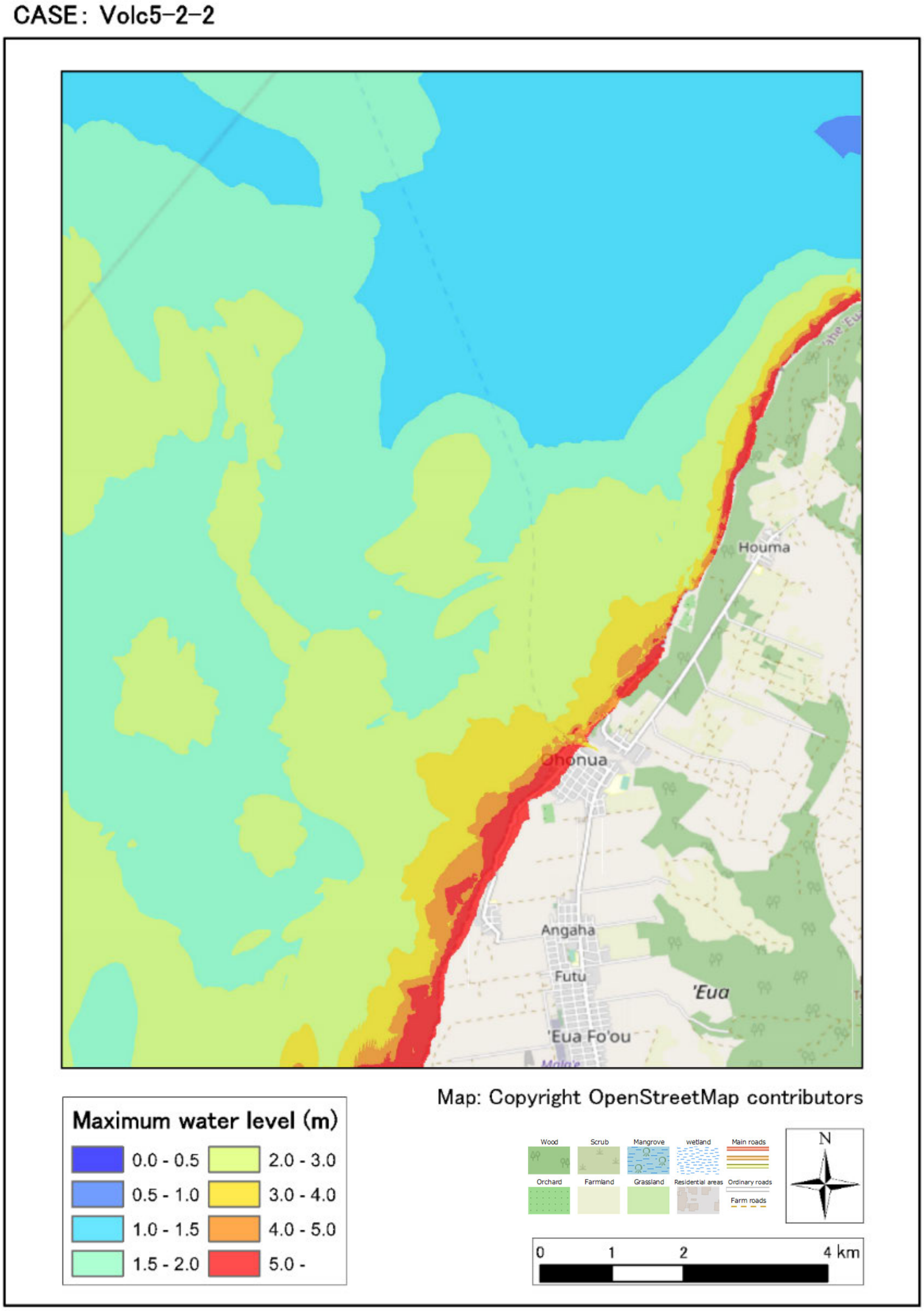
Source: JICA Study Team

Figure 2.6.110 Max Water Level Distribution (Lateiki, H=60m)



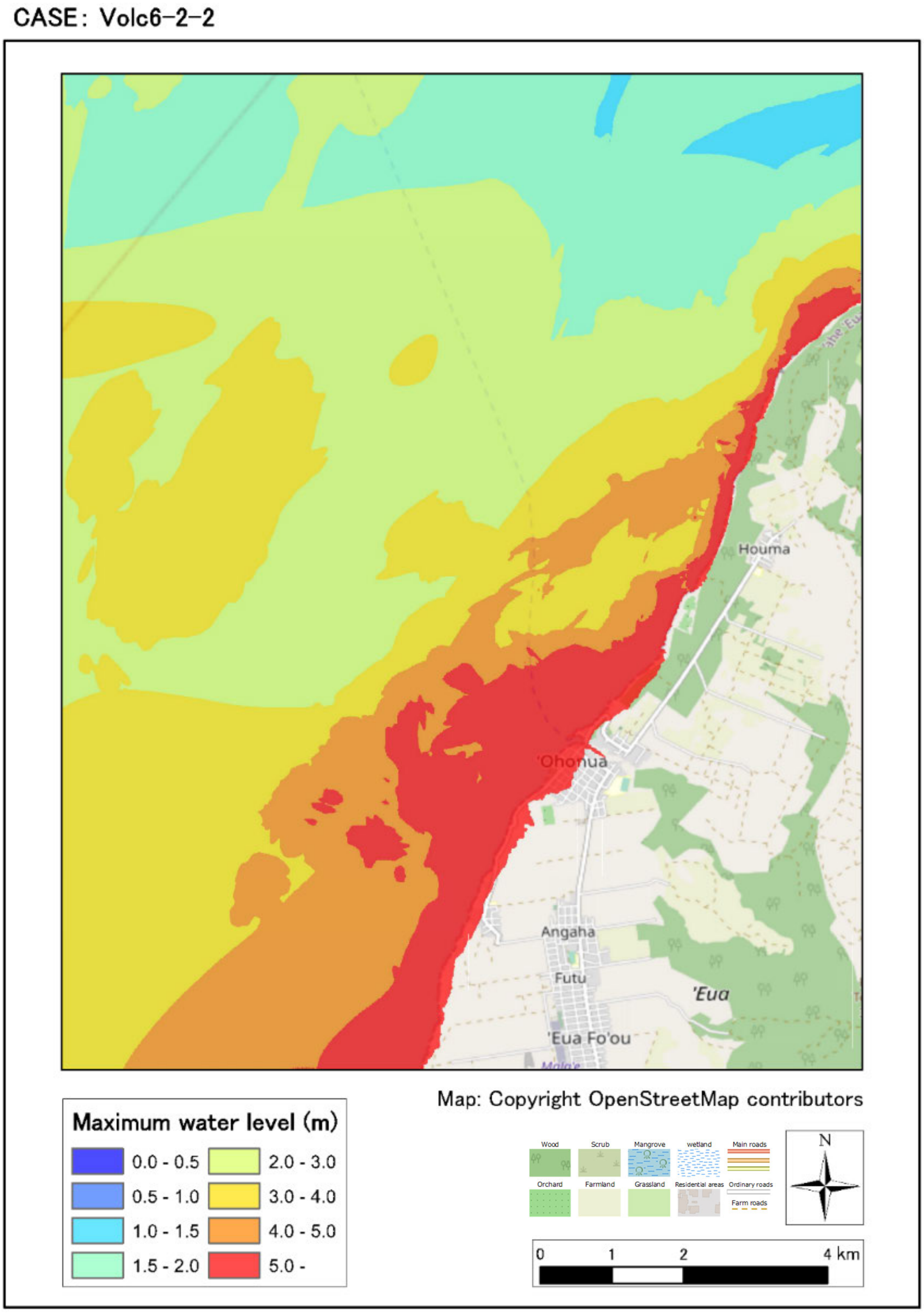
Source: JICA Study Team

Figure 2.6.111 Max Water Level Distribution (Fonuafo'ou, H=60m)



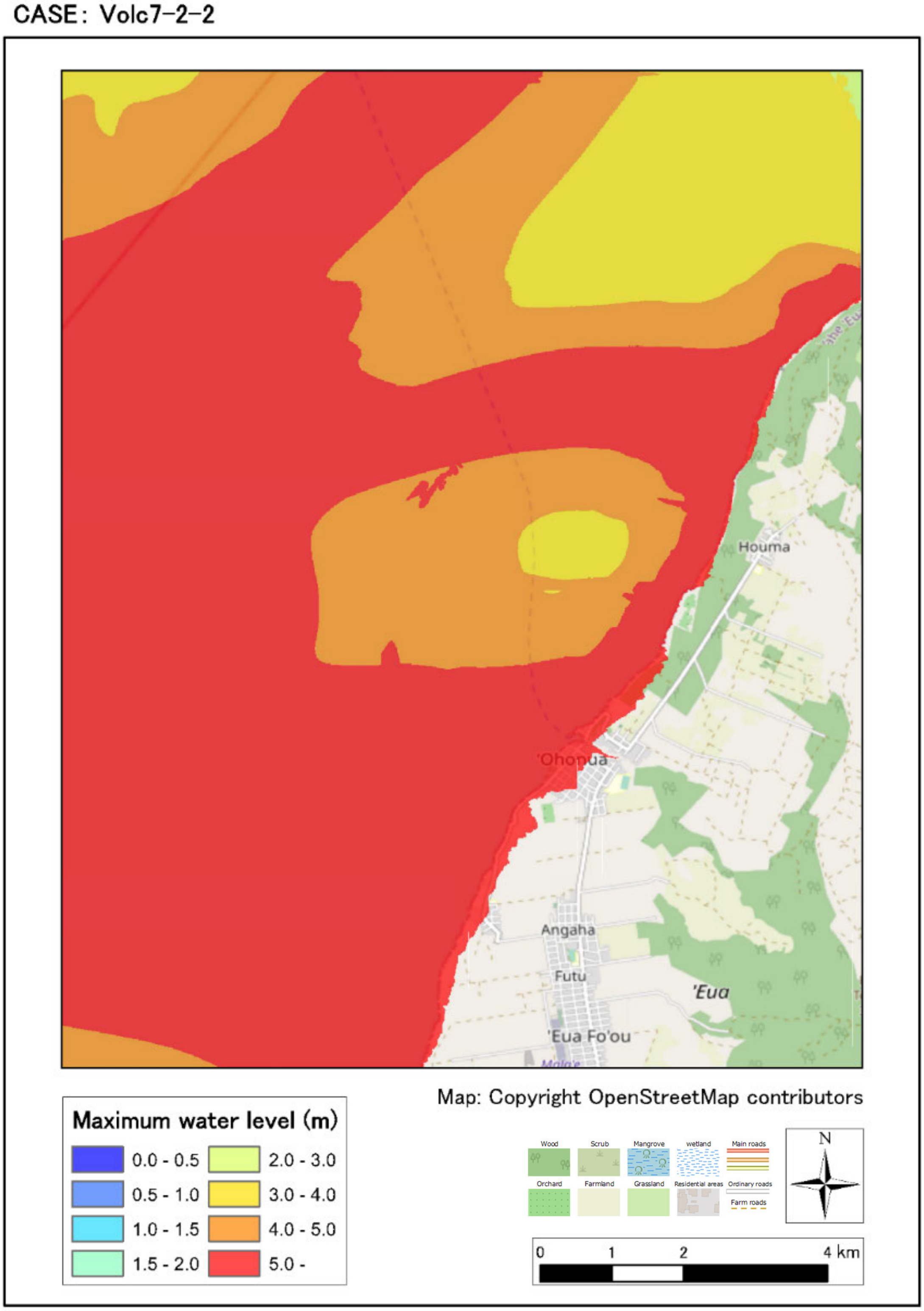
Source: JICA Study Team

Figure 2.6.112 Max Water Level Distribution (Unamed2, H=60m)



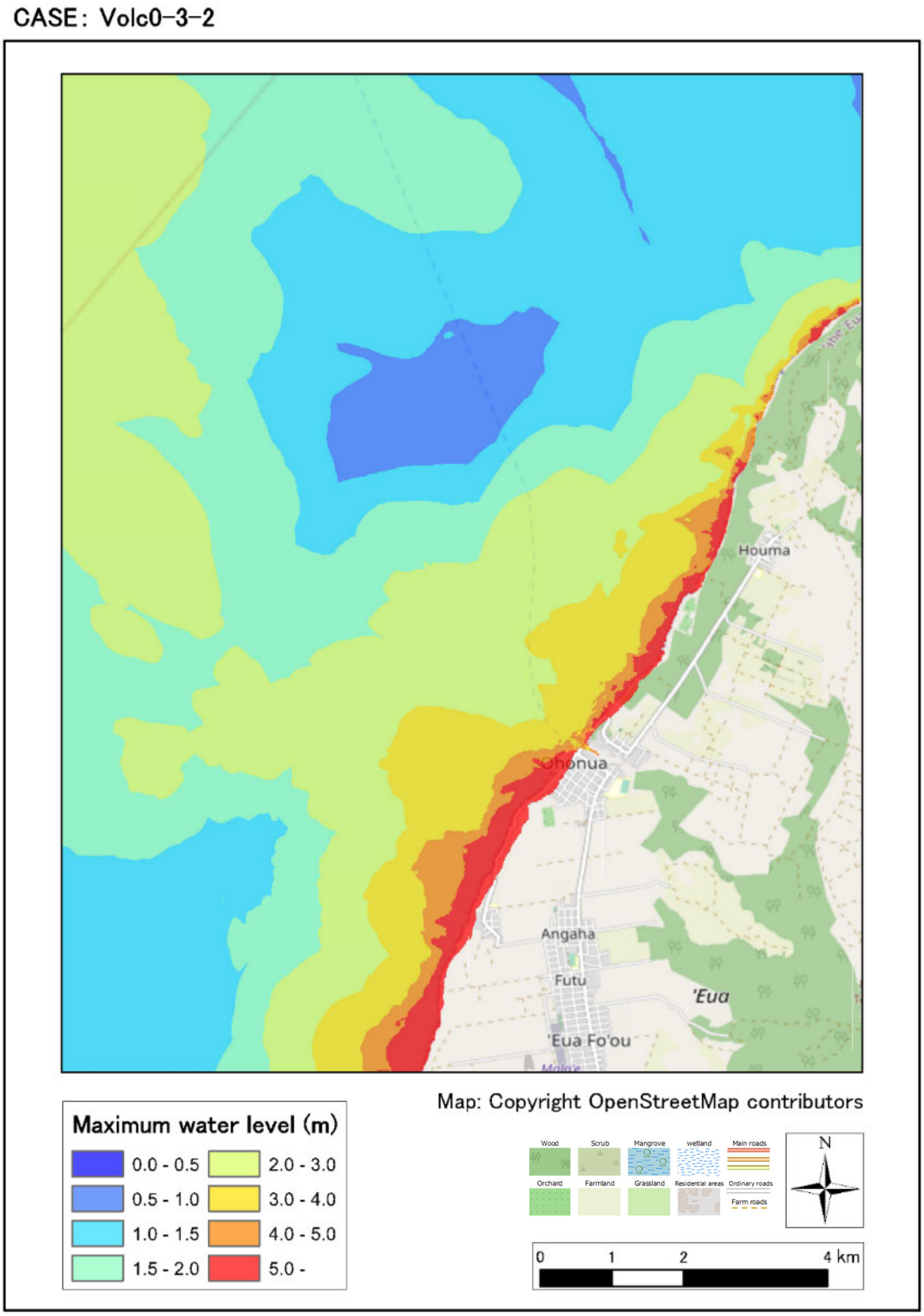
Source: JICA Study Team

Figure 2.6. 113 Max Water Level Distribution (Unamed3, H=60m)



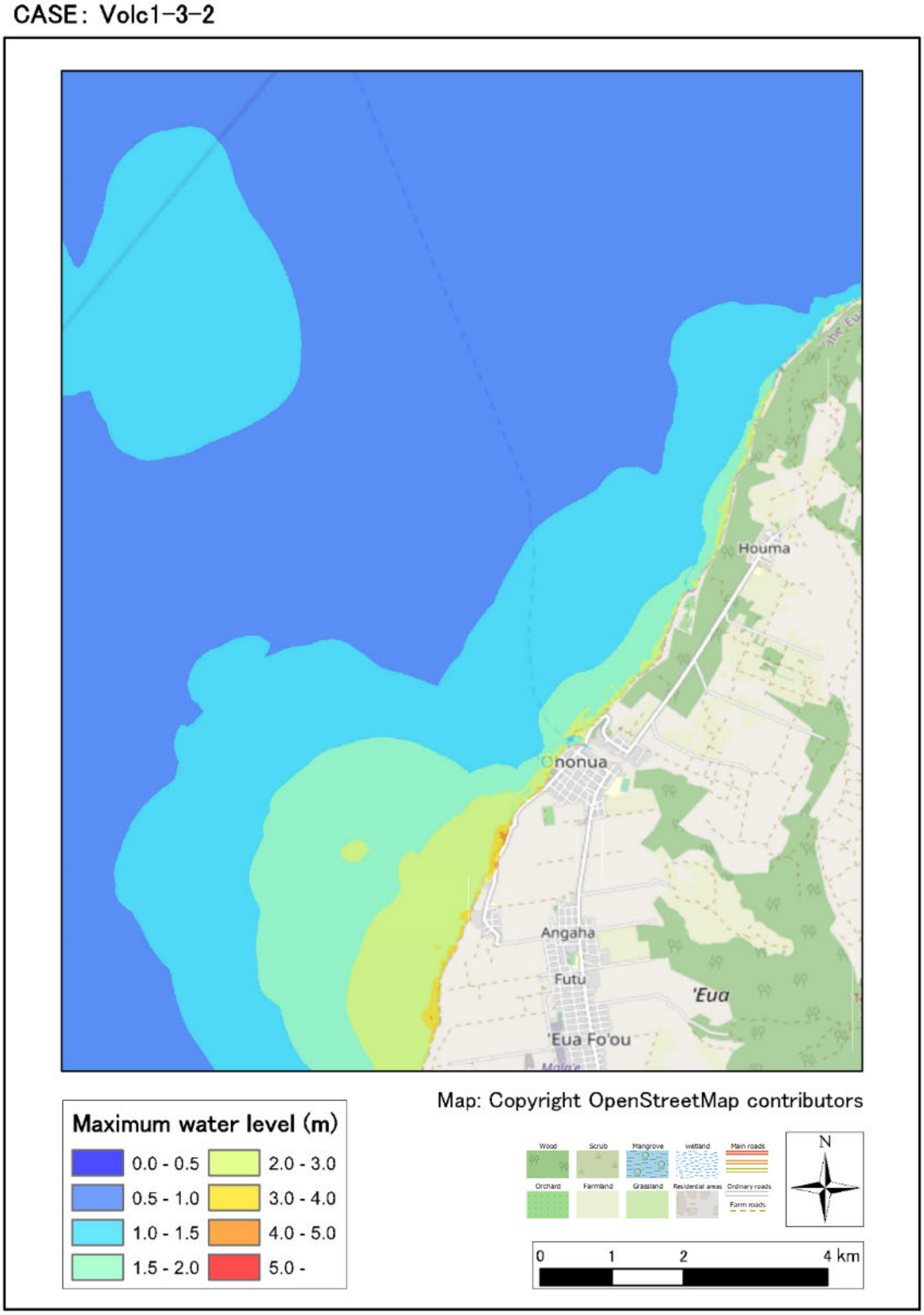
Source: JICA Study Team

Figure 2.6.114 Max Water Level Distribution (Unamed4, H=60m)



