

Projected Intensification of Urban Flooding in Antananarivo under Climate Change: RRI Modeling and Infrastructure Implications

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A B S T R A C T

Urban flooding in Antananarivo, Madagascar, has intensified due to a combination of rapid urban expansion, inadequate drainage infrastructure, and increasingly frequent extreme rainfall associated with climate change¹⁻³.

This study analyzes flood dynamics using the Rainfall-Runoff-Inundation (RRI) model driven by both ground-gauge observations and GSMaP satellite rainfall data⁴⁻⁶. Extreme flood years between 1990 and 2024 (1996, 2007, 2019, and 2020) were examined, together with a projected 100-year return-period event for 2050 derived by scaling February 2020 rainfall.

Results show clear differences across scenarios. The 2007 GSMaP-based simulation produced moderate flooding, with peak discharges exceeding 100 m³/s. In contrast, the 2020 gauge-driven simulation produced severe and repeated inundation, with surface water depth (hs) reaching 5.5 m, river water depth (hr) approaching 8 m, and discharge (qr) up to 3000 m³/s.

The 2050 projection reveals a shift toward prolonged flooding, characterized by sustained river water depth (hr ≈ 1.7 m) and persistent surface water depth (hs = 2.3–2.5 m), indicating a saturated and highly vulnerable hydrological system.

These findings highlight increasing flood magnitude and persistence and emphasize the need for integrated, nature-based stormwater management strategies aligned with Sponge City principles⁷.

Keywords: Climate change impact; Rainfall-runoff-inundation (RRI) model; Sponge city strategies; Urban flooding

Introduction

Context of the study

Antananarivo, the capital city of Madagascar, has

experienced increasing urban flooding due to rapid urbanization, limited drainage capacity, and intensifying extreme precipitation associated with cyclone activity in the South-West Indian Ocean¹⁻³.

Importance of flood modeling

Accurate flood modeling supports urban planning, infrastructure design, and disaster risk reduction by quantifying flood extent, depth, and discharge under different scenarios.

Rainfall-runoff-inundation (RRI) model

The RRI model integrates rainfall, runoff, and inundation processes, simulating channel flow, overland flow, and floodplain storage. It is well suited for urban flood assessment and scenario analysis.

Study objective

This study evaluates the performance of the RRI model using gauge and GSMaP rainfall data and assesses future flood risk under a scaled 2050 extreme rainfall scenario⁴⁻⁶.

Materials and Methods

Study area

The study area covers urban and peri-urban Antananarivo, including main river networks and flood-prone lowlands characterized by dense urbanization and inadequate drainage.

Data

Rainfall data include meteorological station records (1990-2024) and GSMaP satellite rainfall products (hourly, 0.1° resolution)⁴⁻⁶.

RRI model setup

Key simulated variables:

- hs (m):** surface water depth (floodplain/urban inundation)
- hr (m):** river water depth (channel flow)
- qr (m³/s):** river discharge (flow rate)

Simulation scenarios

Selected extreme years from 1990-2024: 1996, 2007, 2019, and 2020. 2020 had the highest recorded annual rainfall (3,094.1 mm), associated with multiple cyclones and prolonged wet spells. GSMaP performance was compared against gauges for these intense years¹⁻³.

Generation of the scaled 2050 extreme rainfall scenario

A 100-year return-period event for 2050 was generated by scaling the identified extreme five-day February 2020 event using: a scaling factor, the ratio of projected to observed rainfall.

Factor = P2050,total / P2020,total

This preserves temporal rainfall variability while adjusting magnitude to future projections.

Results

RRI simulation: 2007 (GSMaP)

The GSMaP-driven simulation captured moderate flooding conditions, although peak discharges were underestimated⁴⁻⁶. Simulated qr exceeded 100 m³/s, while localized hs and hr values indicated significant inundation (Figures 1,2), (Table 1).

Table 1: Quantitative Summary of Wet-Season RRI Simulation Jan-Mar 2007.

