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Methodology for constructing a flood-hazard map for a future climate

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Table S1. Inundation area near the Chao Phraya River obtained using each GCM and method (km^2)

From top to bottom: IPSL-CM6A-LR, MIROC6, MRI-ESM2-0, GFDL-CM4, NorESM2-MM, ACCESS-CM2, INM-CM5-0, MPI-ESM1-2-HR, and EC-Earth3

GCM	Historical Climate			Future Climate		
	Reference	Uncorrected GCM	Runoff Corrected	Uncorrected GCM	Runoff Corrected	Lookup
IPSL	42,321	48,925	47,069	60,000	59,320	49,803
MIROC		43,886	44,948	47,992	49,307	45,970
MRI		49,322	48,898	51,308	51,598	43,980
GFDL		48,224	49,431	53,566	54,312	48,246
Nor		41,732	40,781	43,832	43,927	45,247
ACC		48,542	48,587	57,434	56,908	48,699
INM		58,426	54,121	56,643	51,052	39,192
MPI		24,865	34,475	35,054	40,085	48,106
EC		42,196	41,260	49,715	49,397	46,976
average	42,321	45,124	45,508	50,616	50,656	46,247
median	42,321	48,224	47,069	51,308	51,052	46,976

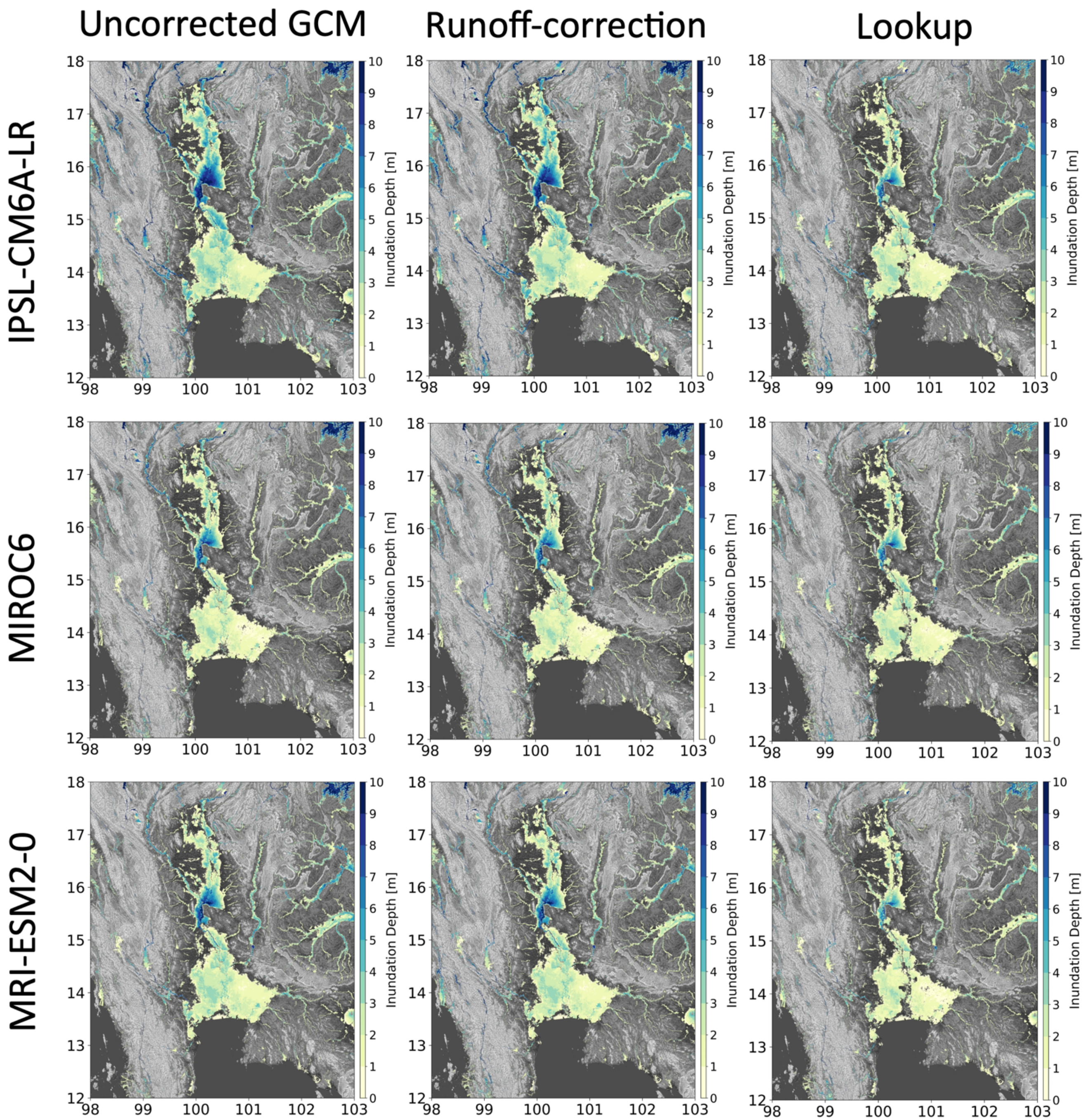
Table S2. Results of Backwater_Modification validation for each river (Indicator 1, Indicator 2)