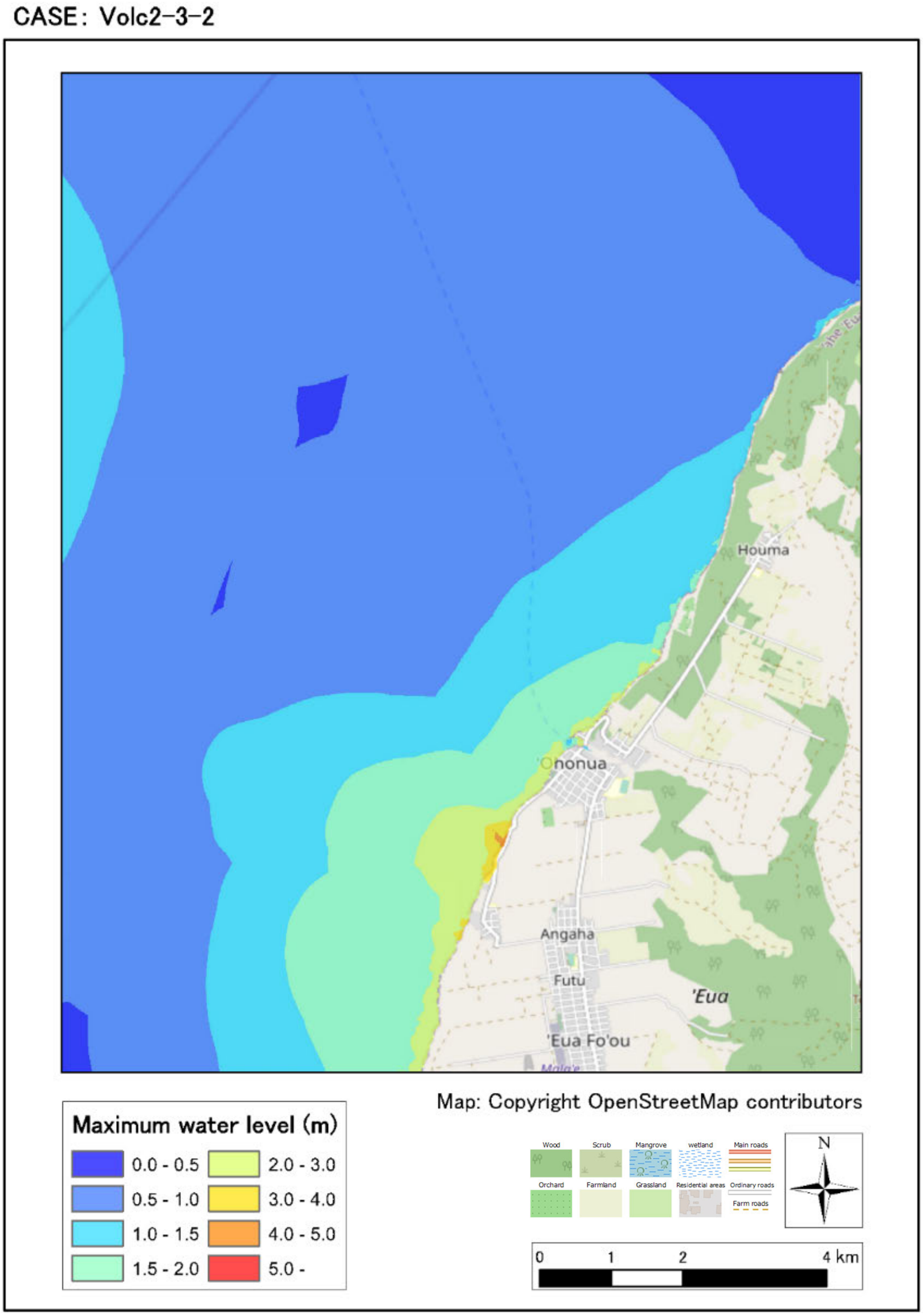
Source: JICA Study Team

Figure 2.6.115 Max Water Level Distribution (Hunga Tonga-Hunga Ha'pai, H=90m)



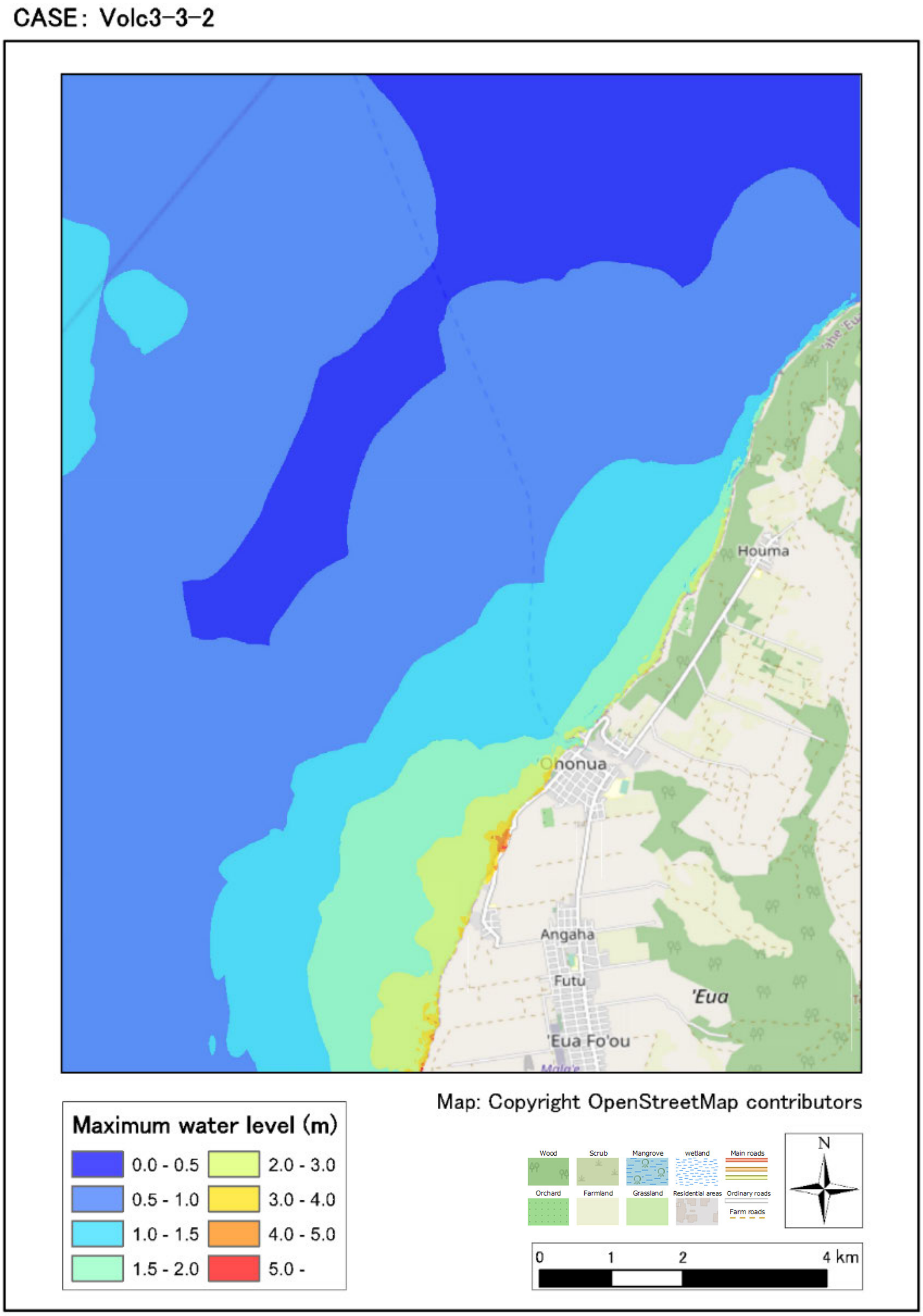
Source: JICA Study Team

Figure 2.6.116 Max Water Level Distribution (Unnamed1, H=90m)



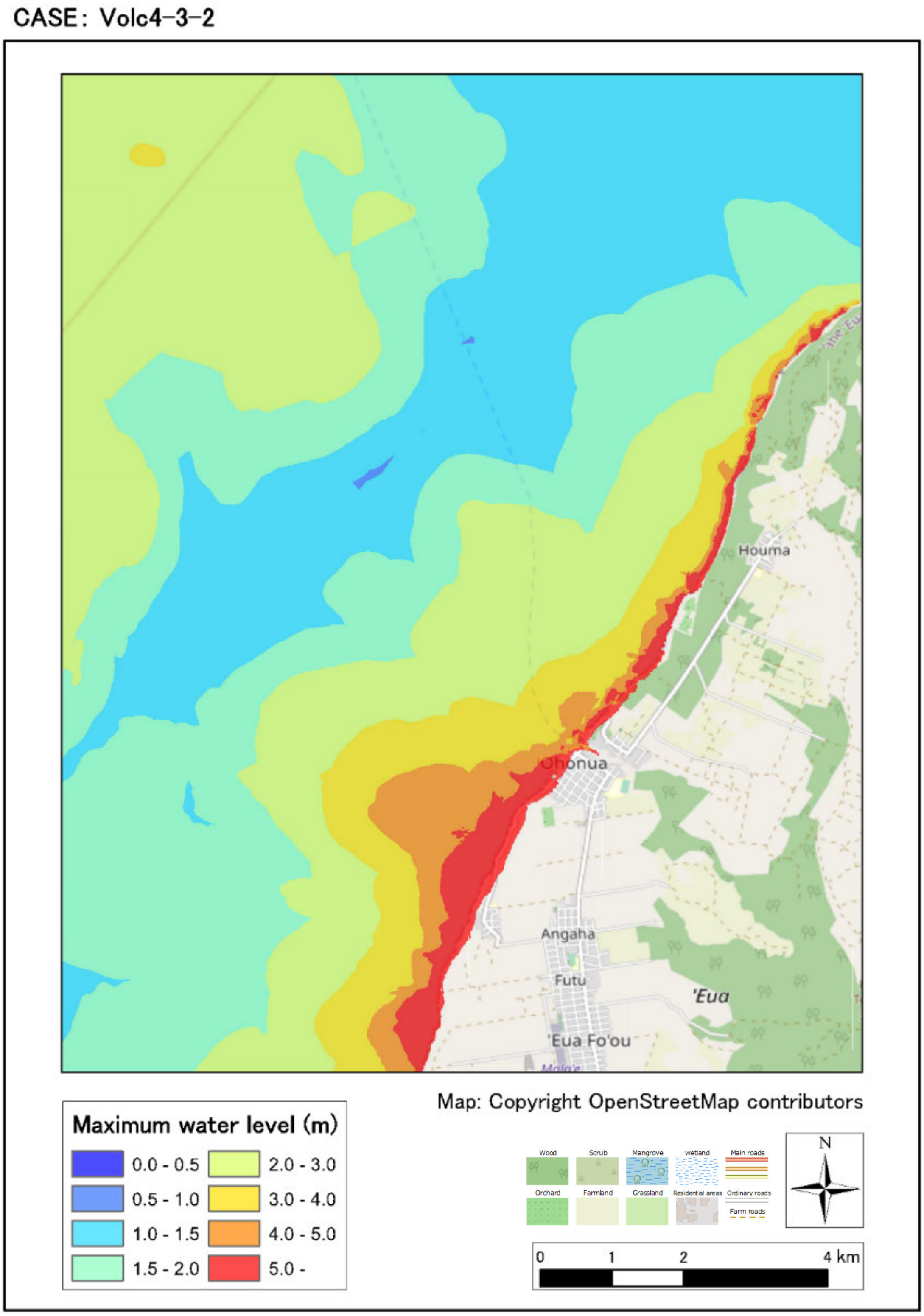
Source: JICA Study Team

Figure 2.6.117 Max Water Level Distribution (HomeReef, H=90m)



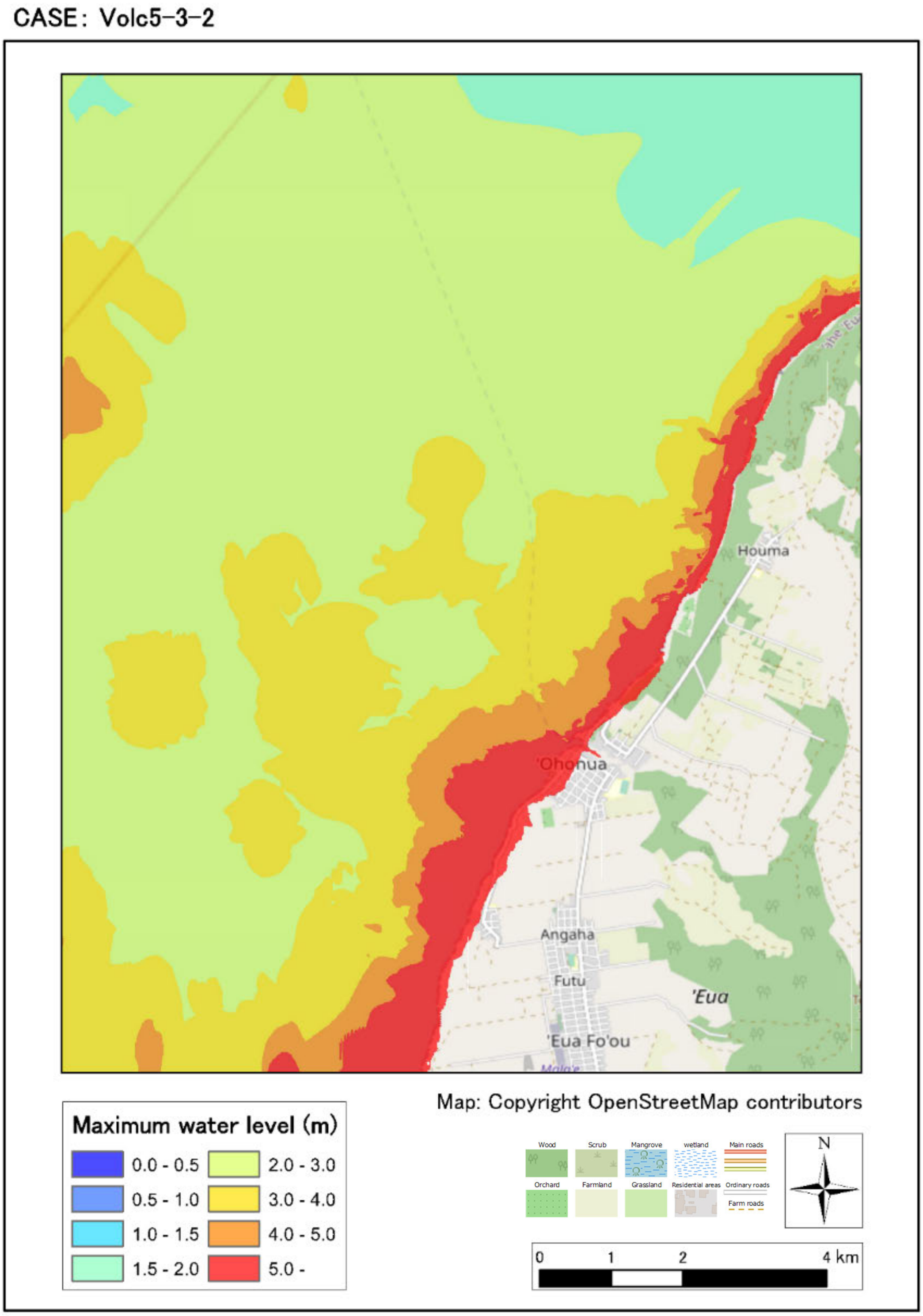
Source: JICA Study Team

Figure 2.6.118 Max Water Level Distribution (Lateiki, H=90m)



Source: JICA Study Team

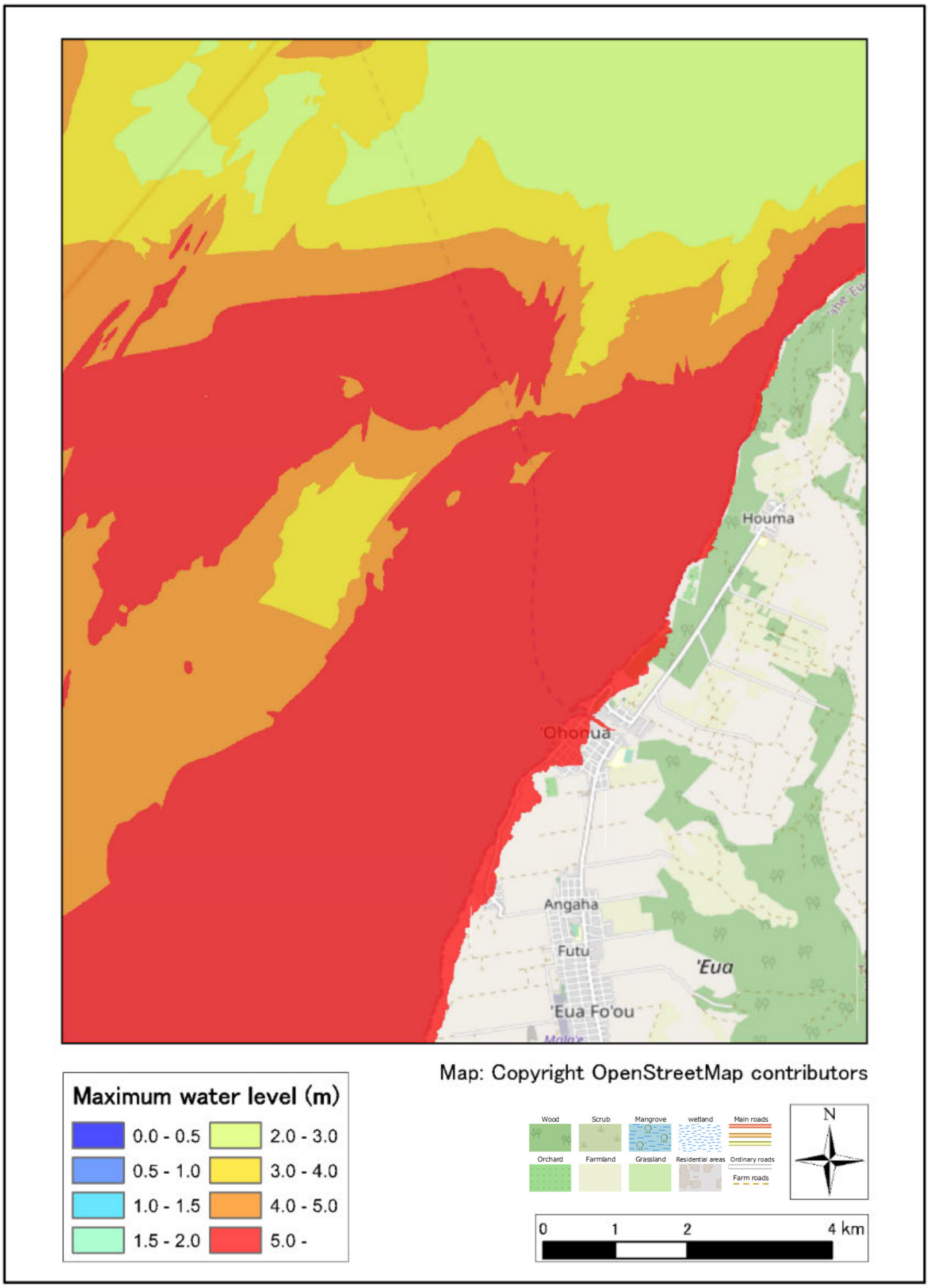
Figure 2.6.119 Max Water Level Distribution (Fonuafo'ou, H=90m)



Source: JICA Study Team

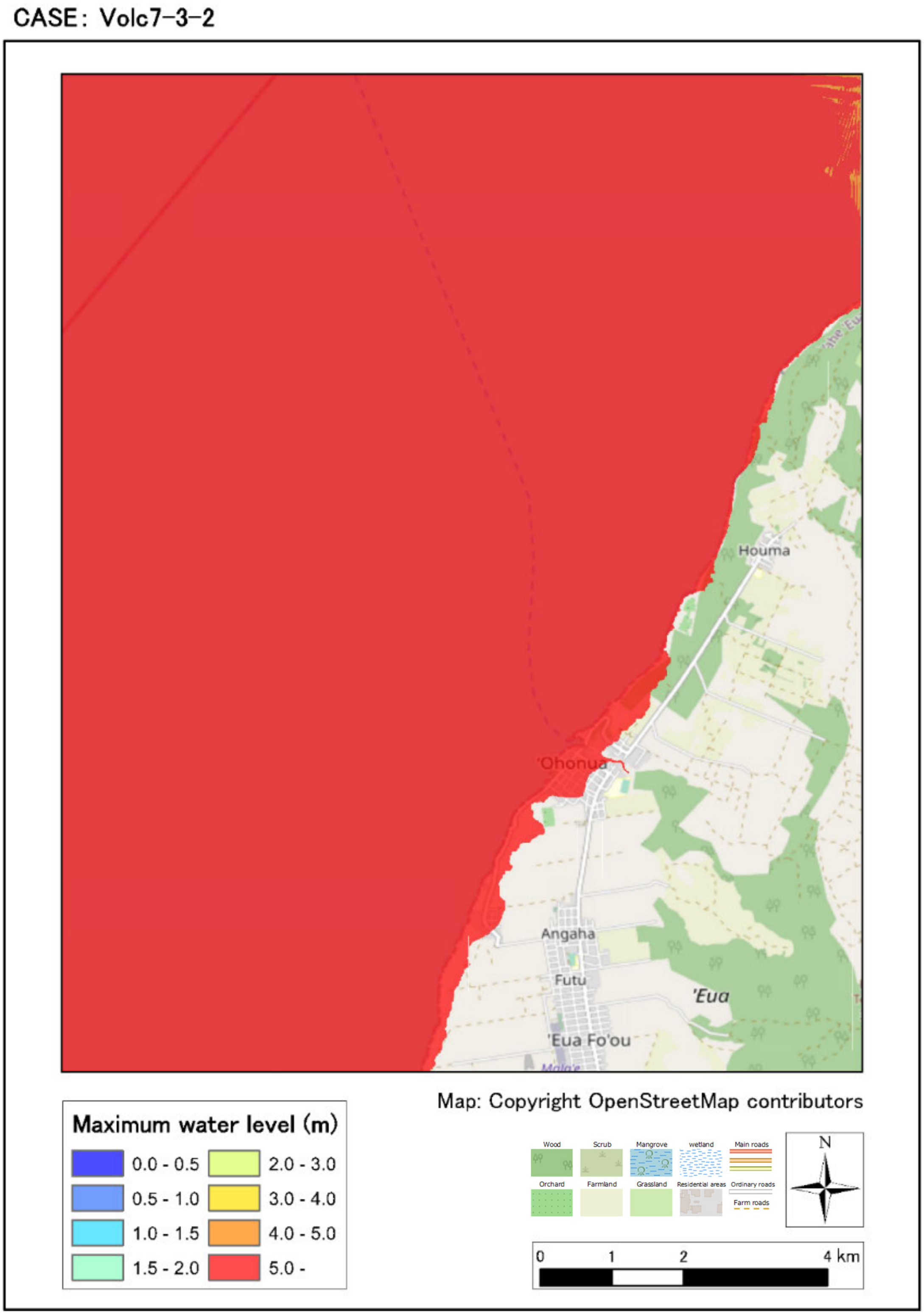
Figure 2.6.120 Max Water Level Distribution (Unamed2, H=90m)

CASE: Volc6-3-2



Source: JICA Study Team

Figure 2.6.121 Max Water Level Distribution (Unamed3, H=90m)



Source: JICA Study Team

Figure 2.6.122 Max Water Level Distribution (Unamed4, H=90m)

5) Max inundation depth distribution (Ohonua, Eua Island).