Parameter	Description	Observed Values	Hydrological Interpretation
hs	Depth of water over floodplain/urban areas	0 m → > 20 m in flooded cells	Demonstrates extensive and persistent inundation over low-lying areas
hr	River water depth	< 1 m under normal conditions → ~15 m at peak	Exceeds bankfull capacity; indicates river overtopping and onset of flooding
qr	Flow rate of the river (m³/s)	Peaks exceeding 100 m³/s	Represents a major flood wave; confirms high-intensity runoff and channel overflow

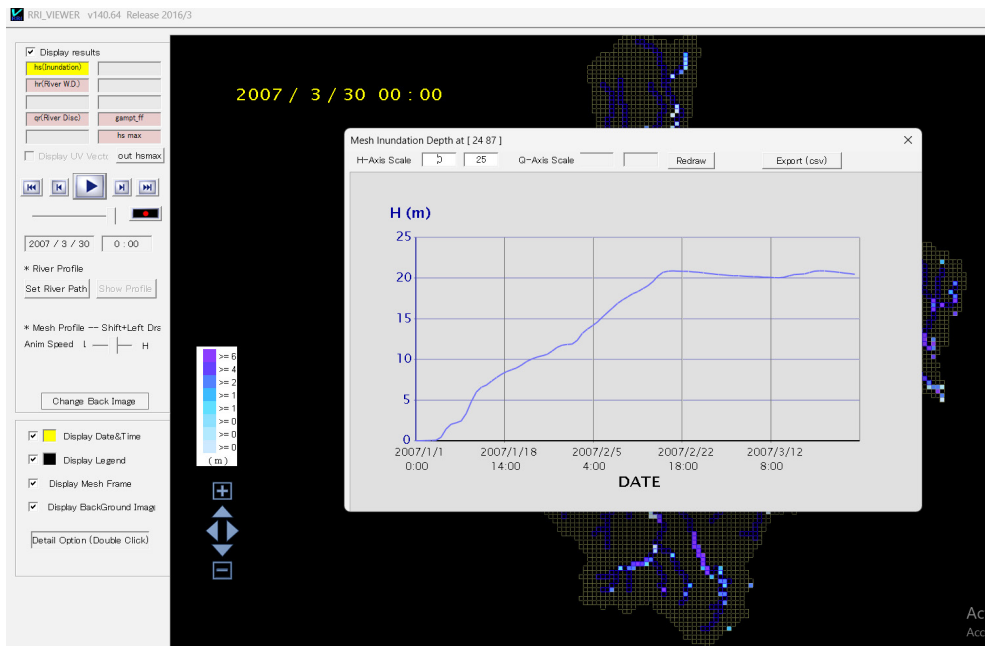


Figure 1: Flood Inundation Depth Hydrograph 2007.

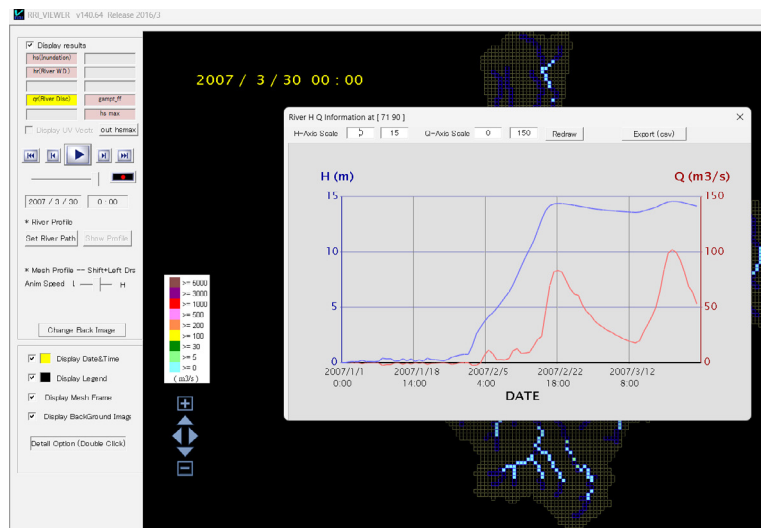


Figure 2: River Water Depth (blue) and River discharge (red) Hydrograph 2007.