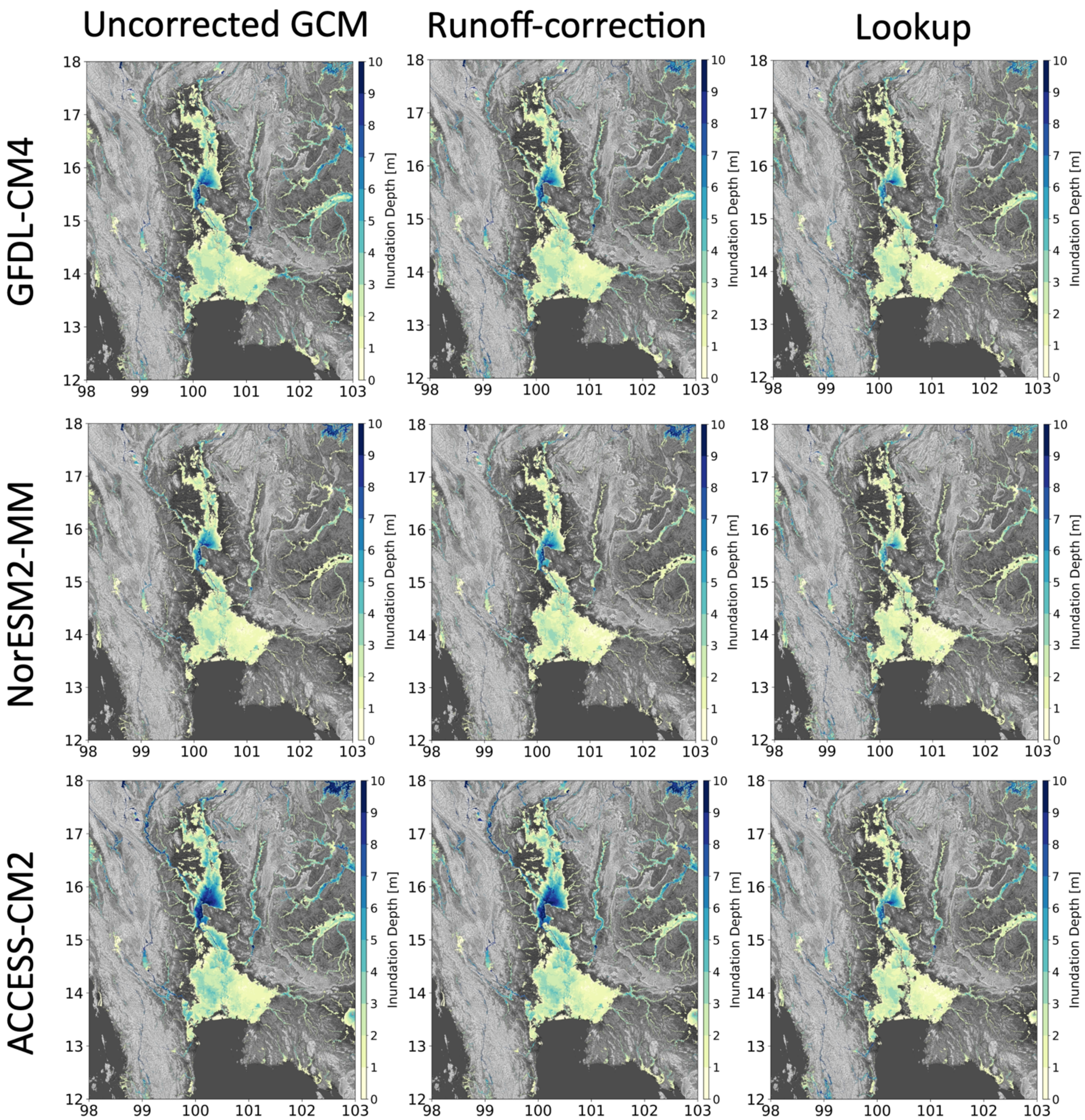
River Name	Indicator 1	Indicator 2	
		without Backwater_Modification	with Backwater_Modification
Chikuma river	75.68%	70.32%	81.75%
Ohta river	96.80%	58.88%	60.66%
Kamanashi river	94.60%	38.54%	42.57%
Takahashi river	95.07%	76.33%	79.05%
Abukuma river	59.26%	83.10%	90.59%