Source: JICA Study Team

Figure 2.6.123 Max inundation depth distribution (Hunga Tonga-Hunga Ha'pai, H=30m)

Source: JICA Study Team

Figure 2.6.124 Max inundation depth distribution (Unnamed1, H=30m)

Source: JICA Study Team

Figure 2.6.125 Max inundation depth distribution (HomeReef, H=30m)

CASE: Volc3-1-2

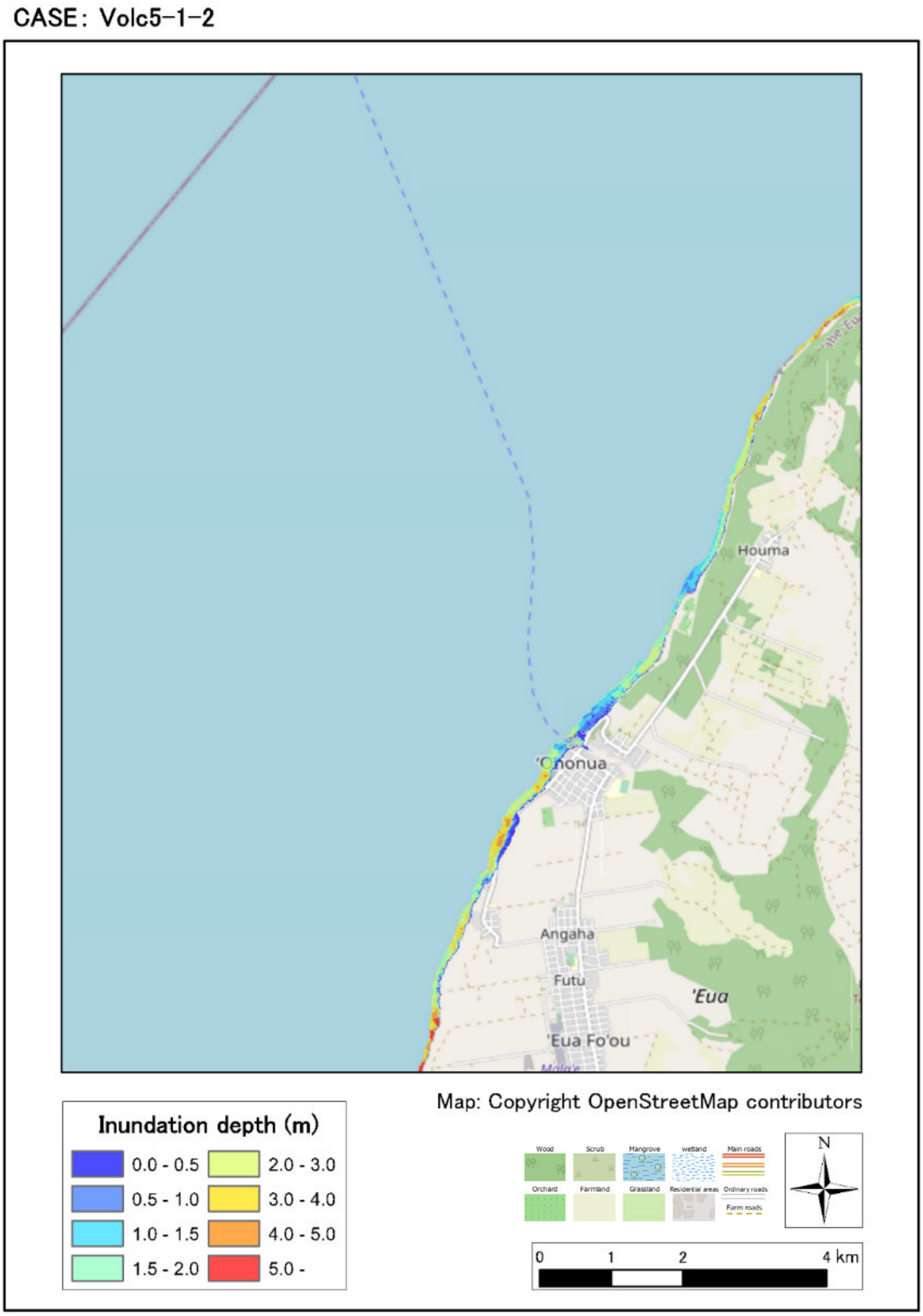
Source: JICA Study Team

Figure 2.6.126 Max inundation depth distribution (Lateiki, H=30m)

CASE: Volc4-1-2

Source: JICA Study Team

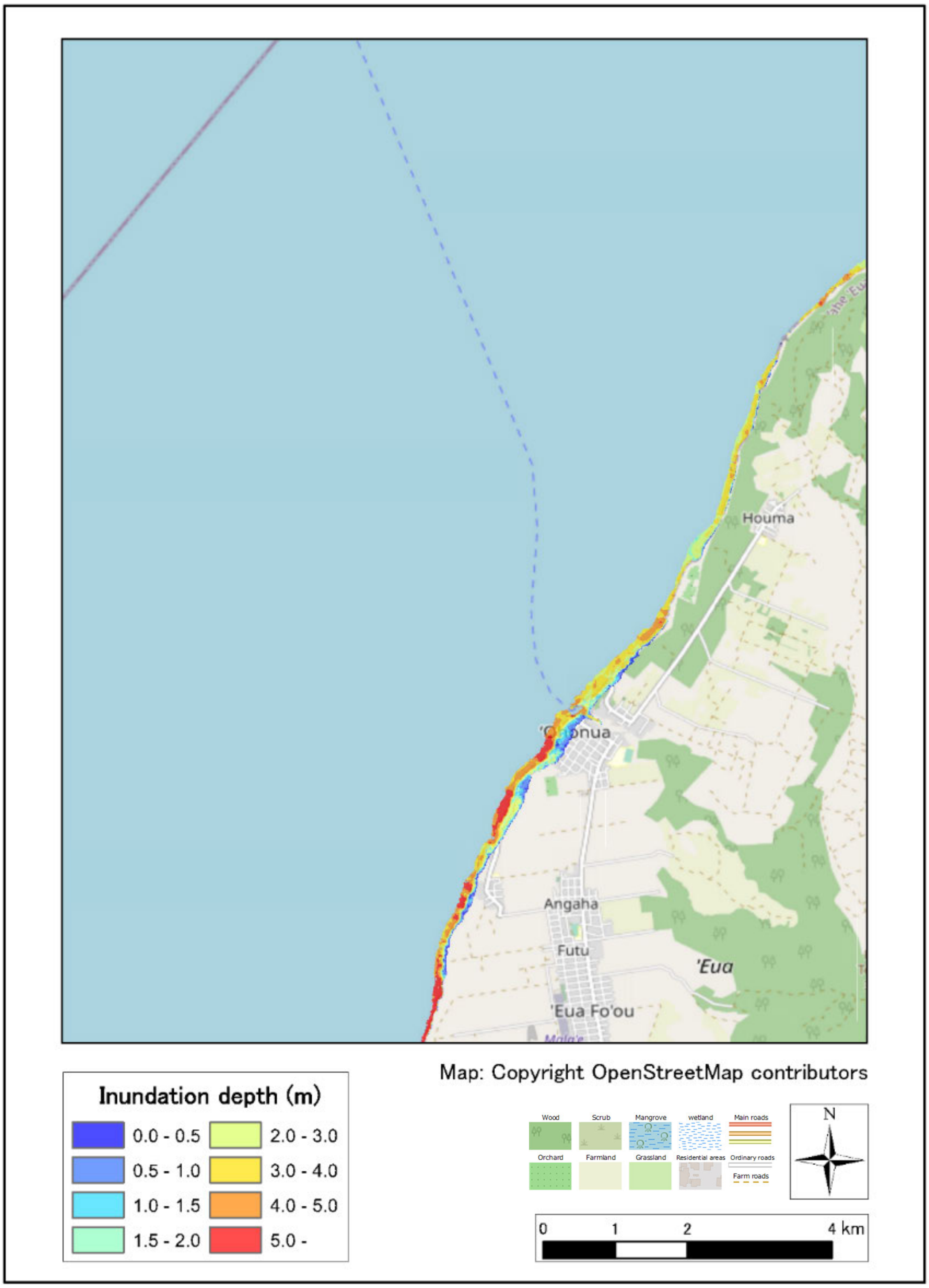
Figure 2.6.127 Max inundation depth distribution (Fonuafo'ou H=30m)



Source: JICA Study Team

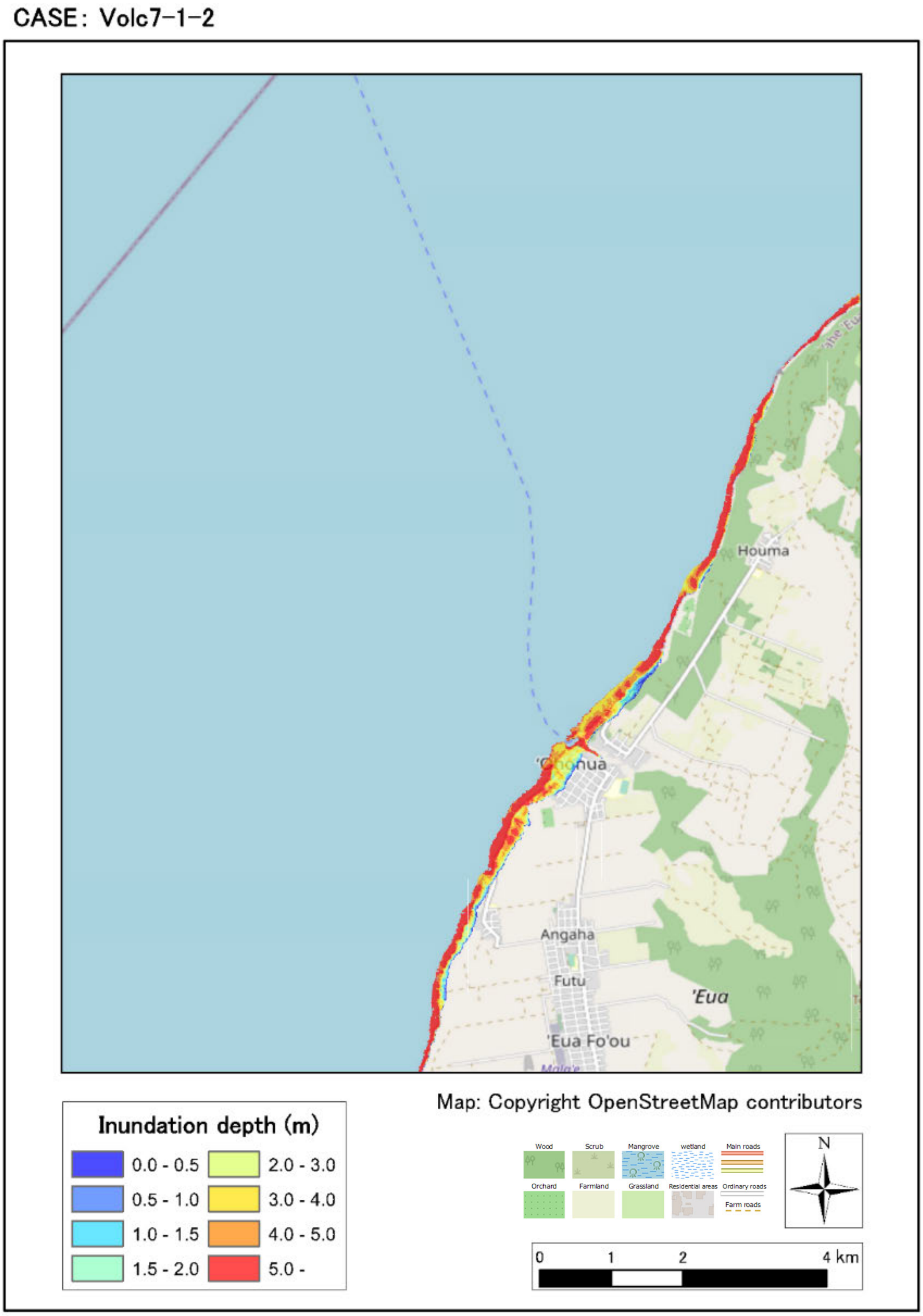
Figure 2.6.128 Max inundation depth distribution (Unamed2, H=30m)

CASE: Volc6-1-2



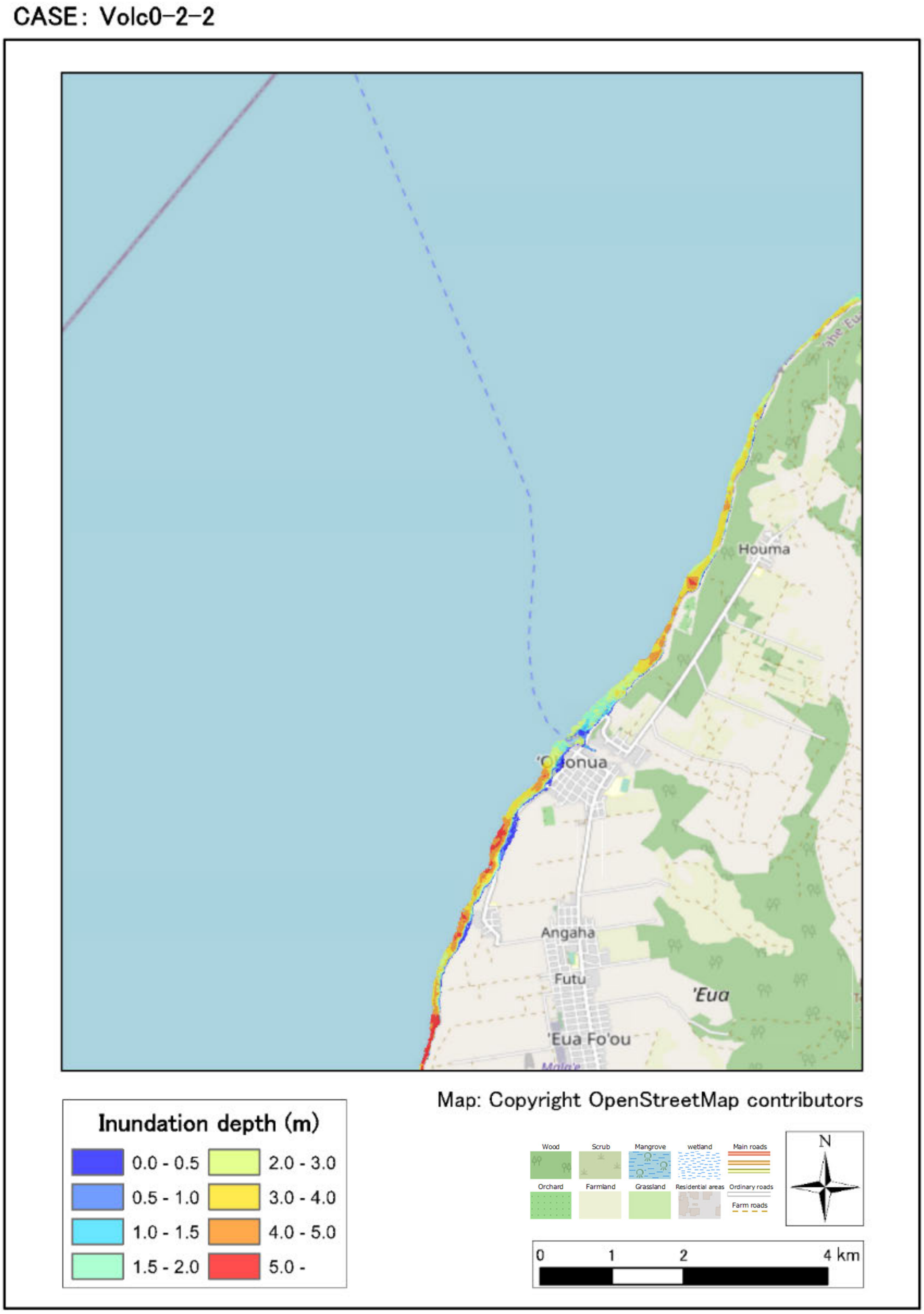
Source: JICA Study Team

Figure 2.6.129 Max inundation depth distribution (Unamed3, H=30m)



Source: JICA Study Team

Figure 2.6.130 Max inundation depth distribution (Unamed4, H=30m)



Source: JICA Study Team

Figure 2.6.131 Max inundation depth distribution (Hunga Tonga-Hunga Ha'pai, H=60m)

CASE: Volc1-2-2

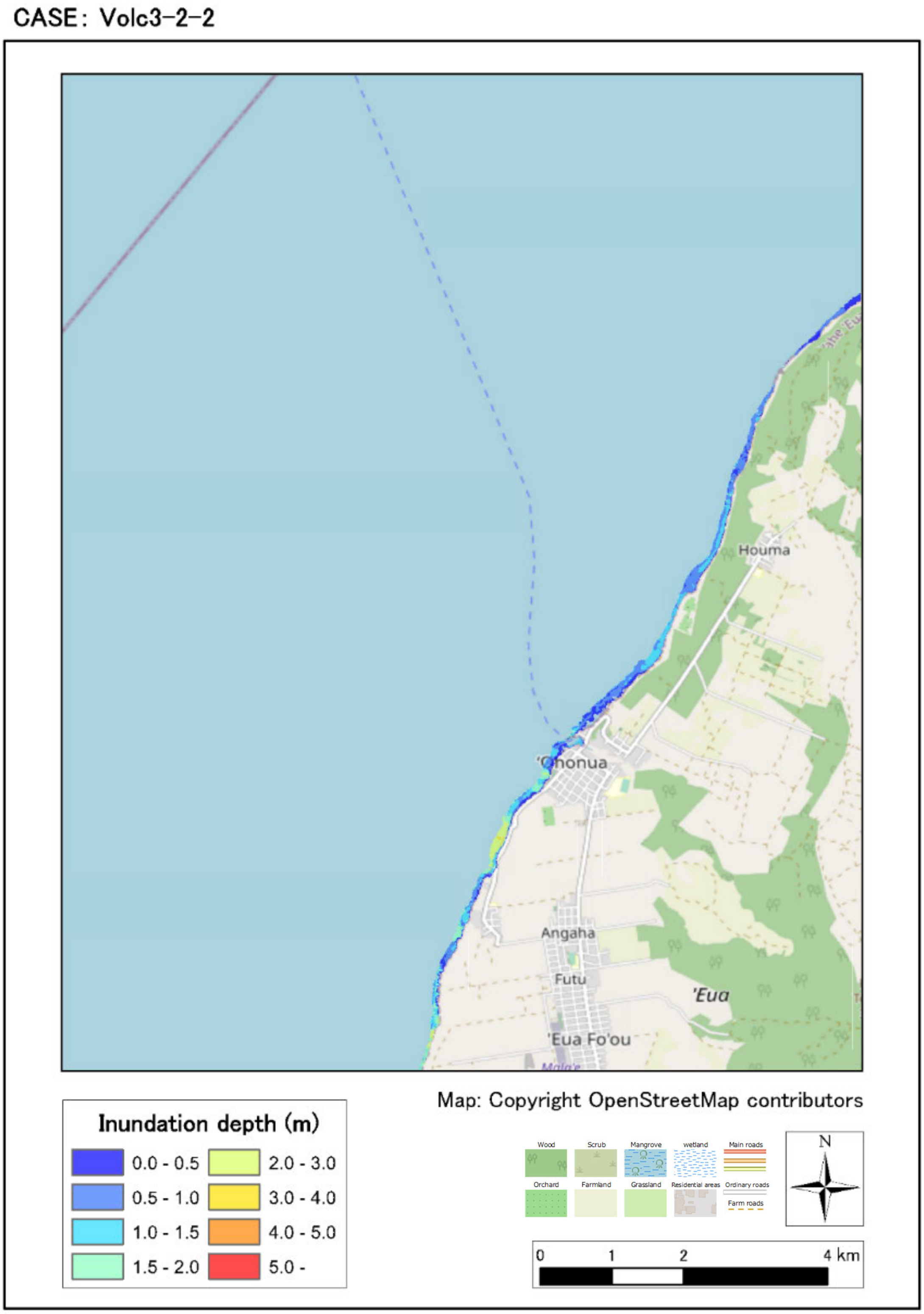
Source: JICA Study Team

Figure 2.6.132 Max inundation depth distribution (Unnamed1, H=60m)