RRI simulation:2020 (Gauge data)

The 2020 simulation represents an extreme flood scenario driven by cyclone-related rainfall¹⁻³.

- hs reached up to 5.5 m
- hr peaked around 8 m
- qr ranged from 200 to 3000 m³/s

Four major flood peaks correspond to rainfall events between January and March, confirming repeated flooding and strong interaction between surface runoff and river overflow (**Table 2**), (**Figures 3,4**).

Table 2: Quantitative Summary of 2020 Wet-Season RRI Simulation.

Variable	Definition	Unit	Correct Range / Peak Observed	Hydrological Interpretation
hs	Surface water depth (accumulated water on land surface)	m	0.00 - 5.5	Positive hs values indicate significant surface inundation across the catchment. Multiple peaks between 3-5.5 m reflect repeated major flood events during 2020. Depths above 2 m correspond to severe flooding affecting homes, roads, and low-lying urban areas (Andavamamba, Ankorondrano, Anosibe). The recurrence of high peaks shows persistent saturation and limited drainage capacity during intense rainfall episodes.
hr	River water depth (channel flow)	m	0.5 - 8.0	Minimum values reflect low baseflow; peaks around 8 m show that river channels exceeded their conveyance capacity. This indicates repeated overbank flooding events that contributed directly to urban inundation.
qr	River discharge (flow rate)	m ³ /s	200 - 3000	High discharge peaks align with rainfall events, indicating rapid runoff response and strong riverine contribution to flooding. Peaks approaching 3000 m ³ /s confirm extreme wet-season flow conditions and the likelihood of overflow into adjacent floodplain areas.
Flood extent / duration	Spatial and temporal coverage	-	Concentrated in low-lying and urban zones	Inundation persisted in central floodplain neighborhoods, remained moderate along transport and industrial corridors, and was shallow but widespread in peripheral agricultural areas. Confirms combined surface and channel flooding throughout the period.

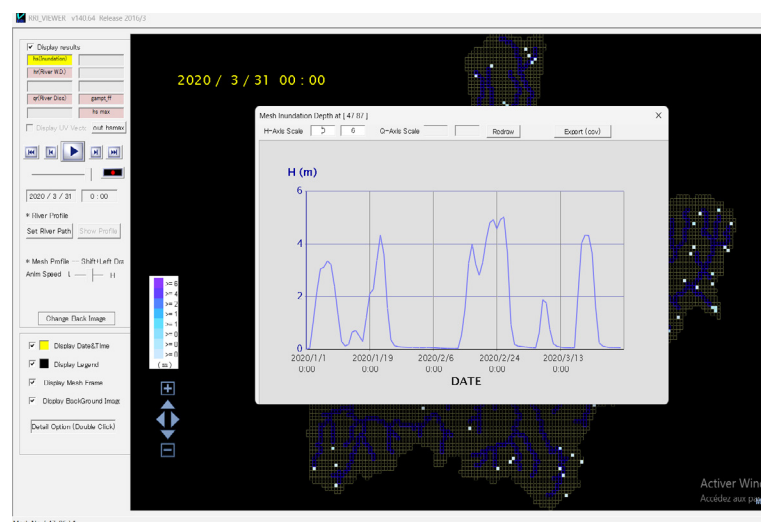


Figure 3: Flood Inundation Depth Hydrograph 2020.