Indicator 1 represents $\frac{\text{Inundation area increase with Backwater\_Modification(included in MLIT Hazard Map)}}{\text{Inundation area increase with Backwater\_Modification}}$

Indicator 2 represents $\frac{\text{Inundation area of CaMa}-\text{Flood}-\text{hazard map(included in MLIT Hazard Map)}}{\text{Inundation area of MLIT Hazard Map}}$

MLIT, Ministry of Land, Infrastructure, Transport and Tourism of Japan.


Uncorrected GCM
Runoff-correction
Lookup
IPSL-CM6A-LR
MIROC6
MRI-ESM2-0
Inundation Depth [m]


Uncorrected GCM
Runoff-correction
Lookup
GFDL-CM4
NorESM2-MM
ACCESS-CM2
Inundation Depth [m]

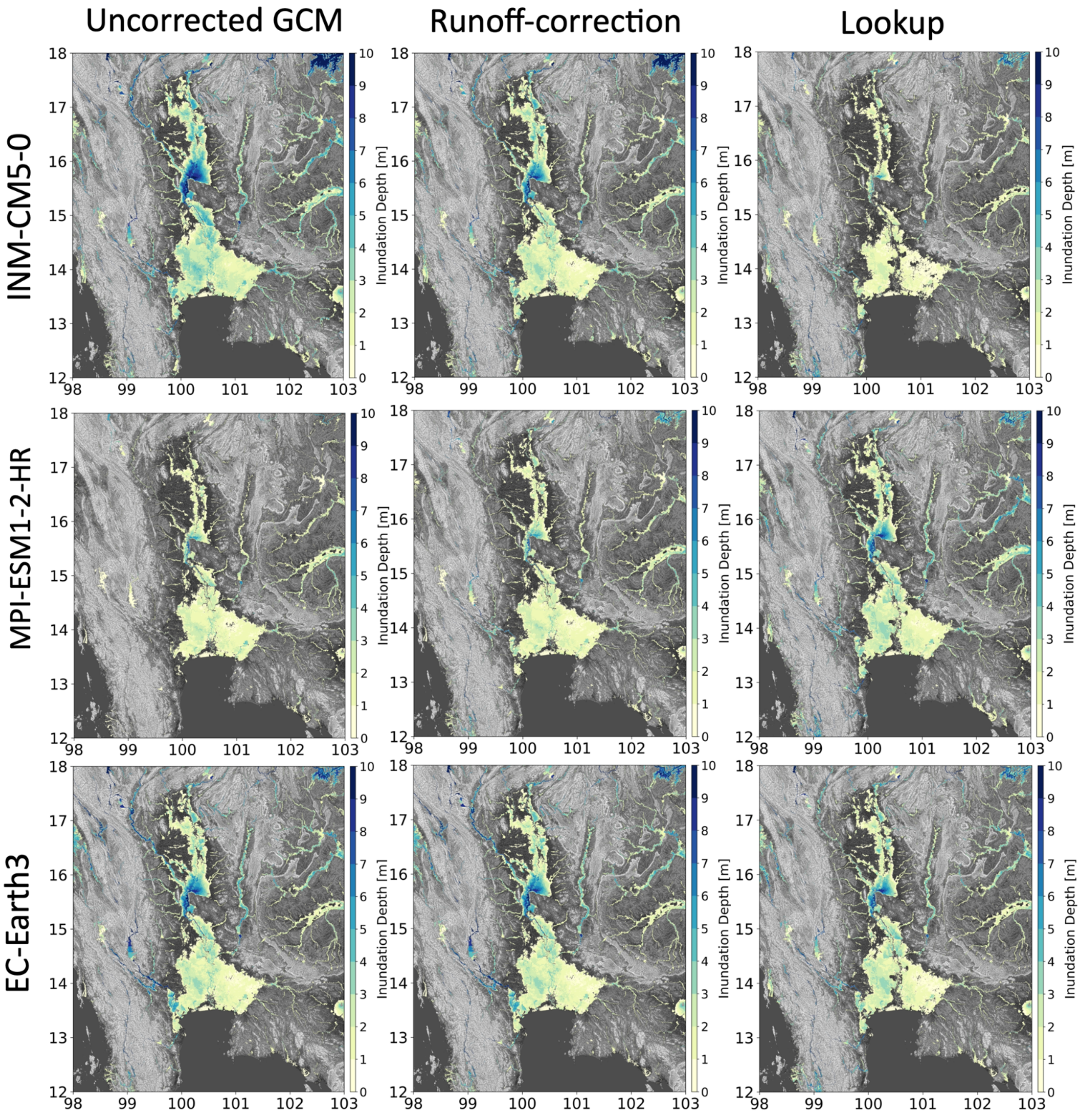


Figure S1. The 100-year return period future climate hazard map around the Chao Phraya River

GCMs from left to right: Uncorrected, Runoff-corrected, and Lookup; from to top to bottom: IPSL-CM6A-LR, MIROC6, MRI-ESM2-0, GFDL-CM4, NorESM2-MM, ACCESS-CM2, INM-CM5-0, MPI-ESM1-2-HR, and EC-Earth3