CASE: Volc2-2-2

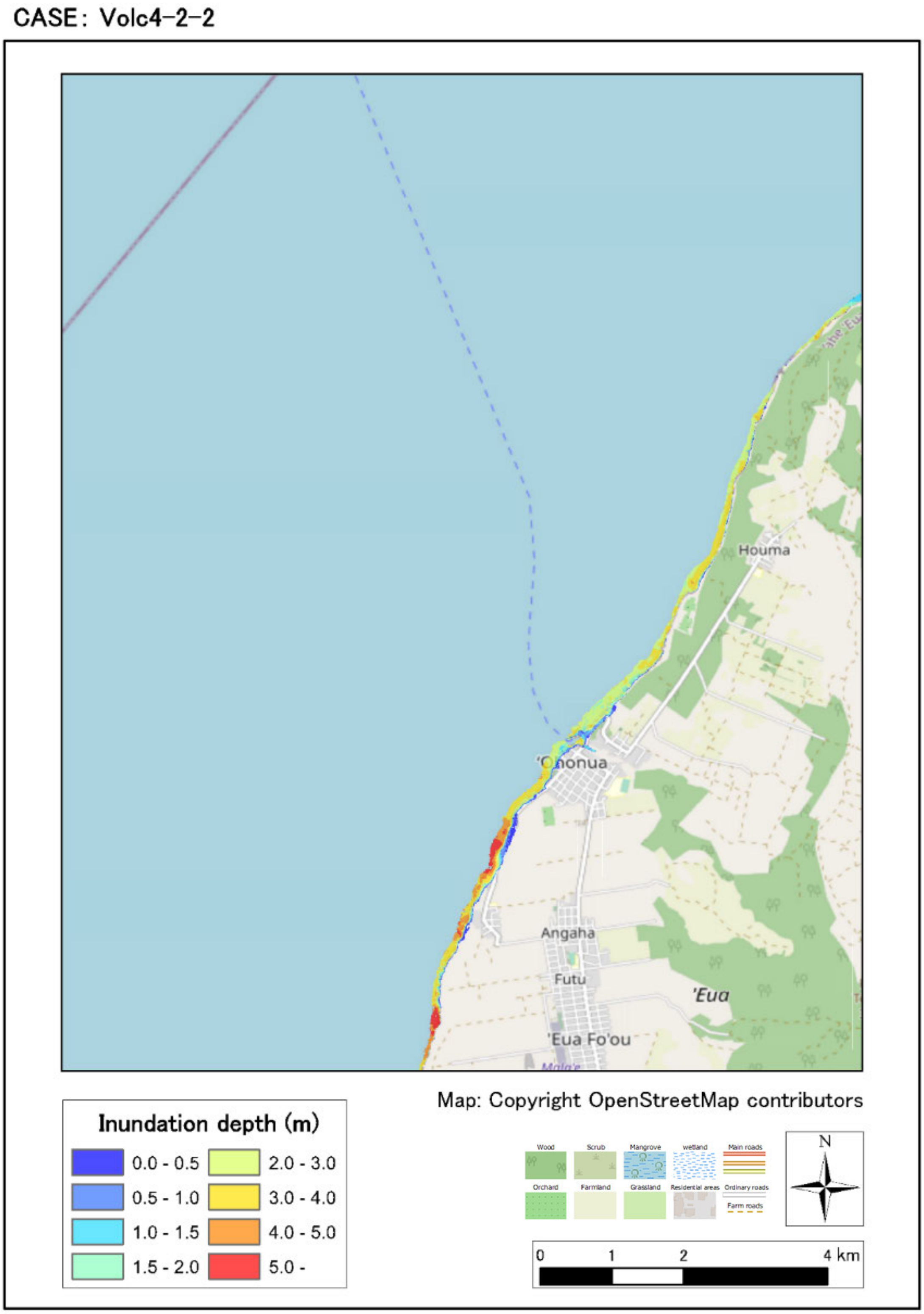
Source: JICA Study Team

Figure 2.6.133 Max inundation depth distribution (HomeReef, H=60m)



Source: JICA Study Team

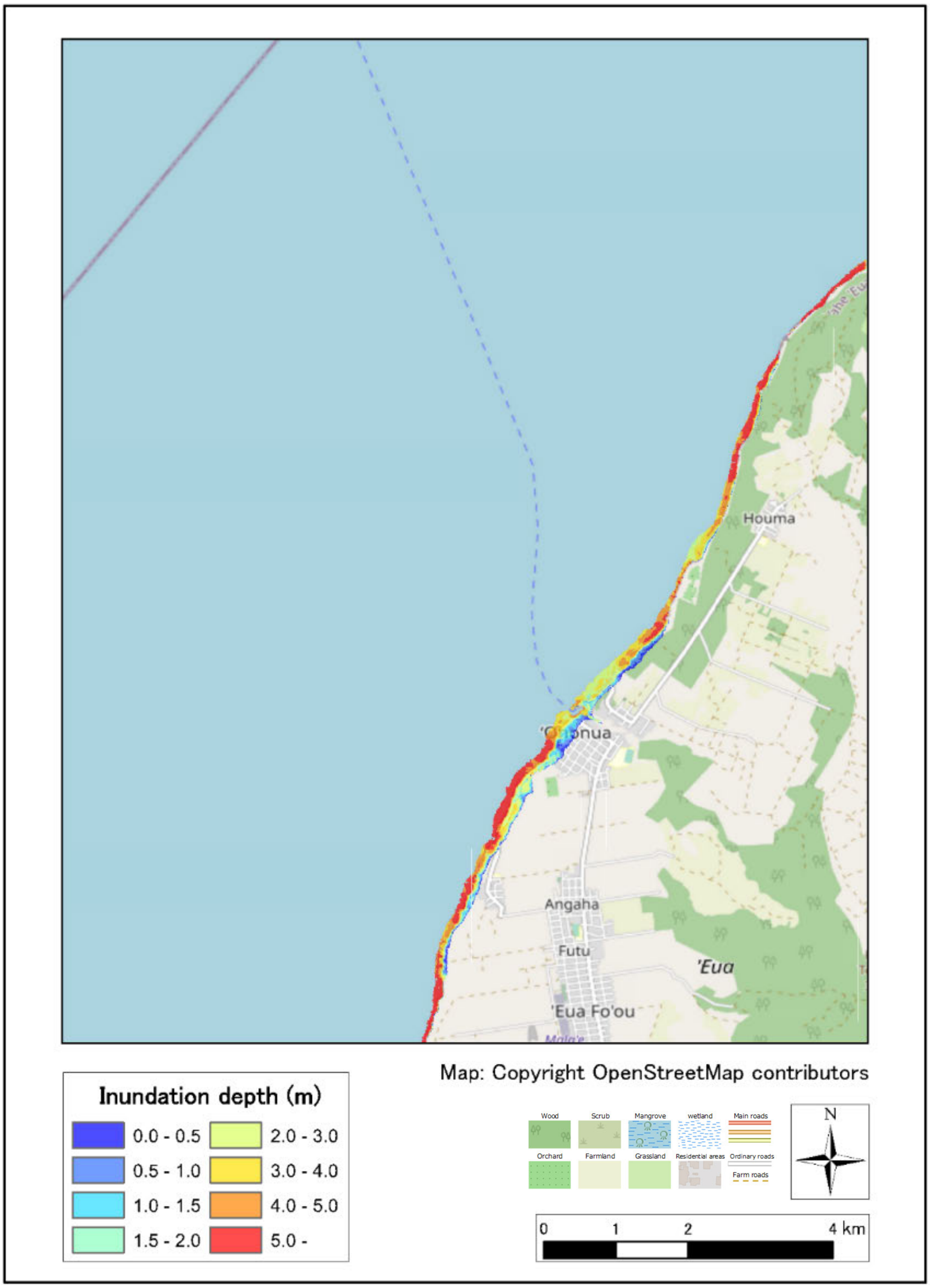
Figure 2.6.134 Max inundation depth distribution (Lateiki, H=60m)



Source: JICA Study Team

Figure 2.6.135 Max inundation depth distribution (Fonuafo'ou, H=60m)

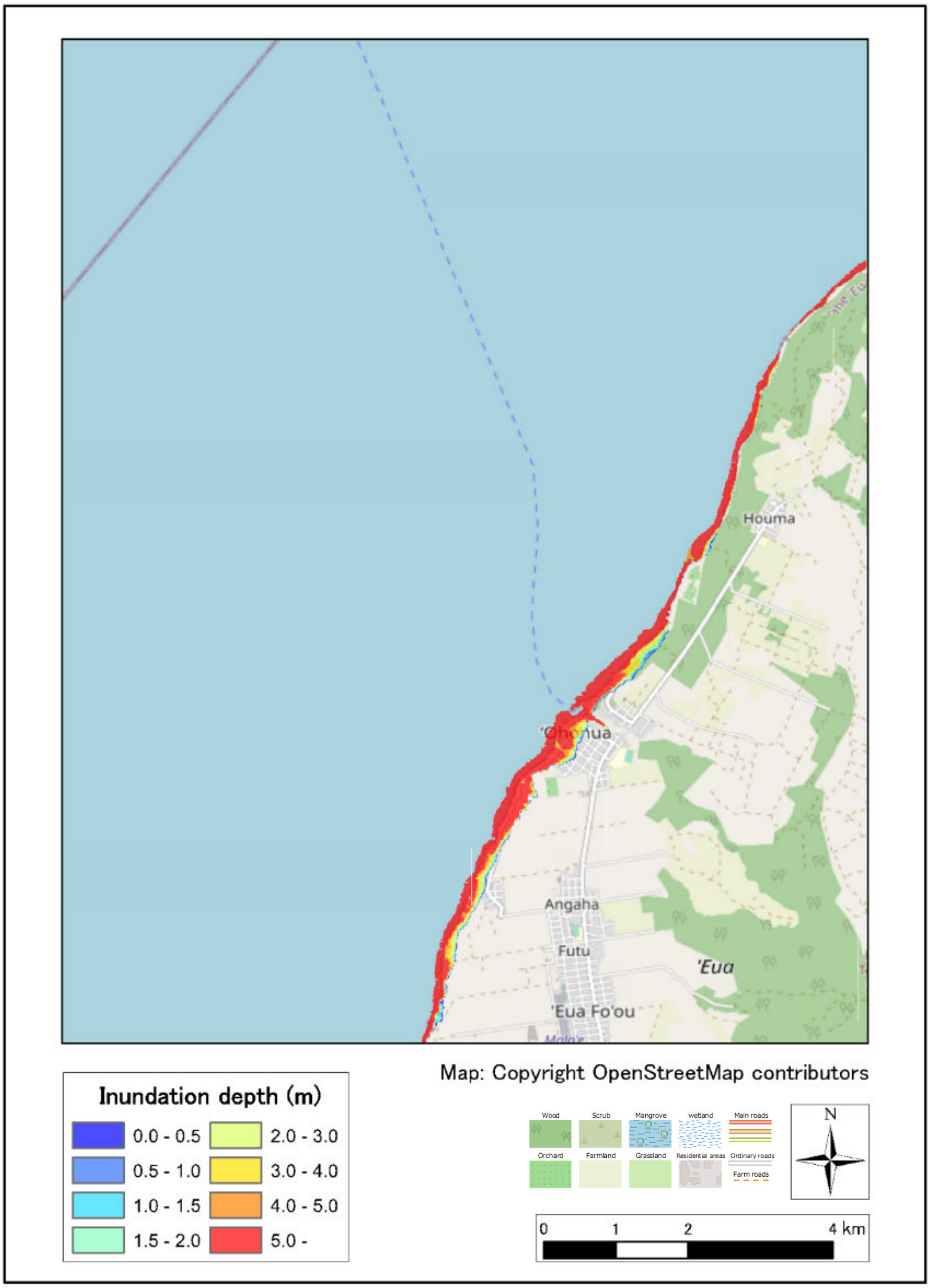
CASE: Volc5-2-2



Source: JICA Study Team

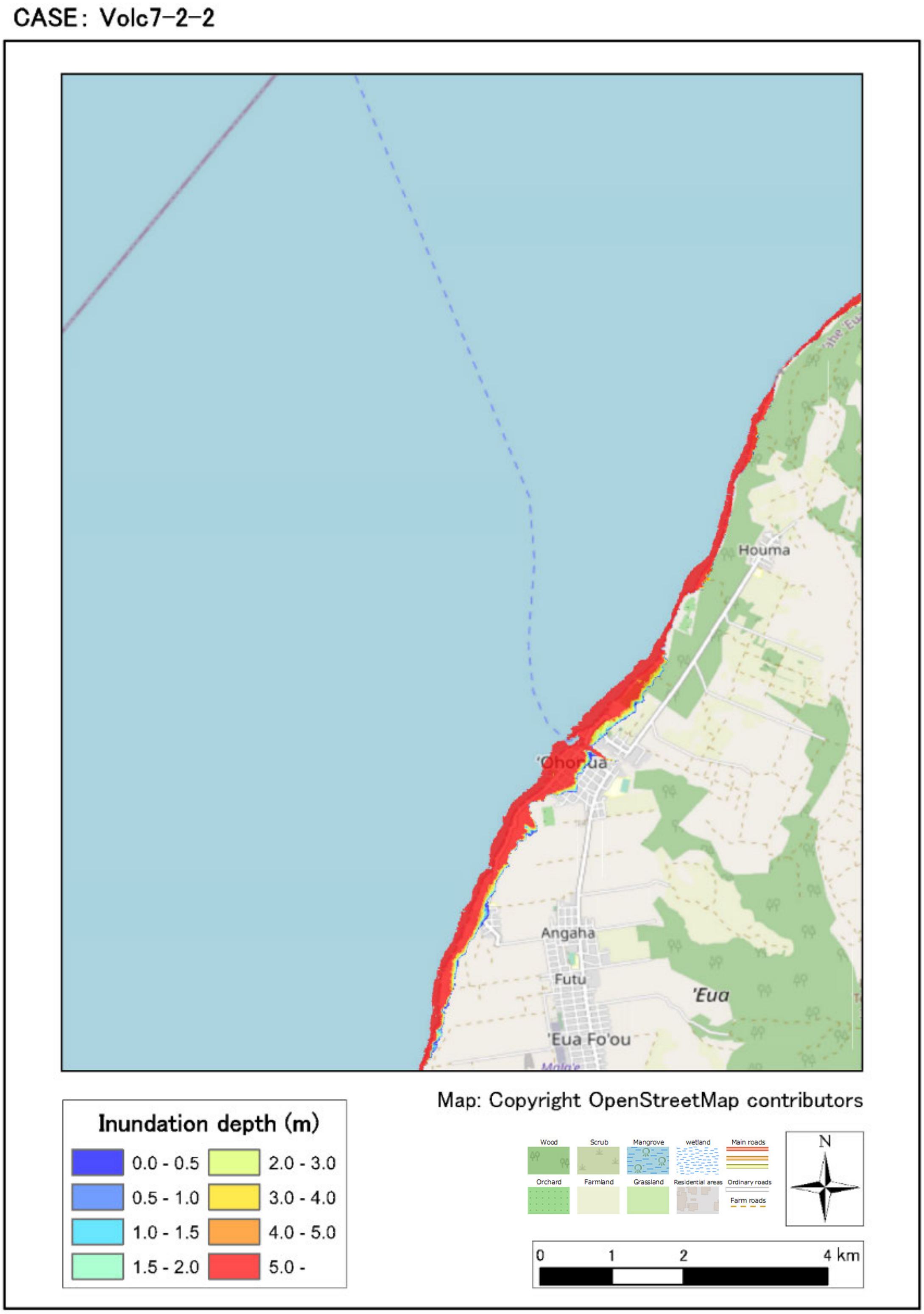
Figure 2.6.136 Max inundation depth distribution (Unamed2, H=60m)

CASE: Volc6-2-2



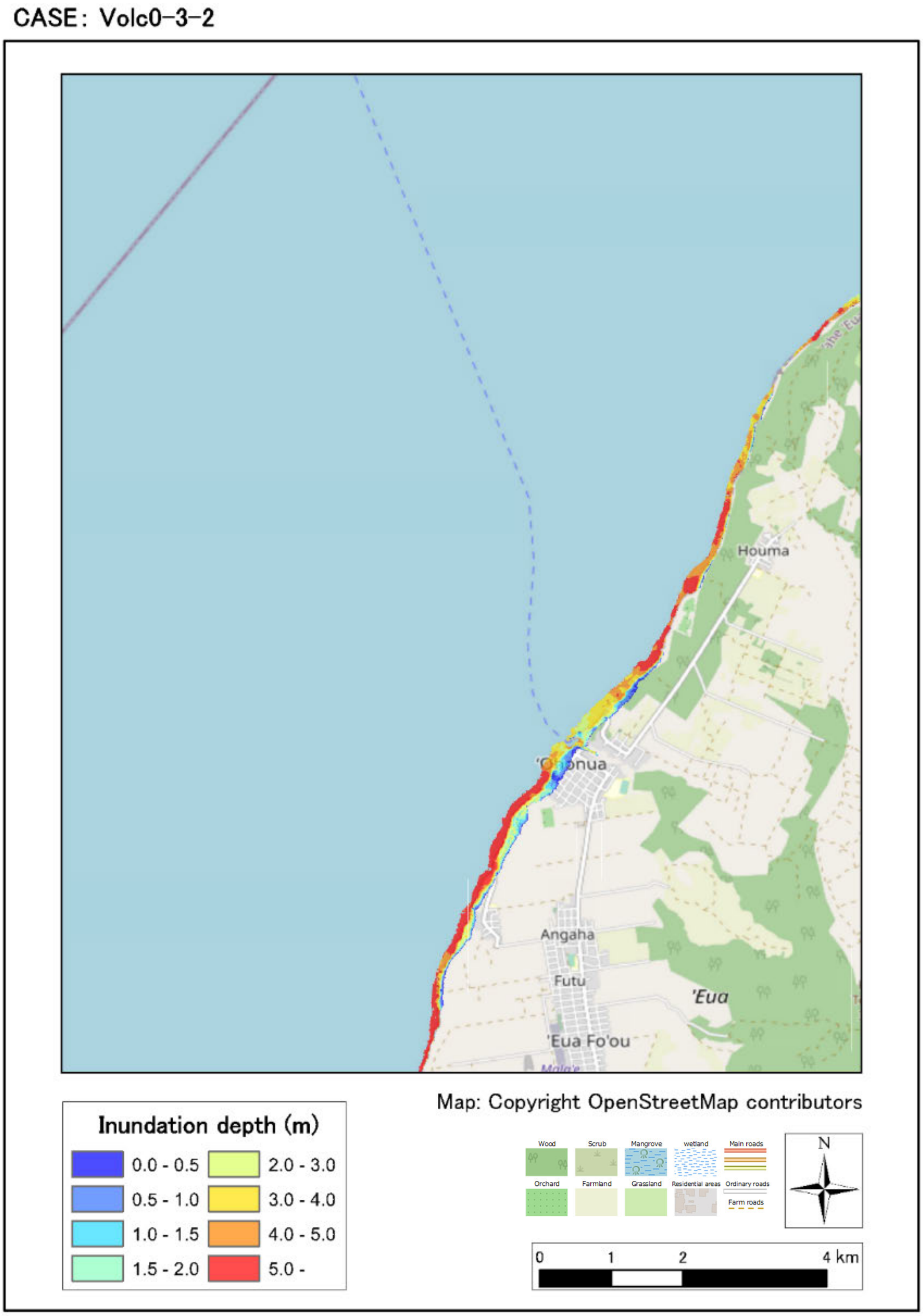
Source: JICA Study Team

Figure 2.6.137 Max inundation depth distribution (Unamed3, H=60m)



Source: JICA Study Team

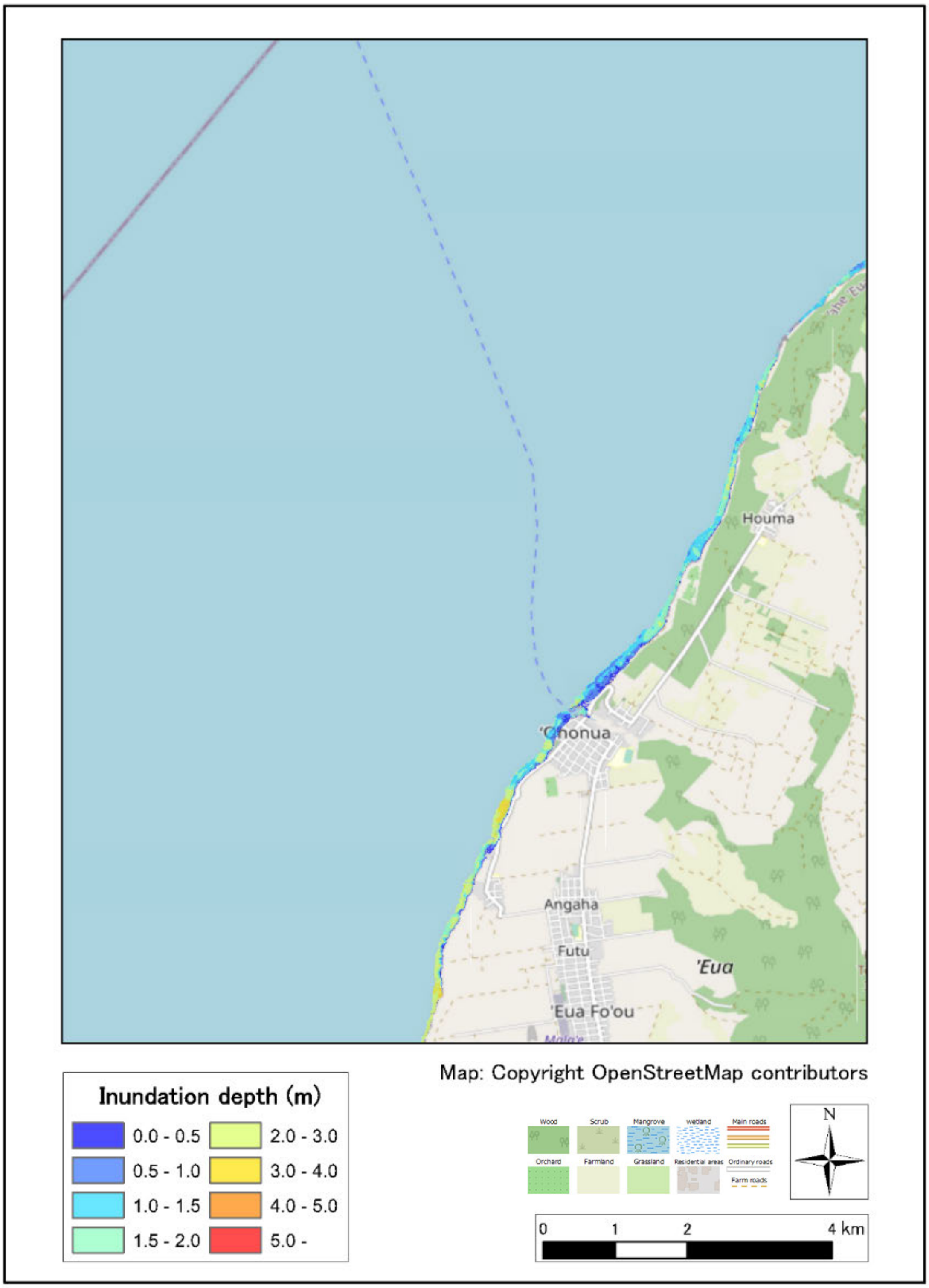
Figure 2.6.138 Max inundation depth distribution (Unamed4, H=60m)