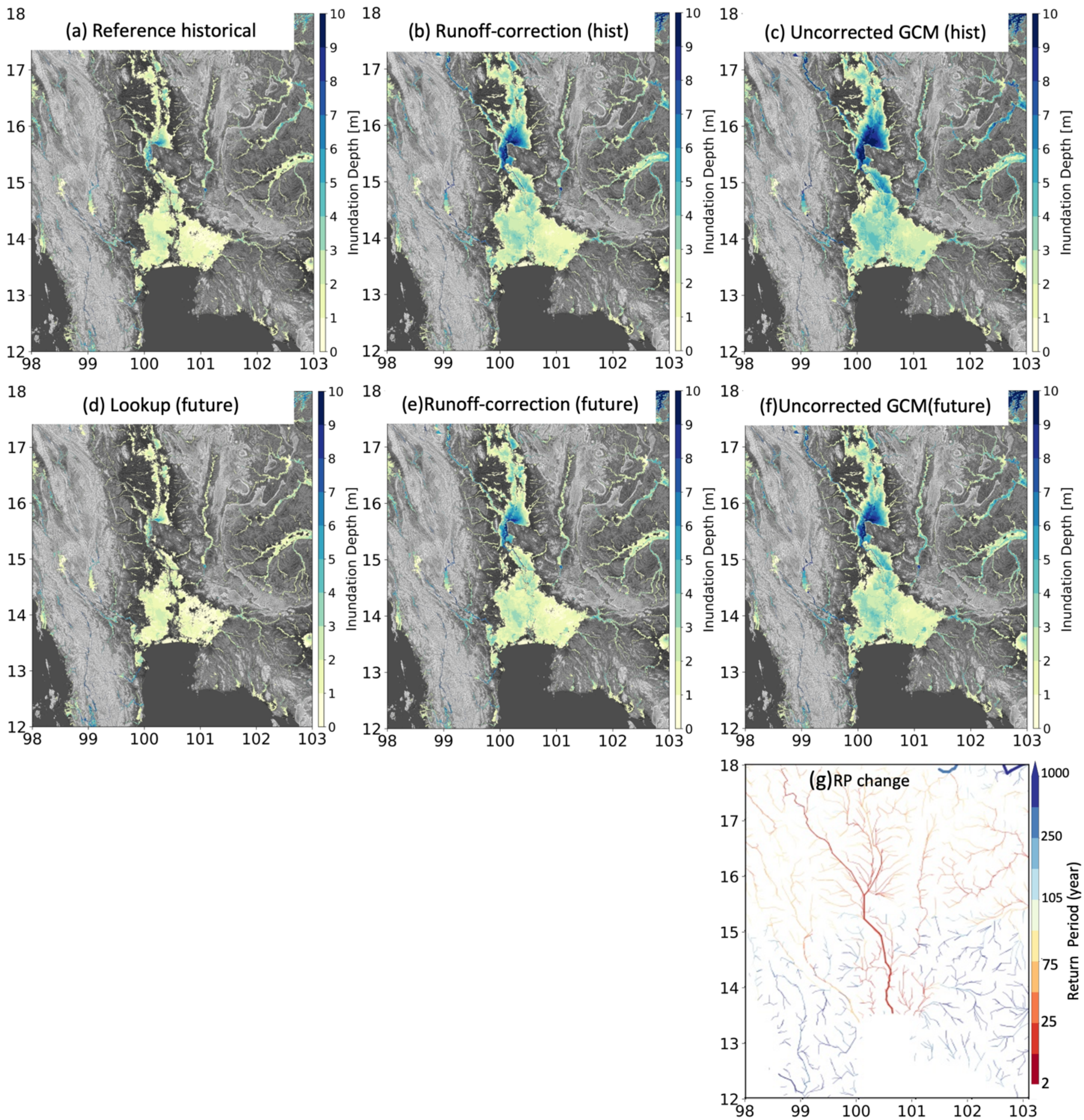


Figure S2. The 100-year return period hazard map around the Chao Phraya River (obtained using INM-CM5-0)

(a) Reference historical hazard map (based on reanalysis data); (b) hazard map obtained using the runoff-correction method (historical); (c) hazard map based on uncorrected GCM runoff (historical); (d) hazard map obtained using the lookup method; (e) hazard map obtained using the runoff-correction method (future); (f) hazard map based on uncorrected GCM runoff (future); and (g) historical return period (RP) of river water level corresponding to the 100-year RP in the future.

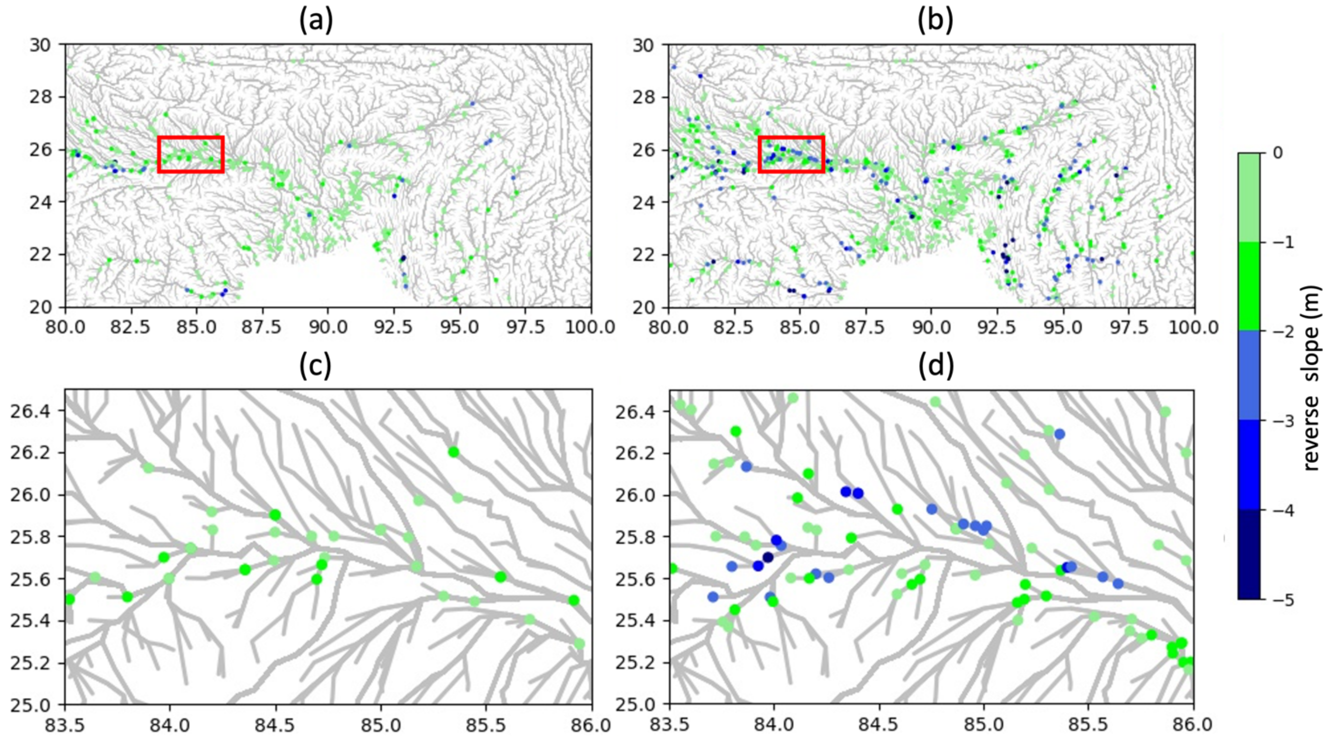


Figure S3. Reverse slope occurrence points around the Ganges River based on the water surface elevation distribution without Backwater_Modification (unit: m)