Source: JICA Study Team

Figure 2.6.139 Max inundation depth distribution (Hunga Tonga-Hunga Ha'pai, H=90m)

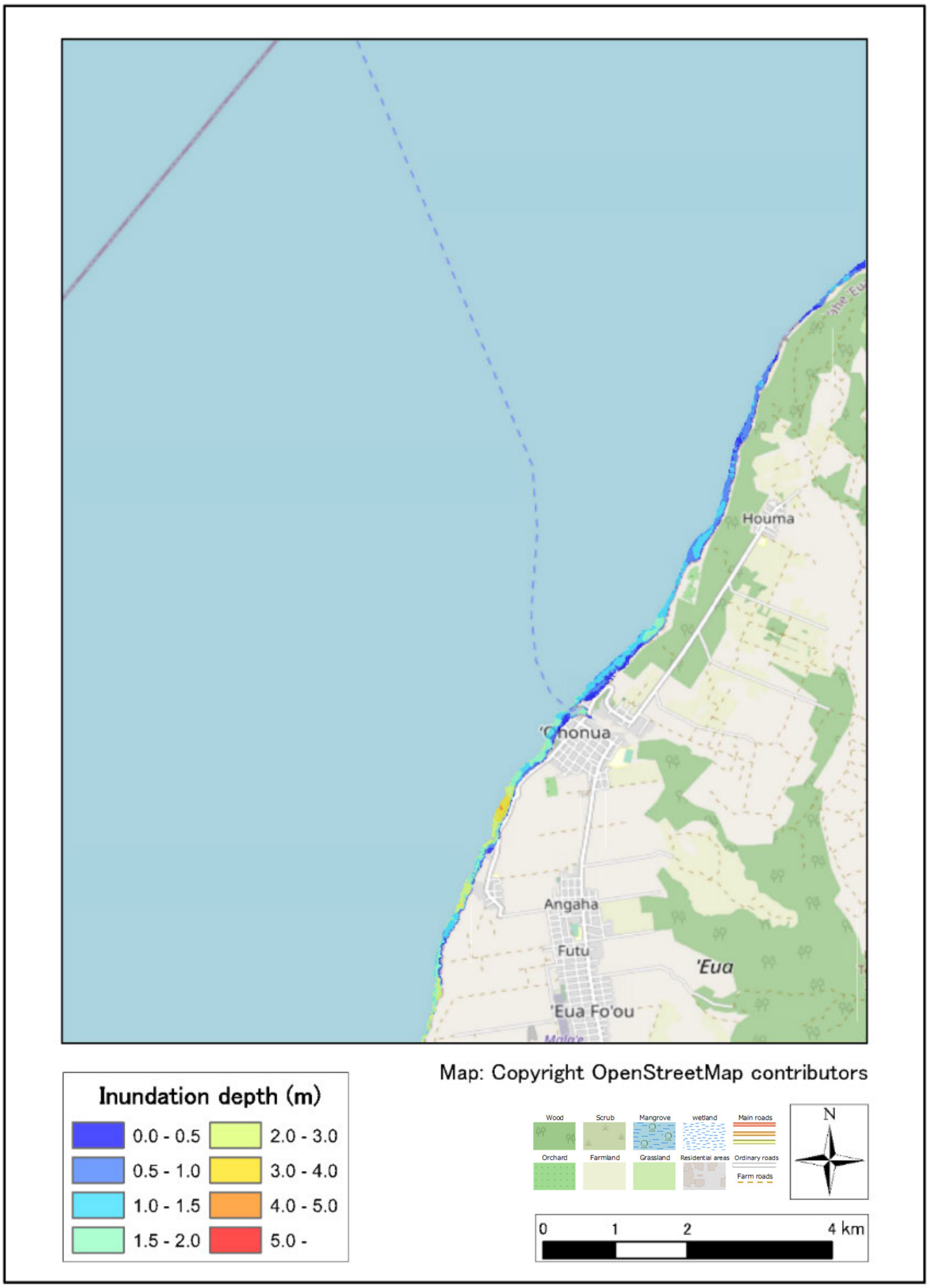
CASE: Volc1-3-2



Source: JICA Study Team

Figure 2.6.140 Max inundation depth distribution (Unnamed1, H=90m)

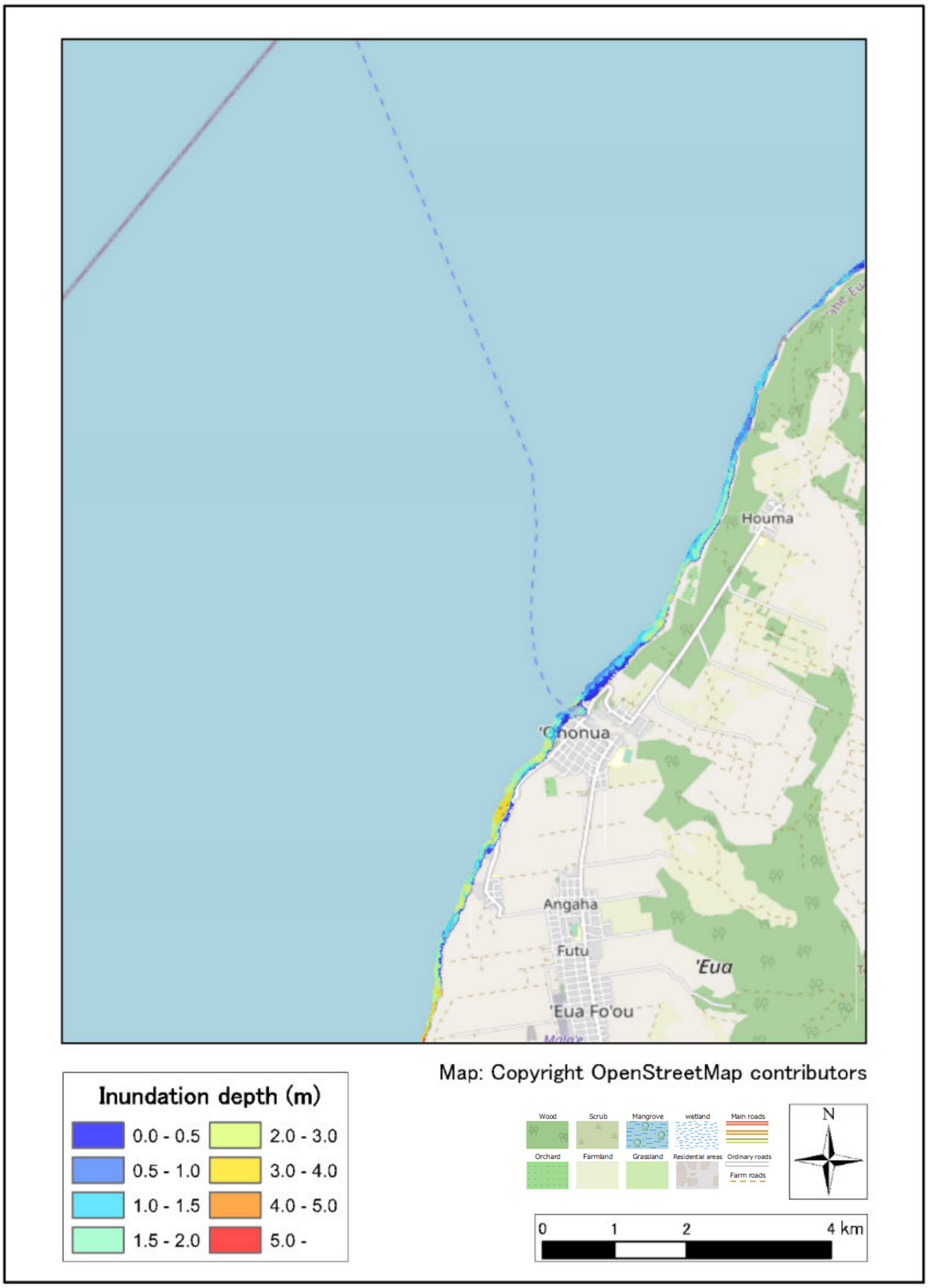
CASE: Volc2-3-2



Source: JICA Study Team

Figure 2.6.141 Max inundation depth distribution (HomeReef, H=90m)

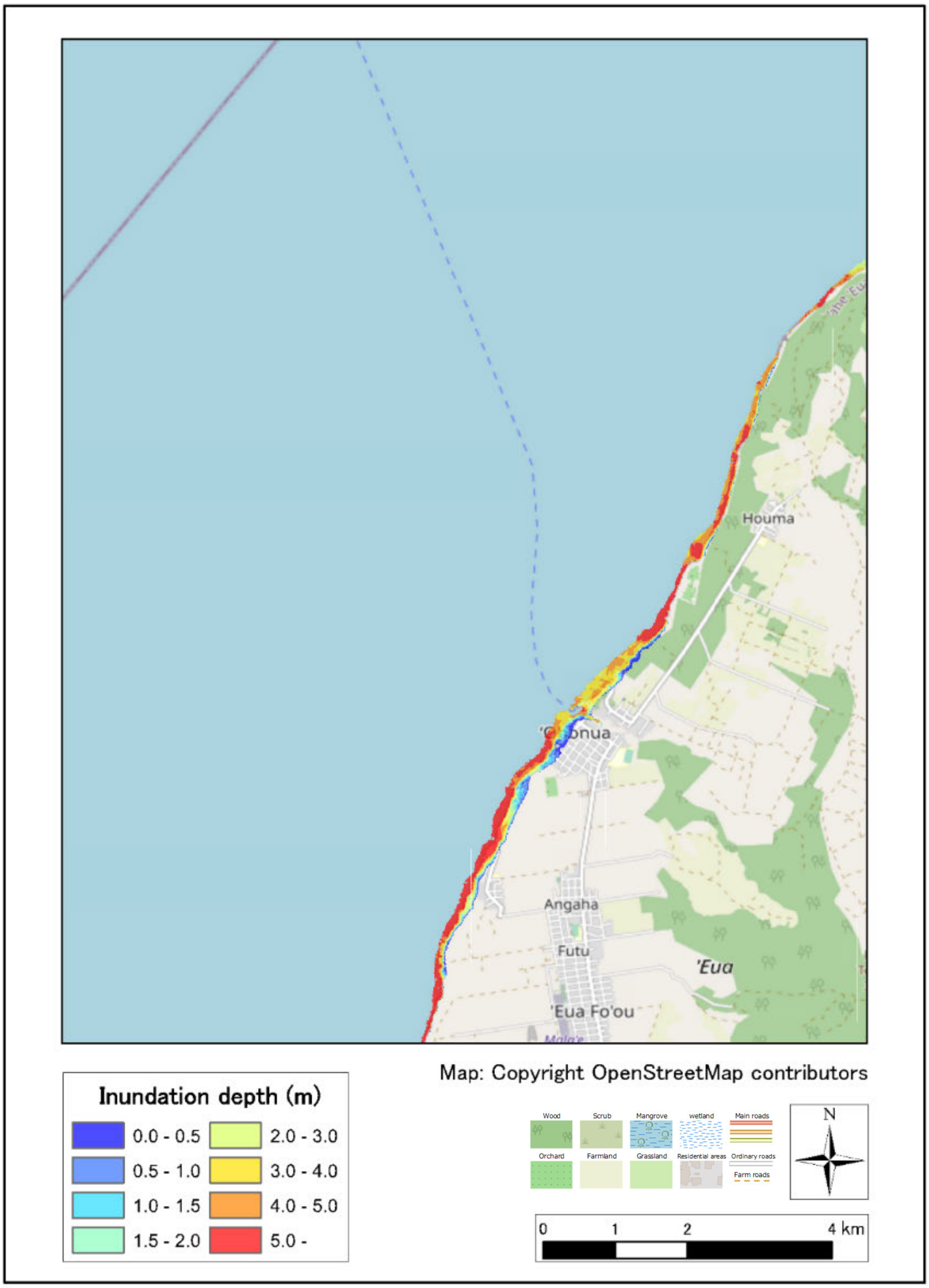
CASE：Volc3-3-2



Source: JICA Study Team

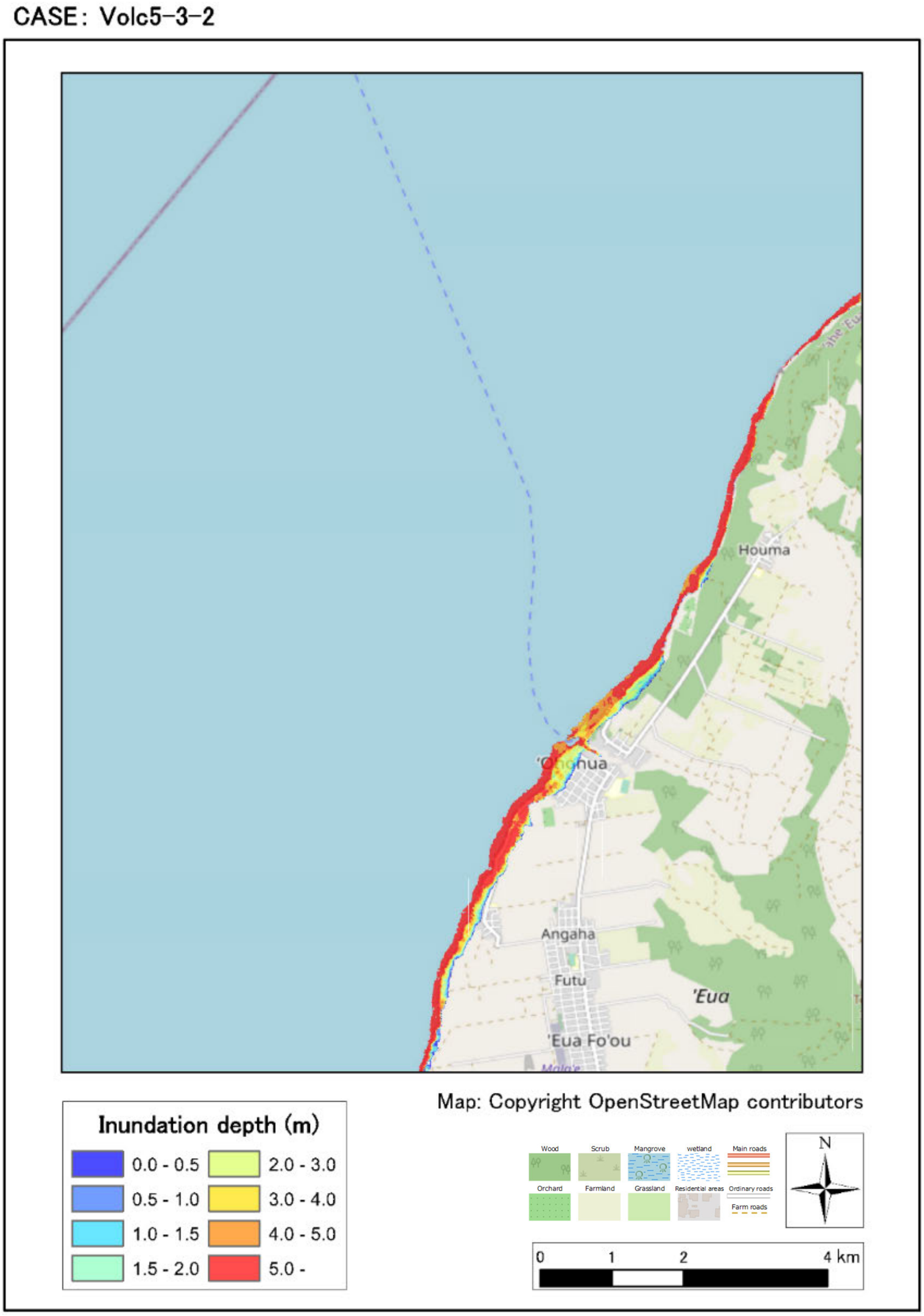
Figure 2.6.142 Max inundation depth distribution (Lateiki, H=90m)

CASE: Volc4-3-2



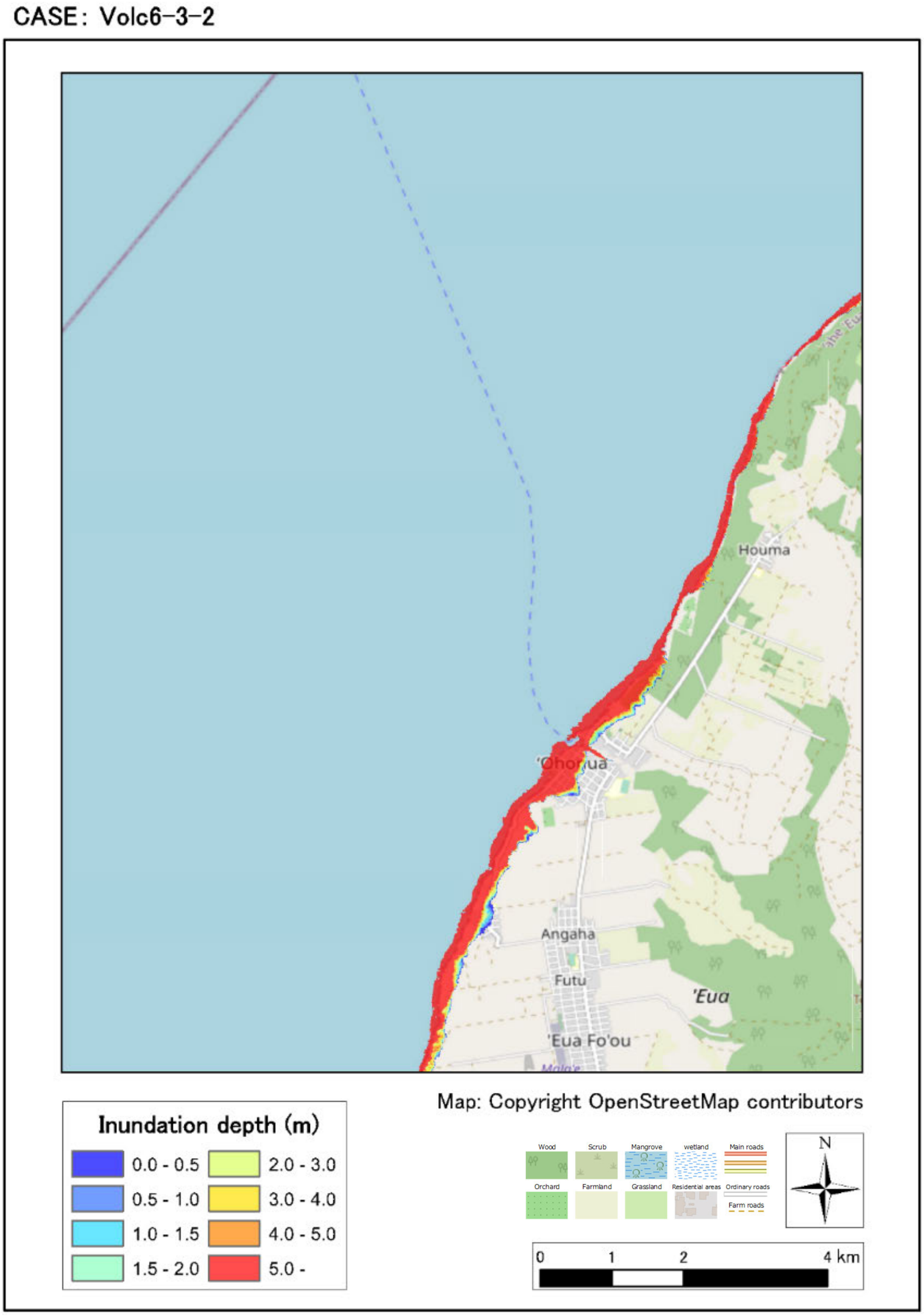
Source: JICA Study Team

Figure 2.6.143 Max inundation depth distribution (Fonuafo'ou, H=90m)