(a) Reanalysis data, (b) lookup method (c) enlarged view of the red square in (a), and (d) enlarged view of the red square in (b) with a threshold of −0.1 m (not shown) applied for display purposes.

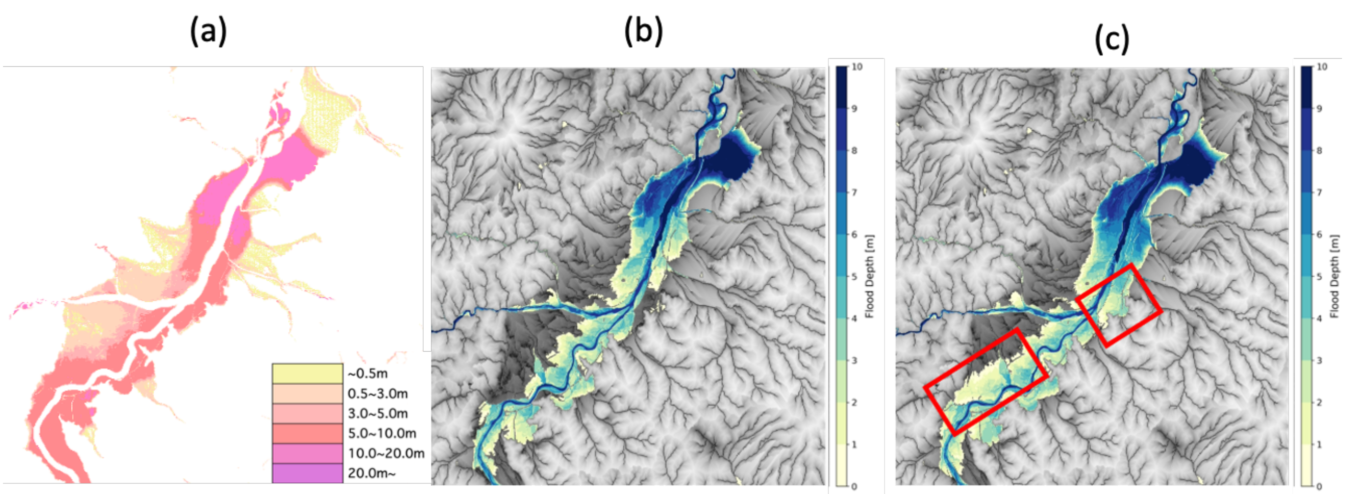


Figure S4. The 1000-year return period hazard map of the Chikuma River

(a) National, (b) CaMa-Flood without Backwater_Modification, (c) CaMa-Flood with Backwater_Modification

Sect. S1: Additional validation of Backwater_Modification

Additional validation of the Backwater_Modification process was conducted. Specifically, we investigated the following questions for Japan, where official hazard maps are available.

1) How much does the inundation area increase with Backwater_Modification?

2) Does the inundation area increase at reasonable locations with Backwater_Modification?

For this analysis, we selected the Chikuma River near Nagano City, the Takahashi River near Kurashiki City, and the Abukuma River near Koriyama City, all of which have experienced river flooding due to heavy rainfall in recent years, as sites for evaluation. We also selected the Ota River near Hiroshima City, which has a branch channel, and the Kamanashi River near Kofu City, as these rivers have historically caused frequent river flooding in inland fan-shaped areas. Flood simulations were conducted using CaMa-Flood ver. 4.01. For comparison with the CaMa-Flood flood-hazard map, we obtained the assumed flood inundation area (assumed maximum size) from the hazard map portal site published by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and the Geospatial Information Authority of Japan (GSI) (hereinafter referred to as the national hazard map). For the detailed experimental setup, see <Experimental Setting> below. To compare these maps, the following quantitative indicators are used. We assessed whether the inundation area expanded to reasonable locations using Indicator 1 and whether the number of missed cases in CaMa-Flood was reduced using Indicator 2

Indicator 1 represents $\frac{\text{Inundation area (included in MLIT Hazard Map) increase with Backwater Modification}}{\text{Inundation area increase with Backwater Modification}}$

Indicator 2 represents $\frac{\text{Inundation area of CaMa}-\text{Flood}-\text{hazard Map(included in MLIT Hazard Map)}}{\text{Inundation area of MLIT Hazard Map}}$

Sect. S1.1 Experiment Setting

Sect. S1.1.1 CaMa-Flood ver. 4.01 River Inundation Simulation

Flood-inundation calculations were performed for all of Japan (120°–150°E, 20°–50°N). Elevation and surface-flow data developed by Yamazaki et al., 2018 were used, and the river network map of CaMa-Flood (1-arcmin resolution in this analysis) was constructed through upscaling of a high-resolution river topography map for the Japanese region. River inundation simulations were performed using CaMa-Flood with daily total runoff data from 1980–2014 as input values. The data used were Variable Infiltration Capacity (VIC)-Bias-Corrected runoff data, as described in maintext section 2.1, with a resolution of 3 arcmin. The hazard map was created by performing extreme-value analysis of the water level in each grid, which is the same procedure as described in maintext section 2.2. Based on the Gumbel distribution for each grid point, the 1000-year RP inundation depth was calculated. After downscaling this water depth to account for the topography of each unit catchment area, we calculated the assumed inundation area and inundation depth for a 1000-year RP with a spatial resolution of 3 arcsec to produce the CaMa-Flood-hazard map.

Sect. S1.1.2 National Hazard Map

As a comparison target for the CaMa-Flood flood-hazard map, we selected the assumed flood inundation area (assumed maximum size) from the national hazard map. Specifically, we used the maximum expected inundation area map for rivers (https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-A31-v2_1.html), which was prepared in accordance with Product Document Version 2.1 (MLIT, 2020). National hazard maps are prepared using the methodology of the Manual for Flood Inundation Area Mapping ver. 4 (MLIT/NILIM, 2015). The basic equation for inundation analysis is the unsteady flow equation, which approximates hydrostatic pressure in the vertical direction; land use and building occupancy are also considered. Rainfall amounts are set for each of 15 regions in Japan (MLIT/NILIM, 2015), and most rivers are set to exceed the annual exceedance probability of 1/1000. The duration of rainfall is determined for each river, and the hyetograph is set to maximize damage in the event of flooding, based on the hyetograph used when considering high water in the general river maintenance policy. Digital elevation models based on methods such as aerial laser surveying are the main elevation data used for grid calculations; when not available, 5-m and 10-m spatial resolution base map information from GSI is used. These elevations are used to downscale from the maximum inundation depth of a 25-m resolution computational grid to a resolution of 5 m. The final flood inundation area is created through overlaying of the inundation areas obtained for each break point. In contrast to the outputs of global river models such as CaMa-Flood, which approximate the topography in catchment units, the national hazard map considers detailed topography and conducts simulations at high resolution for each river, and therefore its accuracy is guaranteed to a certain degree.

Sect. S1.2 Results

The results of Indicators 1 and 2 for the Chikuma River, Ota River, Kamanashi River, Takahashi River, and Abukuma River are presented in Table S2, and imply the following conclusions. Indicator 1 showed that the inundation area increased at reasonable locations on all rivers except the Abukuma River. For the Ota River, Kamanashi River, and Takahashi River, approximately 95% of the inundation area increases obtained with Backwater_Modification were included in the national hazard map. Although we found that the value of Indicator 1 was poor for the Abukuma River, we confirmed that some inundated areas were in tributaries not included in the national hazard map. Indicator 2 showed that the number of missed points in the CaMa-Flood inundation area decreased with Backwater_Modification in the Abukuma River, Chikuma River, and other rivers, indicating that CaMa-Flood-hazard maps became more similar to the national hazard map with that method. The Chikuma River hazard map is shown in Figure S4; the inundation area expanded around the points in the red box, approaching the distribution on the national hazard map. For the Chikuma and Abukuma Rivers, the CaMa-Flood-hazard map with Backwater_Modification captured more than 80% and 90% of the inundation points on the national hazard map, respectively. As shown above, we confirmed that the inundation area became more realistic with application of the Backwater_Modification method introduced in this study.

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