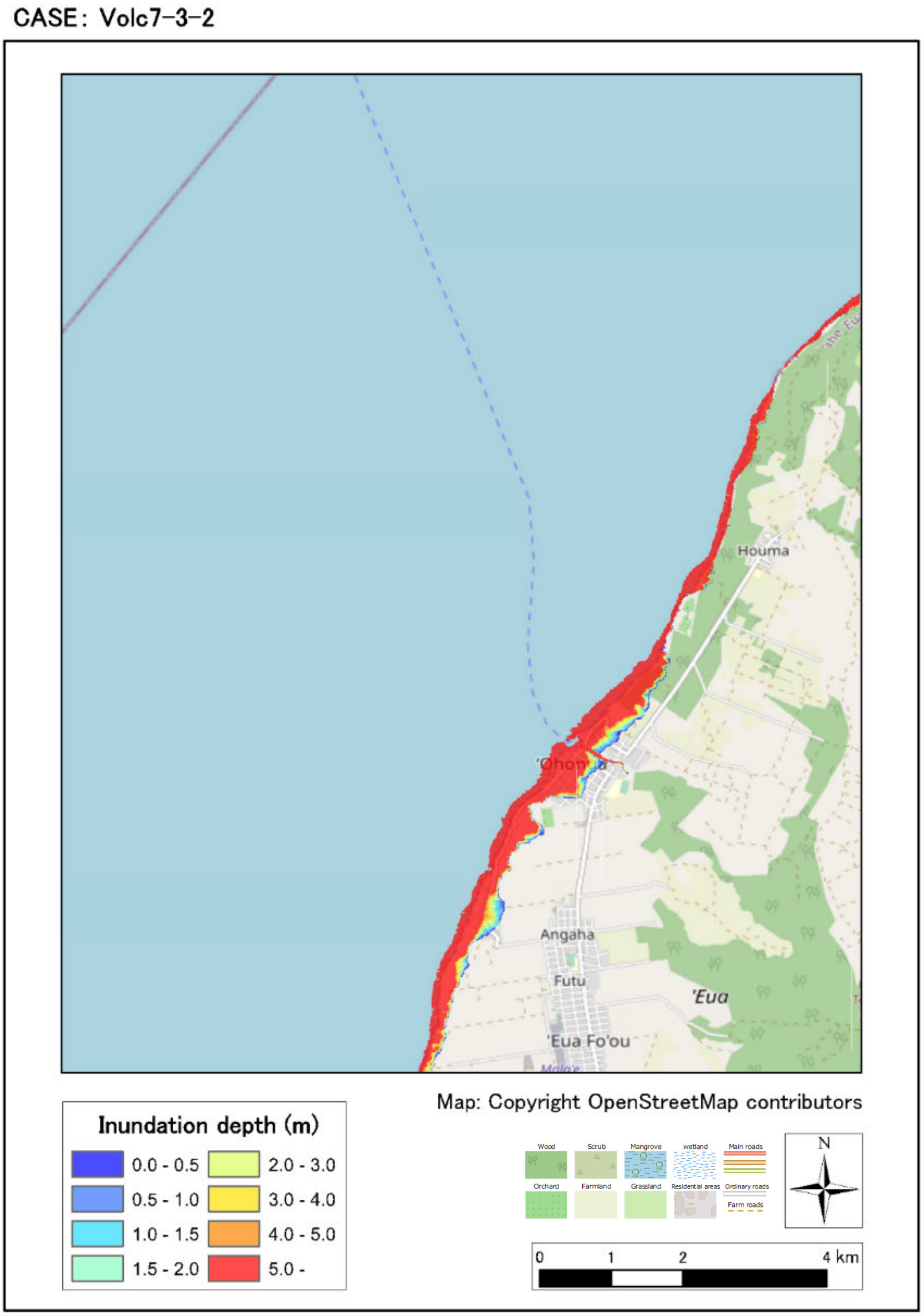
Source: JICA Study Team

Figure 2.6.144 Max inundation depth distribution (Unamed2, H=90m)



Source: JICA Study Team

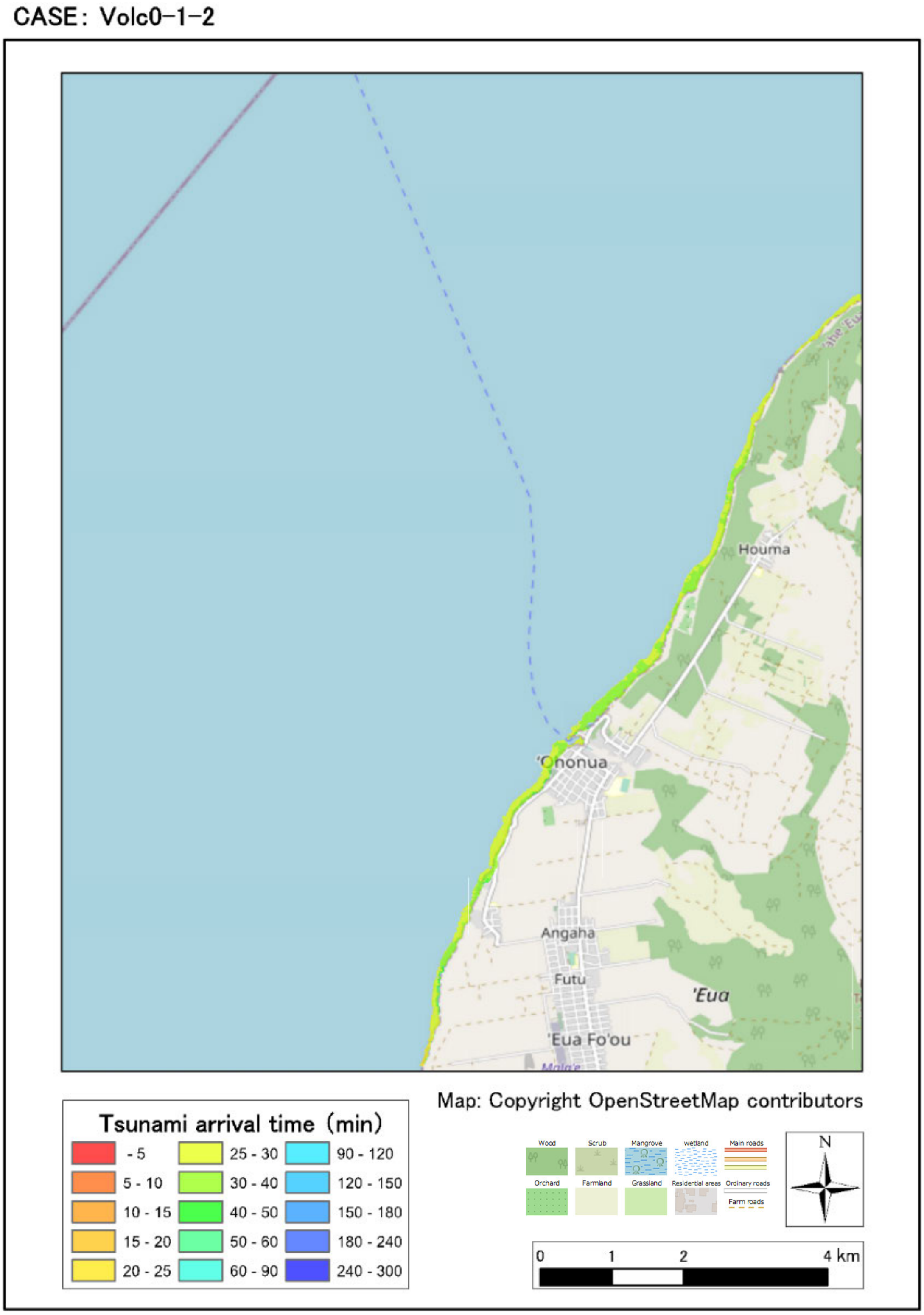
Figure 2.6.145 Max inundation depth distribution (Unamed3, H=90m)



Source: JICA Study Team

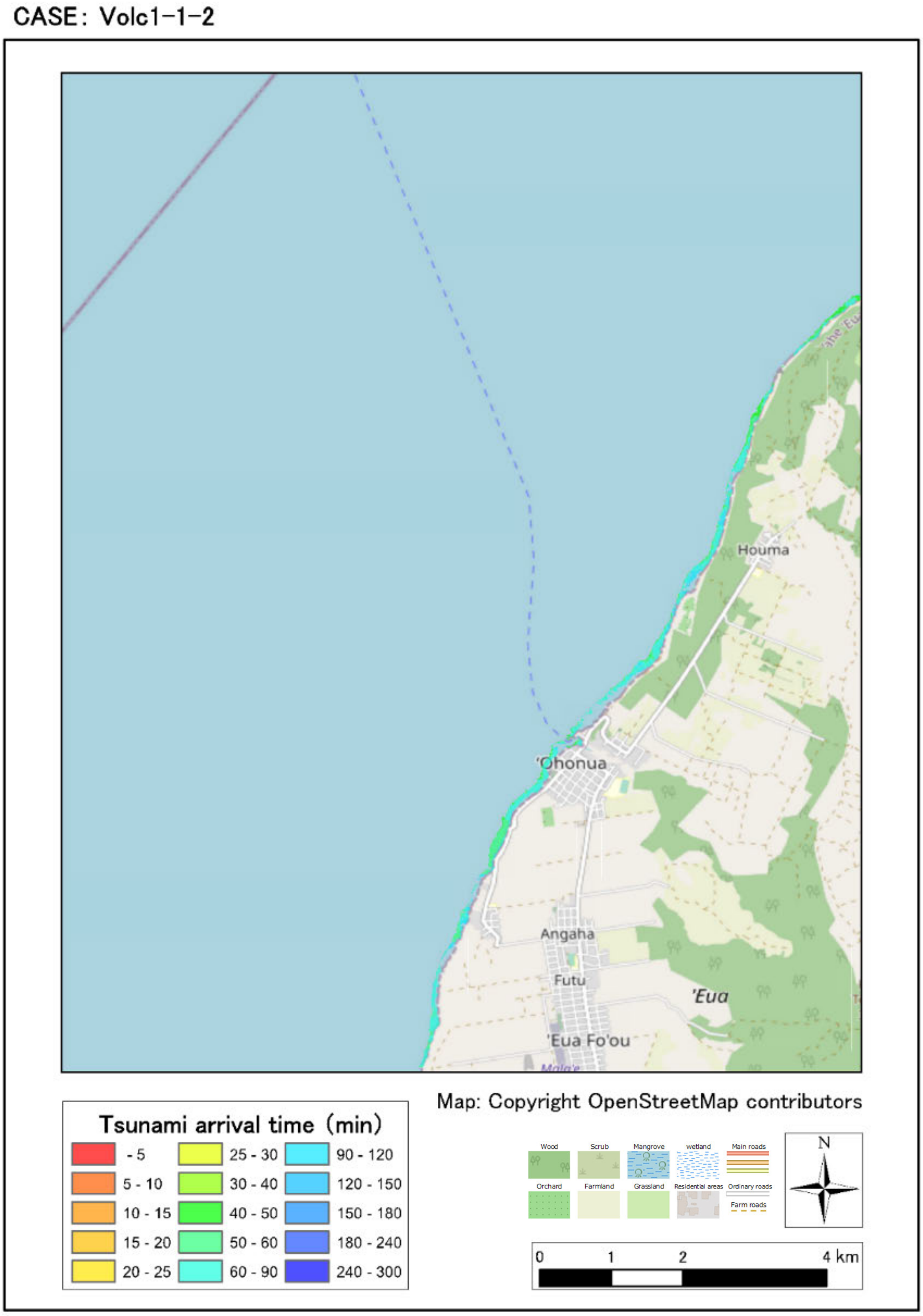
Figure 2.6.146 Max inundation depth distribution (Unamed4, H=90m)

6) Tsunami Arraival Time Distribution (Ohonua, Eua Island).



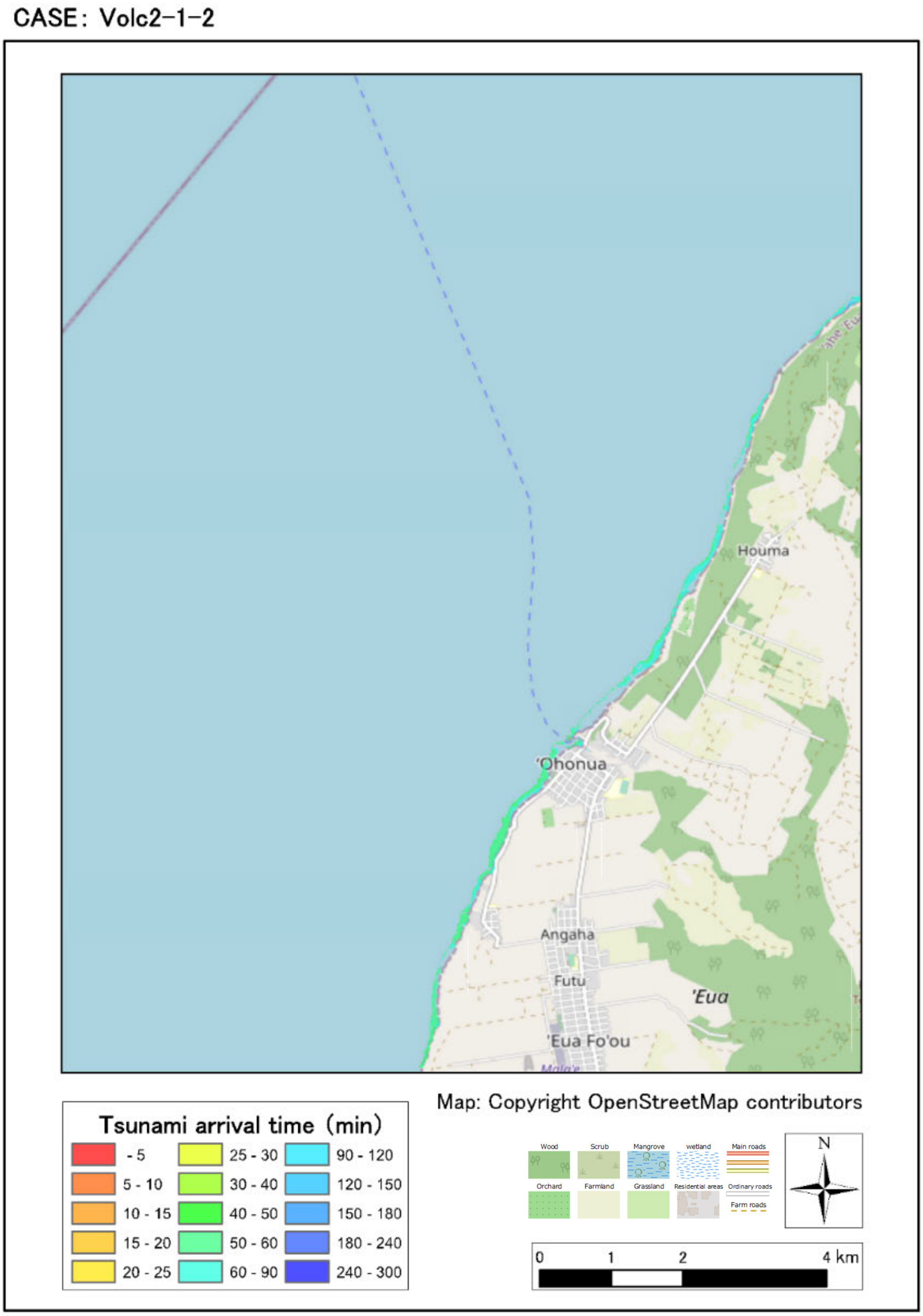
Source: JICA Study Team

Figure 2.6.147 Tsunami Arraival Time Distribution (Hunga Tonga-Hunga Ha'pai, H=30m)



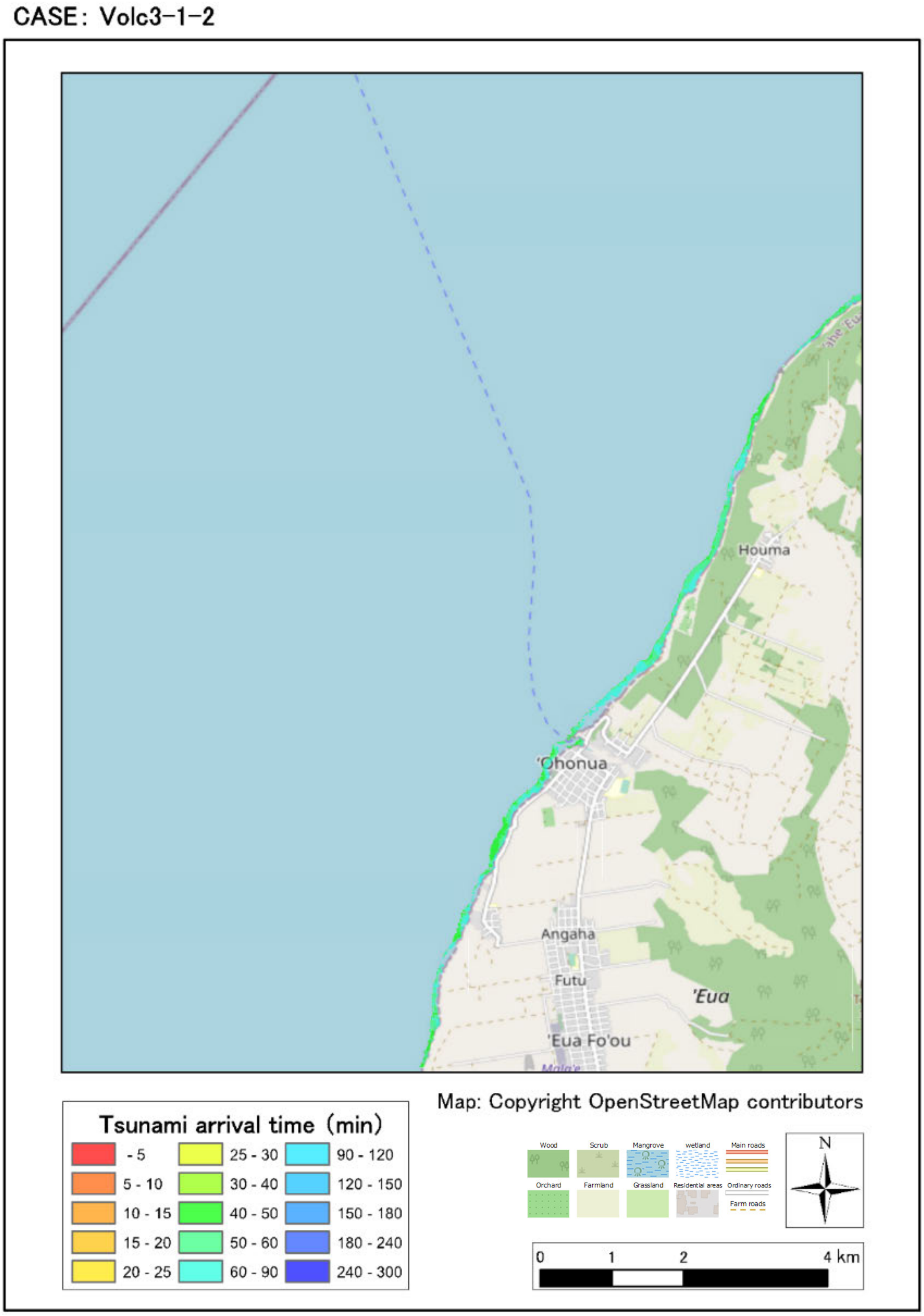
Source: JICA Study Team

Figure 2.6.148 Tsunami Arraival Time Distribution (Unnamed1, H=30m)



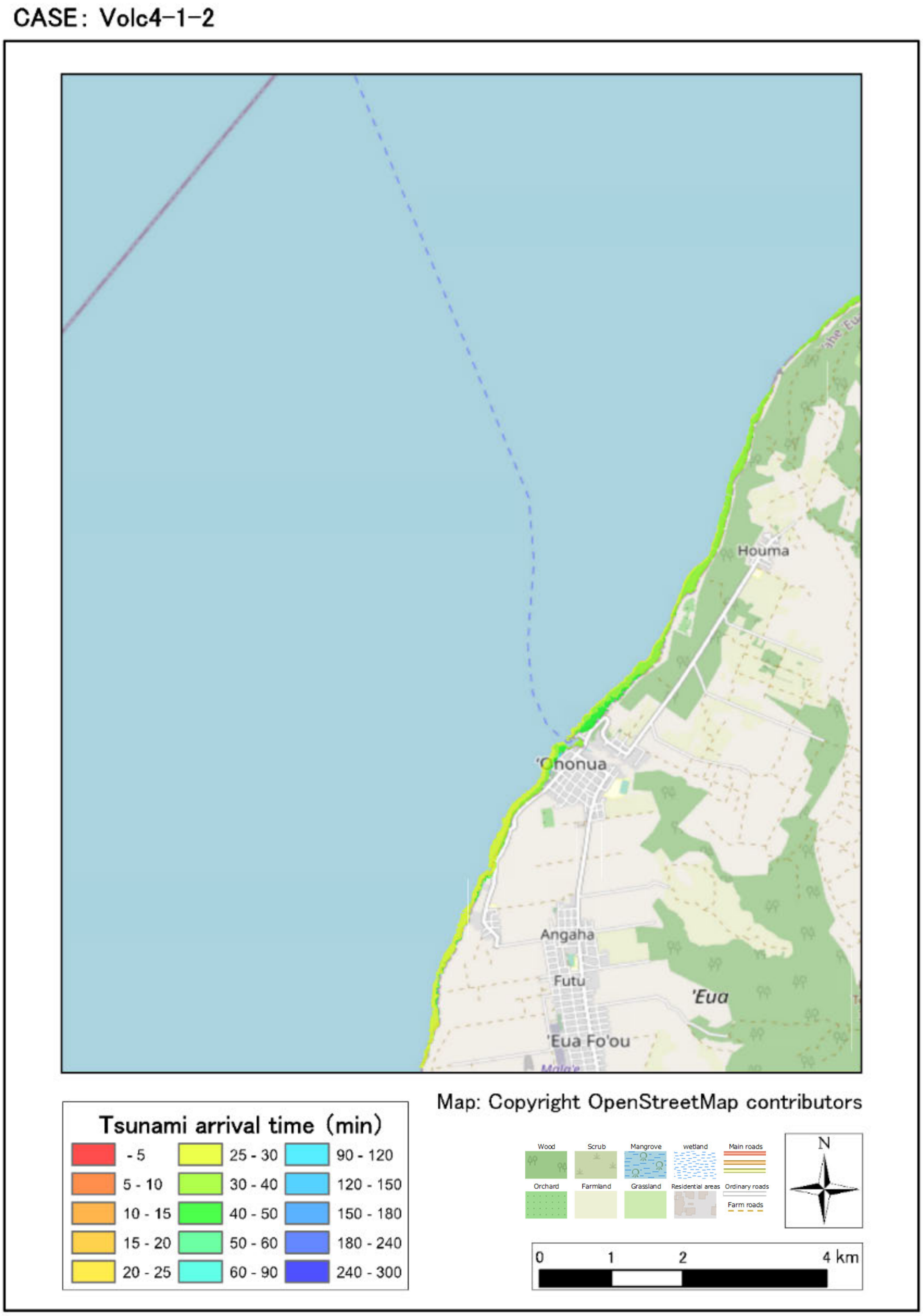
Source: JICA Study Team

Figure 2.6.149 Tsunami Arraival Time Distribution (HomeReef, H=30m)



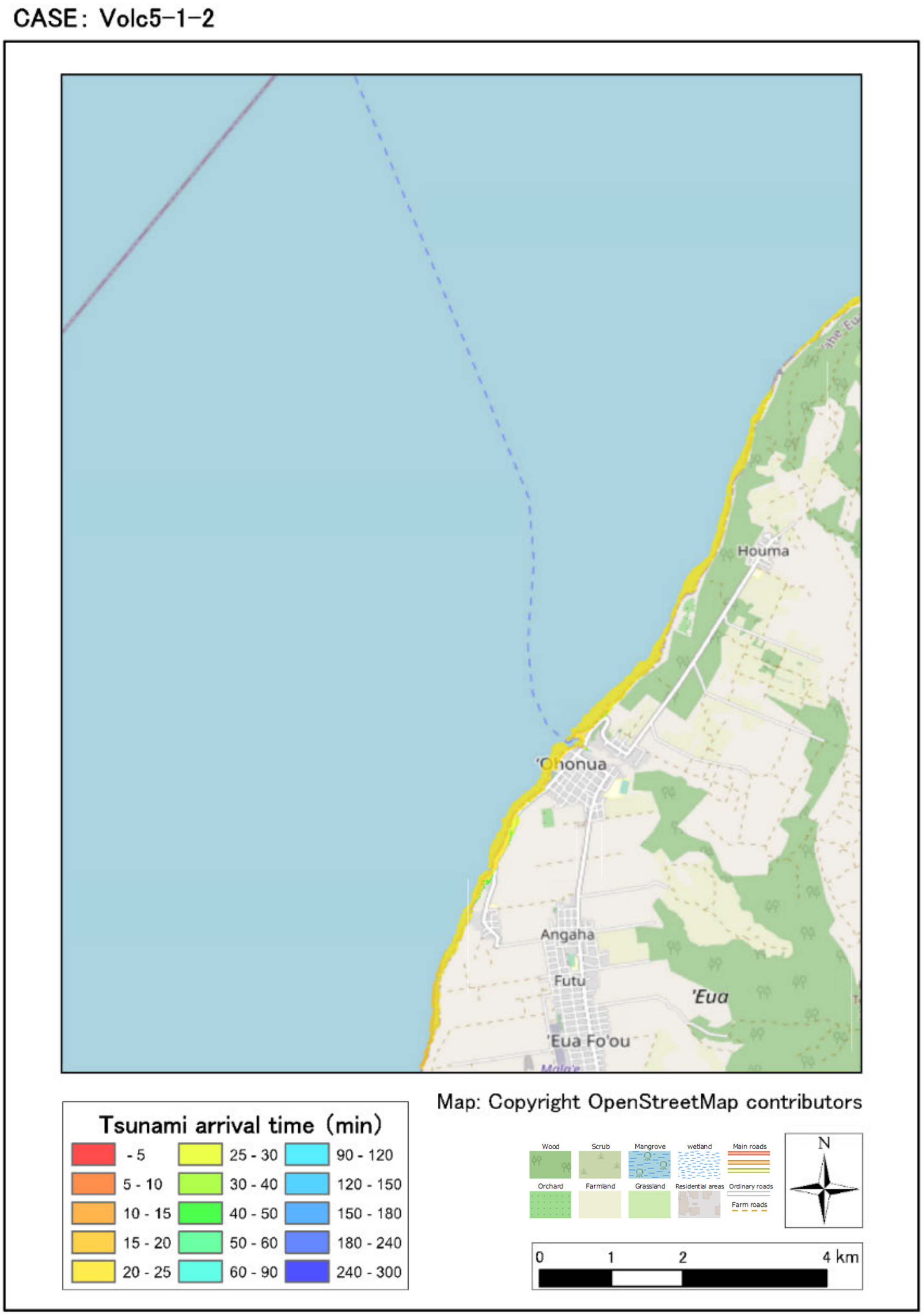
Source: JICA Study Team

Figure 2.6.150 Tsunami Arraival Time Distribution (Lateiki, H=30m)



Source: JICA Study Team

Figure 2.6.151 Tsunami Arraival Time Distribution (Fonuafo'ou H=30m)



Source: JICA Study Team

Figure 2.6.152 Tsunami Arraival Time Distribution (Unamed2, H=30m)

Source: JICA Study Team

Figure 2.6.153 Tsunami Arraival Time Distribution (Unamed3, H=30m)

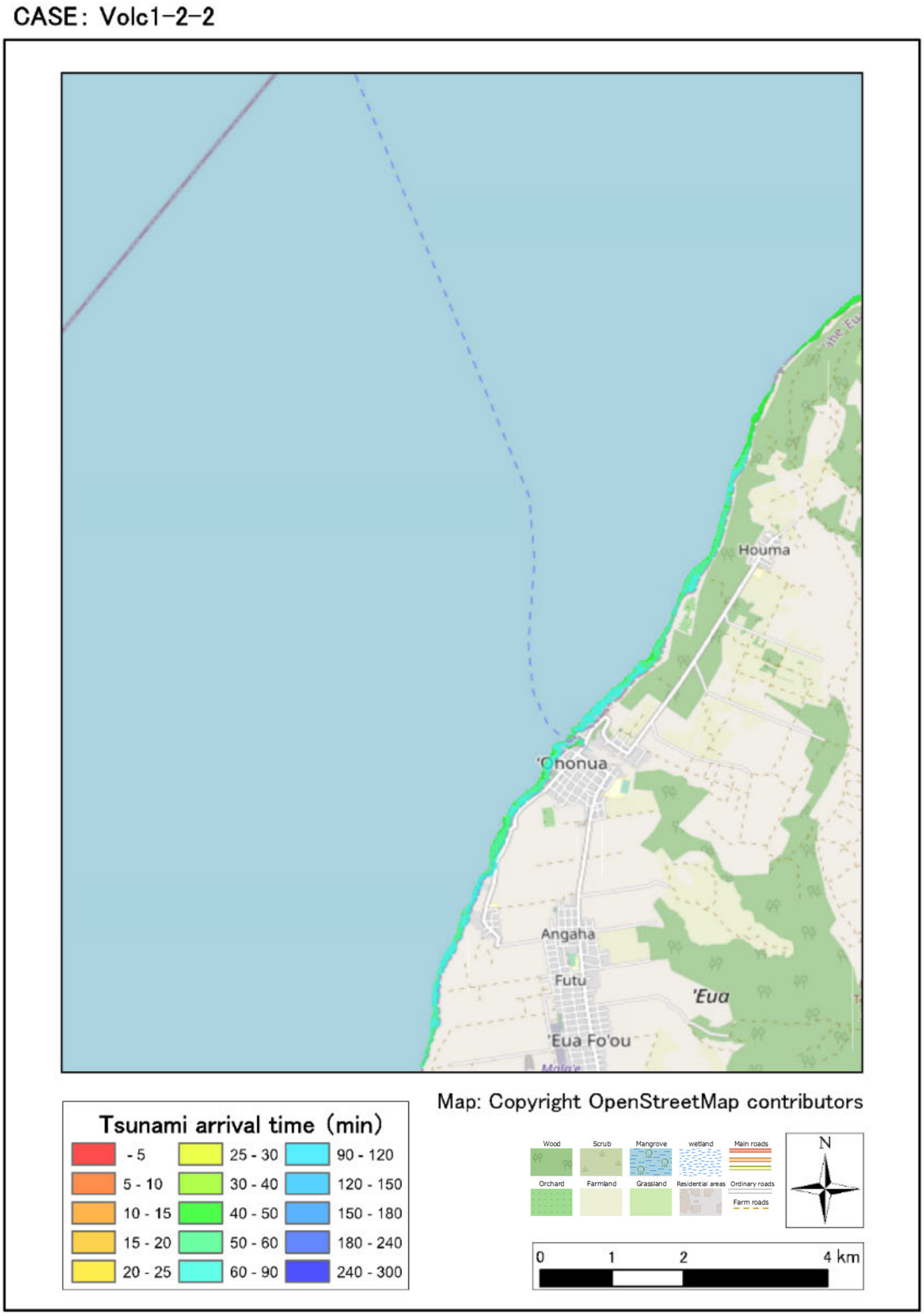
Source: JICA Study Team

Figure 2.6.154 Tsunami Arraival Time Distribution (Unamed4, H=30m)

CASE：Volc0-2-2

Source: JICA Study Team

Figure 2.6.155 Tsunami Arraival Time Distribution (Hunga Tonga-Hunga Ha'pai, H=60m)



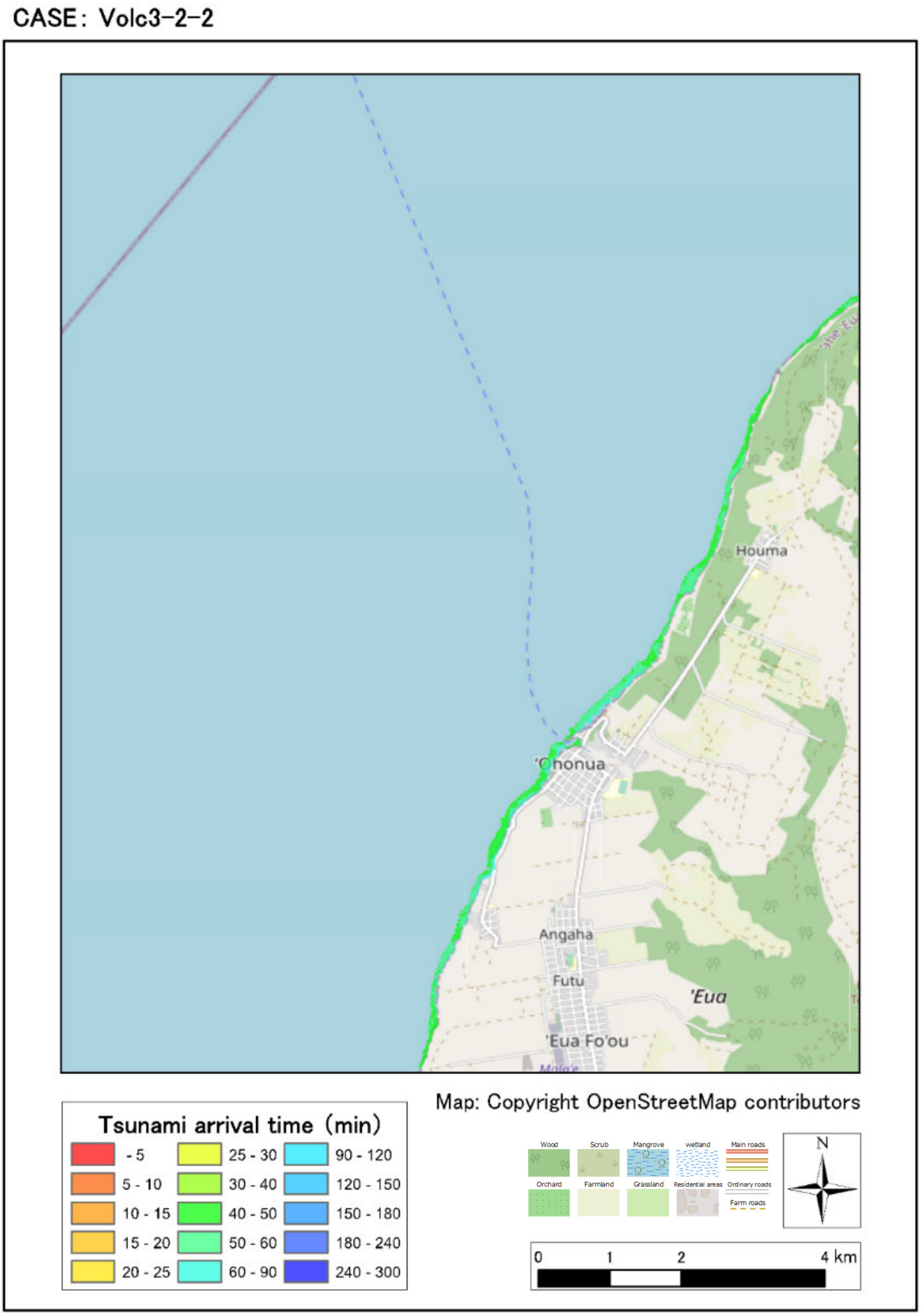
Source: JICA Study Team

Figure 2.6.156 Tsunami Arraival Time Distribution (Unnamed1, H=60m)

CASE：Volc2-2-2

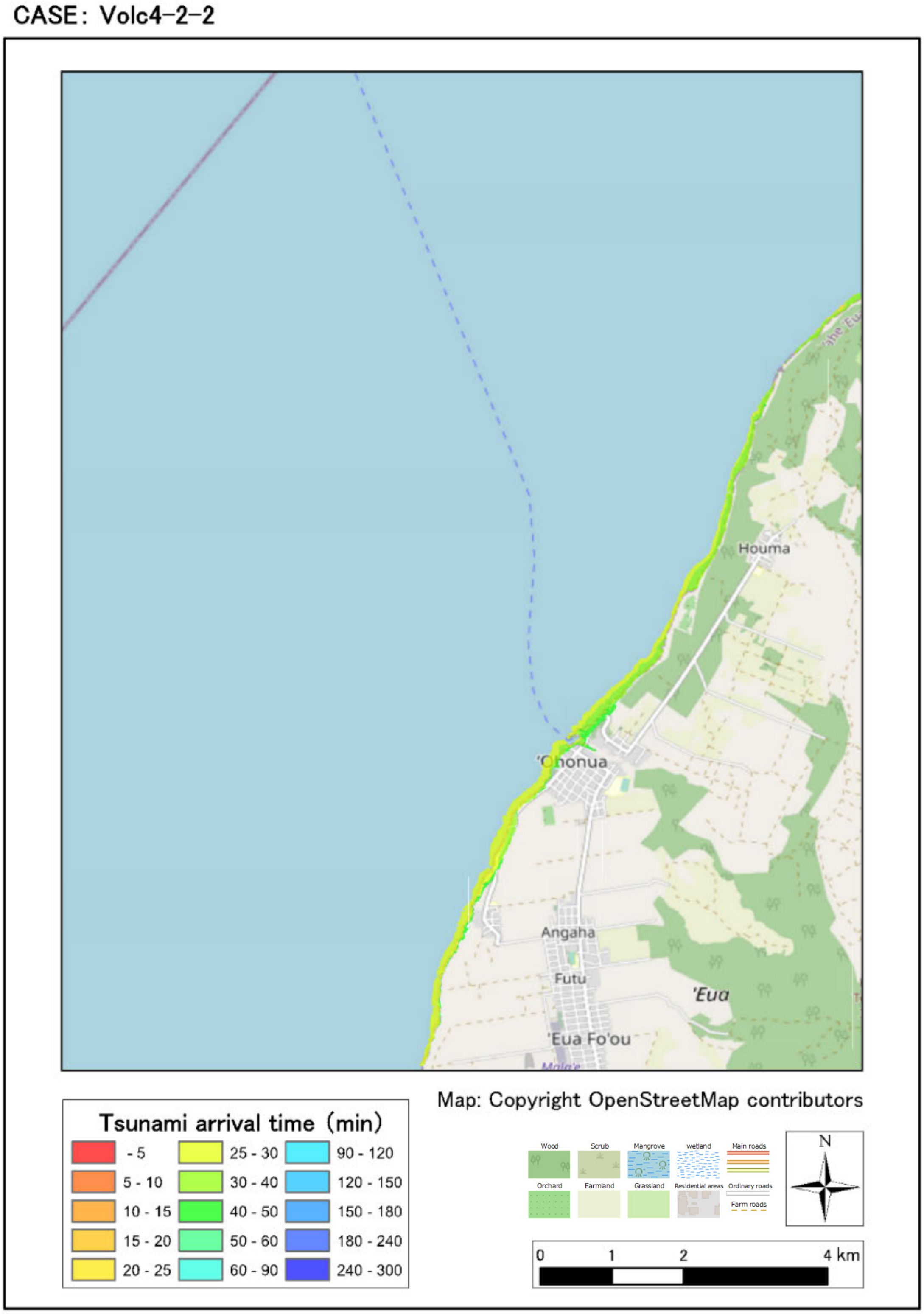
Source: JICA Study Team

Figure 2.6.157 Tsunami Arraival Time Distribution (HomeReef, H=60m)



Source: JICA Study Team

Figure 2.6.158 Tsunami Arraival Time Distribution (Lateiki, H=60m)



Source: JICA Study Team

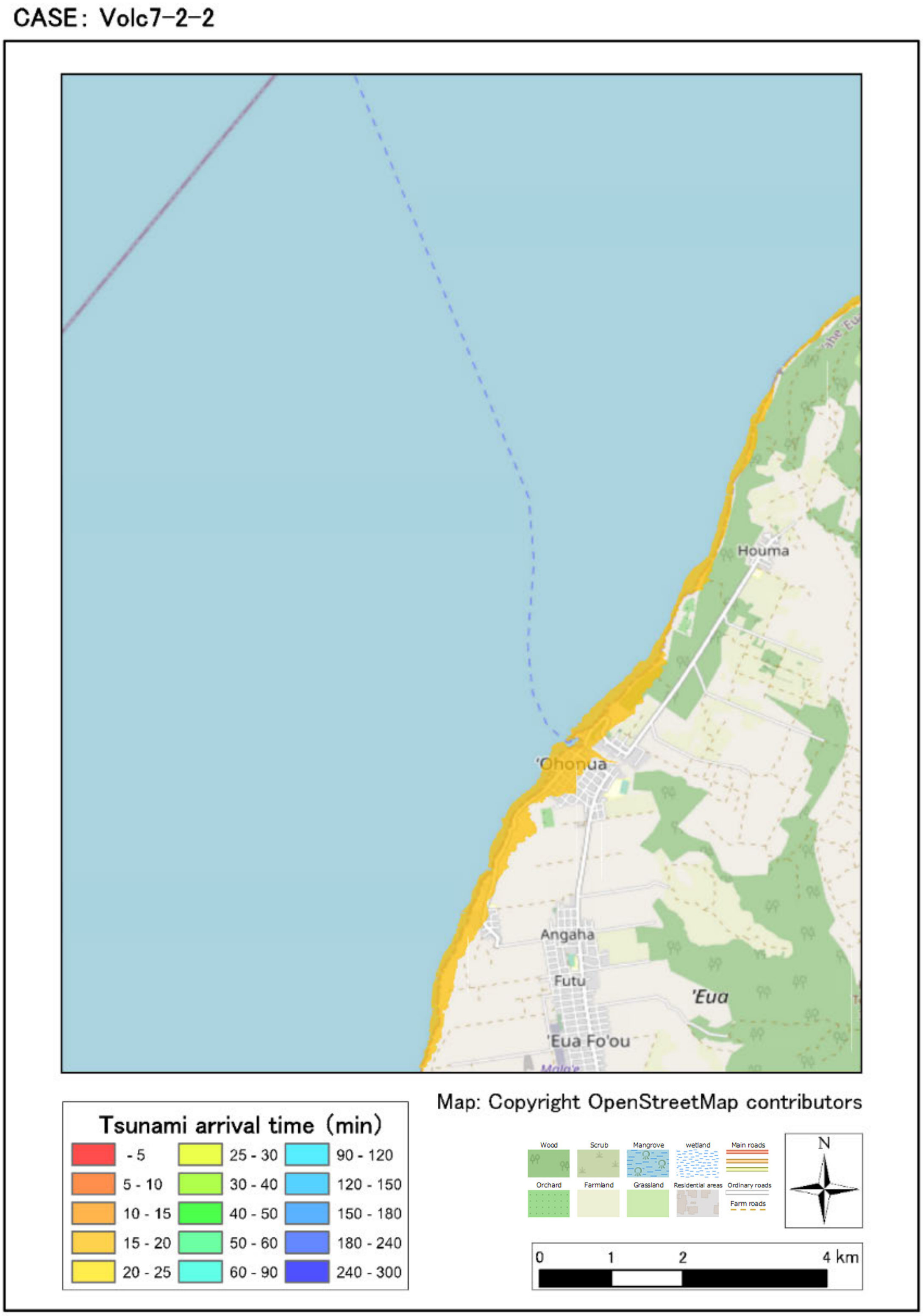
Figure 2.6.159 Tsunami Arraival Time Distribution (Fonuafo'ou, H=60m)

Source: JICA Study Team

Figure 2.6.160 Tsunami Arraival Time Distribution (Unamed2, H=60m)

Source: JICA Study Team

Figure 2.6.161 Tsunami Arraival Time Distribution (Unamed3, H=60m)



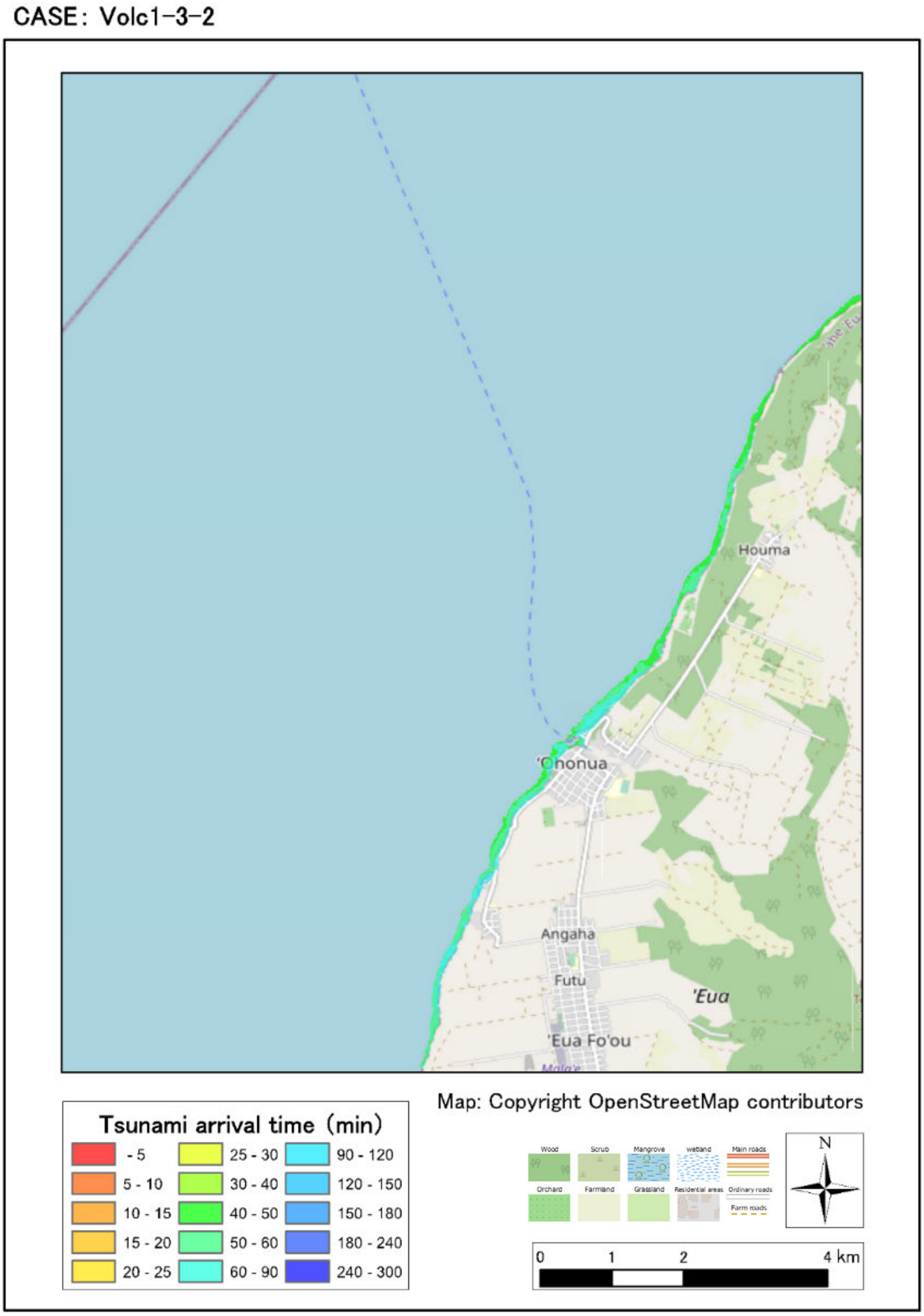
Source: JICA Study Team

Figure 2.6.162 Tsunami Arraival Time Distribution (Unamed4, H=60m)

CASE: Volc0-3-2

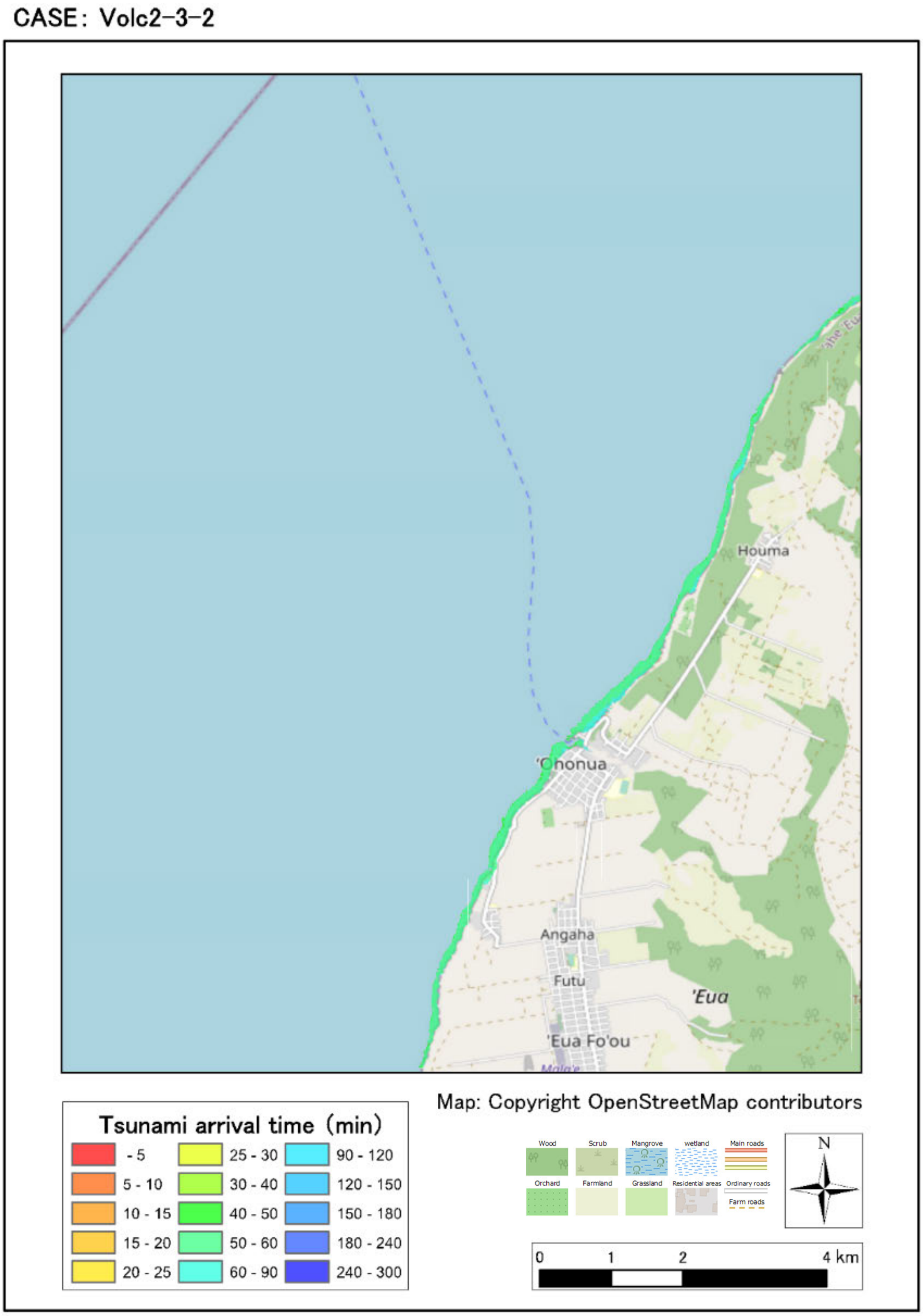
Source: JICA Study Team

Figure 2.6.163 Tsunami Arraival Time Distribution (Hunga Tonga-Hunga Ha'pai, H=90m)



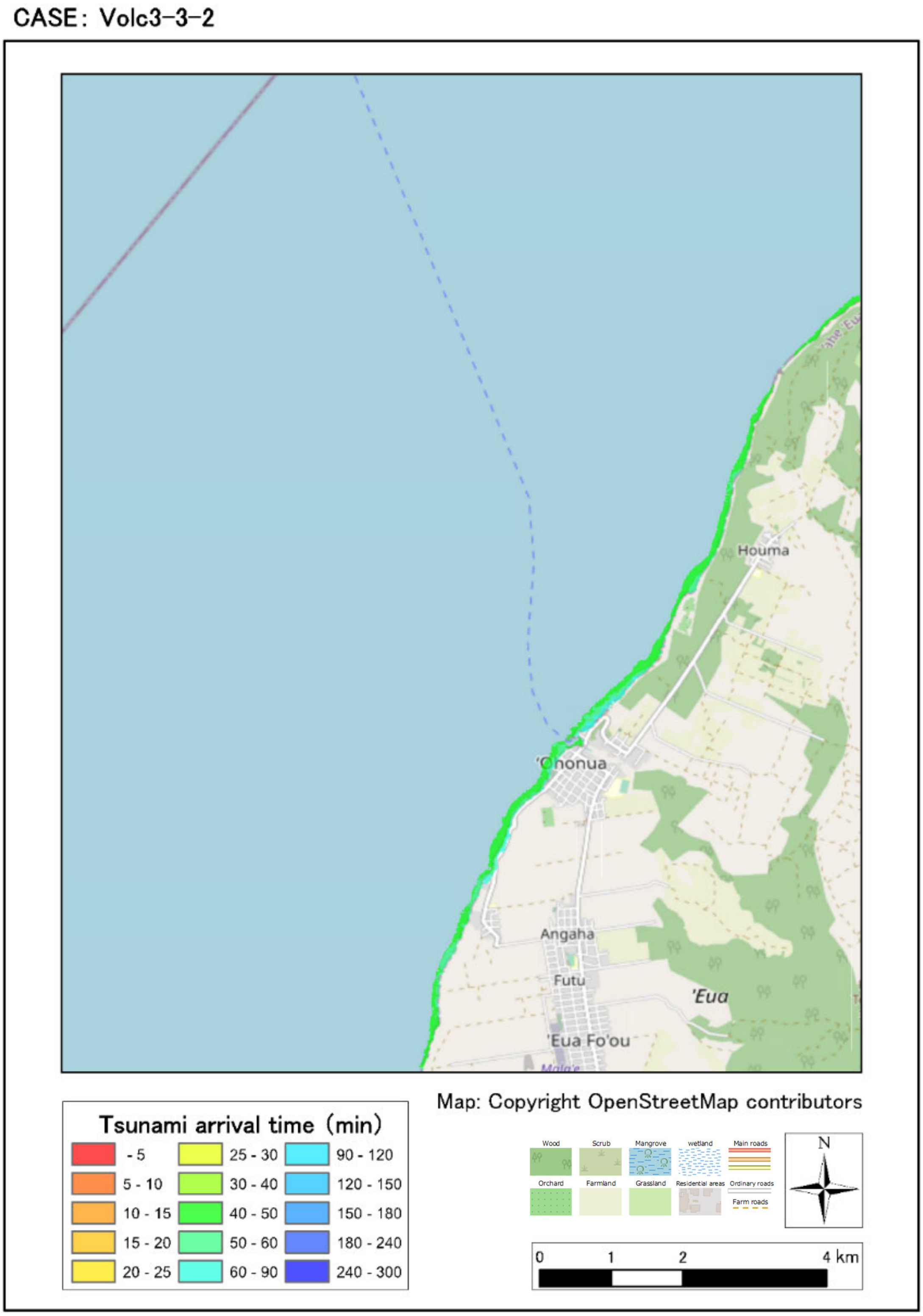
Source: JICA Study Team

Figure 2.6.164 Tsunami Arraival Time Distribution (Unnamed1, H=90m)



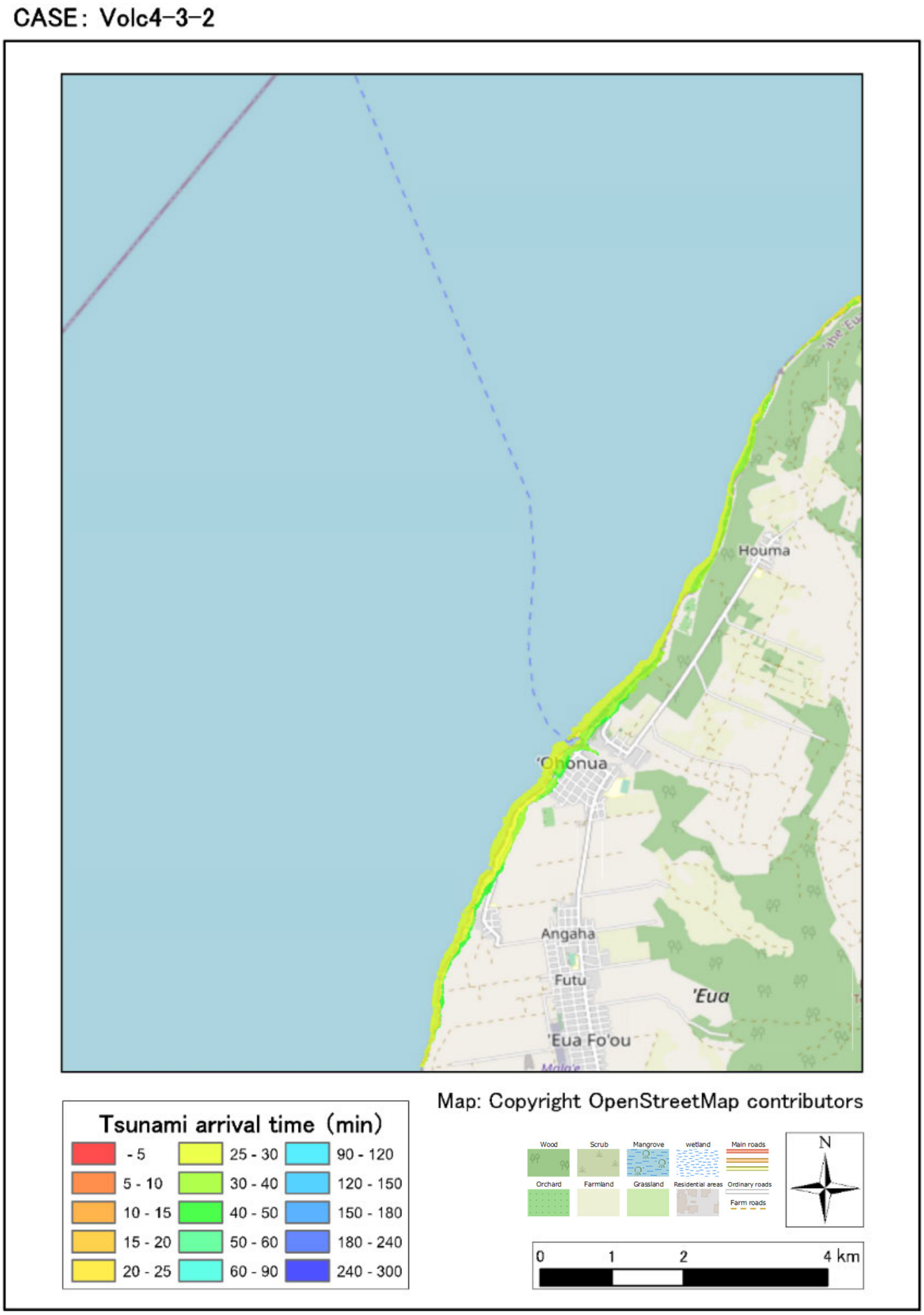
Source: JICA Study Team

Figure 2.6.165 Tsunami Arraival Time Distribution (HomeReef, H=90m)



Source: JICA Study Team

Figure 2.6.166 Tsunami Arraival Time Distribution (Lateiki, H=90m)



Source: JICA Study Team

Figure 2.6.167 Tsunami Arraival Time Distribution (Fonuafo'ou, H=90m)

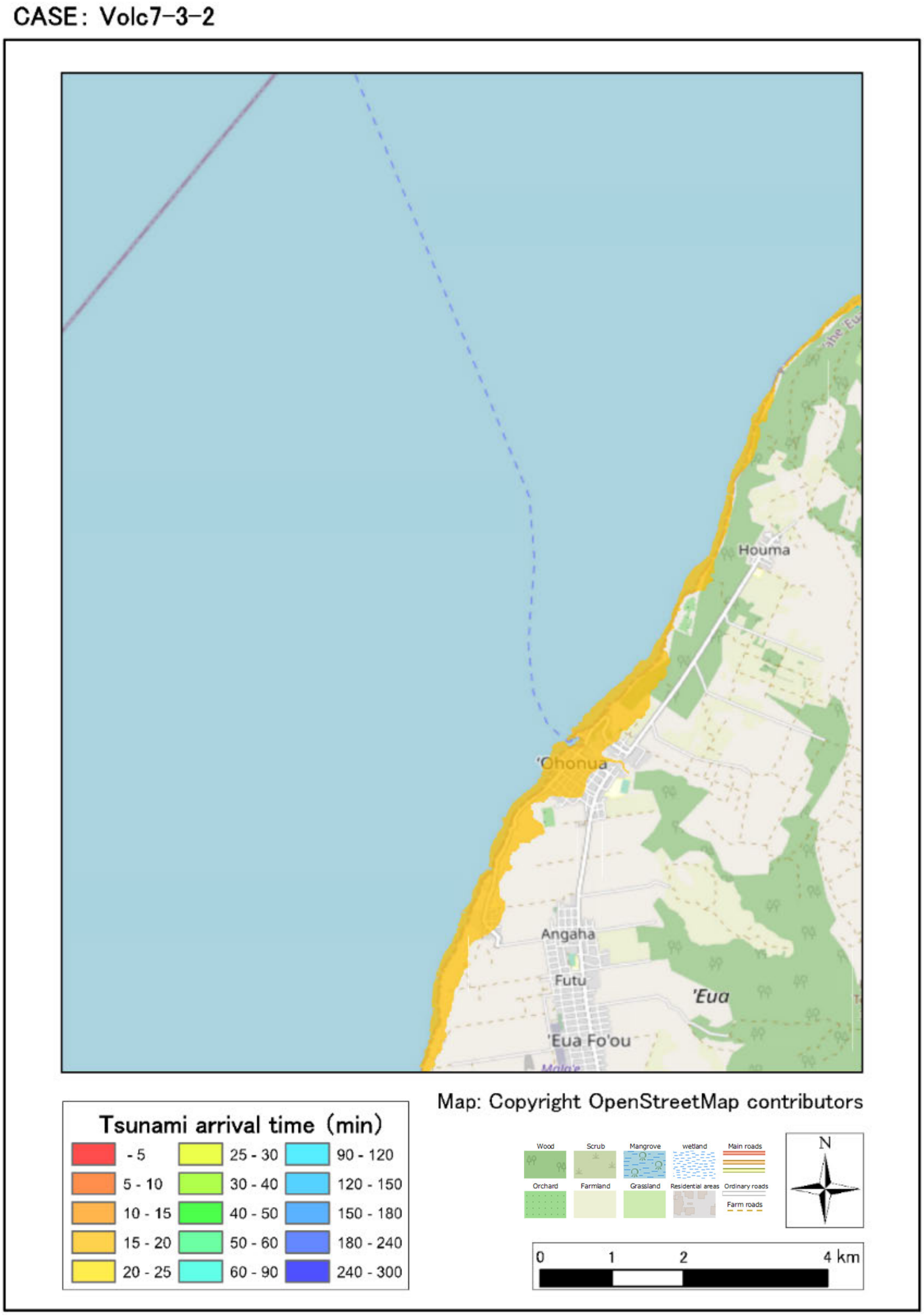
Source: JICA Study Team

Figure 2.6.168 Tsunami Arraival Time Distribution (Unamed2, H=90m)

CASE: Volc6-3-2

Source: JICA Study Team

Figure 2.6.169 Tsunami Arraival Time Distribution (Unamed3, H=90m)



Source: JICA Study Team

Figure 2.6.170 Tsunami Arraival Time Distribution (Unamed4, H=90m)