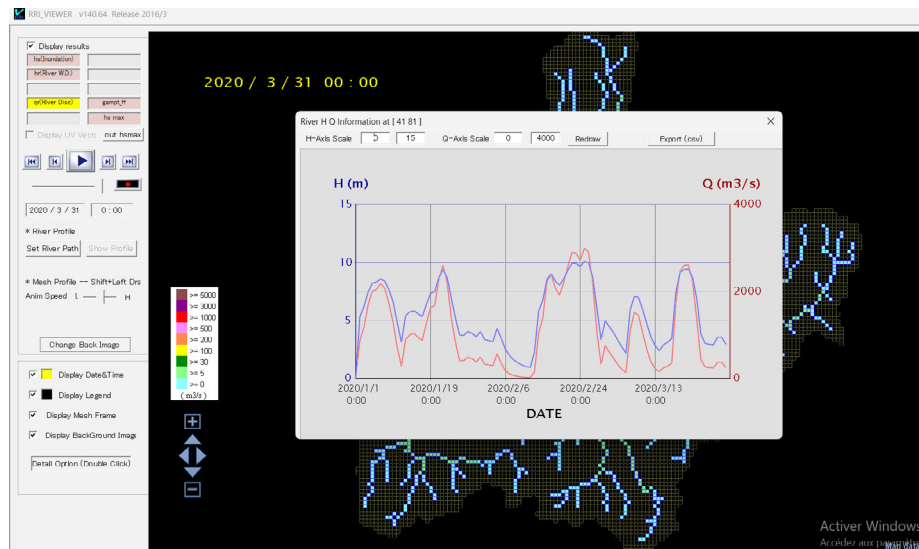


Figure 4: River Water Depth (blue) and River discharge (red) Hydrograph 2020

RRI simulation - Projected Year 2050

The 2050 scenario shows a transition toward persistent flooding conditions.

- hs stabilizes at 2.3-2.5 m
- hr stabilizes around 1.7 m
- qr peaks at approximately 600 m³/s

Unlike previous scenarios, water levels do not recede, indicating a saturated hydrological system with limited drainage capacity (Table 3), (Figures 5,6).

Table 3: Summary Interpretation of RRI Model Outputs (21-25 February 2050).

Indicator	Observation in 2050 Simulation	Interpretation	Flood Implication
hs	Steady rise to 2.3–2.5 m (no recession)	Persistent surface water accumulation due to intense rainfall and low drainage efficiency	Severe and long-duration urban flooding across flood-prone districts
hr	Increase from 0 to ~1.7 m	Channel filling and overtopping likelihood	High risk of riverbank overflow and floodplain inundation
qr	Increase to ~600 m³/s	Rapid runoff concentration and limited river capacity	Potential structural failure of drainage canals and river spillover
Timing pattern	Two-stage peak: 21 Feb and 24–25 Feb	Flash-flood onset followed by a more intense sustained wave	Long-lasting, multi-peak flooding event
Overall system response	Continuous rising trend across all indicators	Saturated catchment under extreme rainfall	Critical flood hazard requiring advanced mitigation strategies

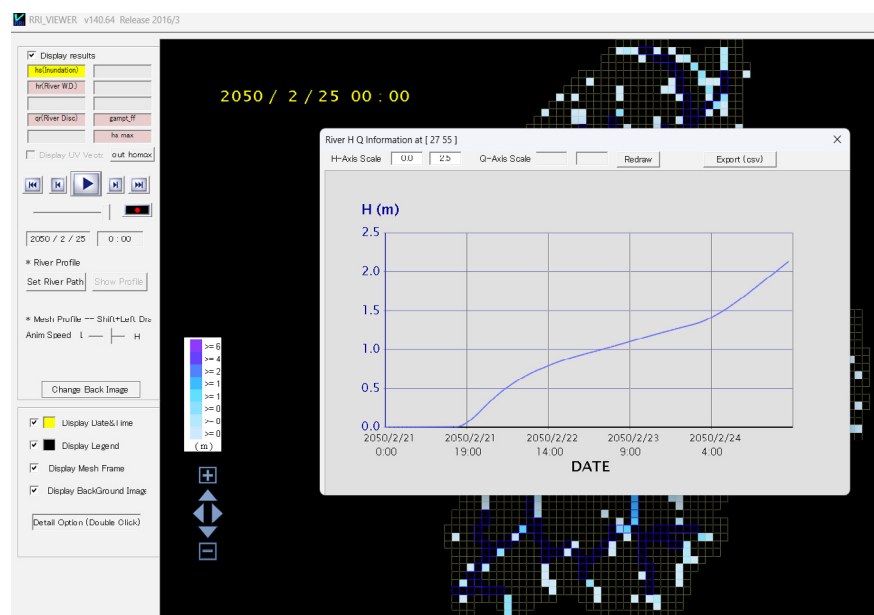


Figure 5: Flood Inundation Depth Hydrograph 2050.

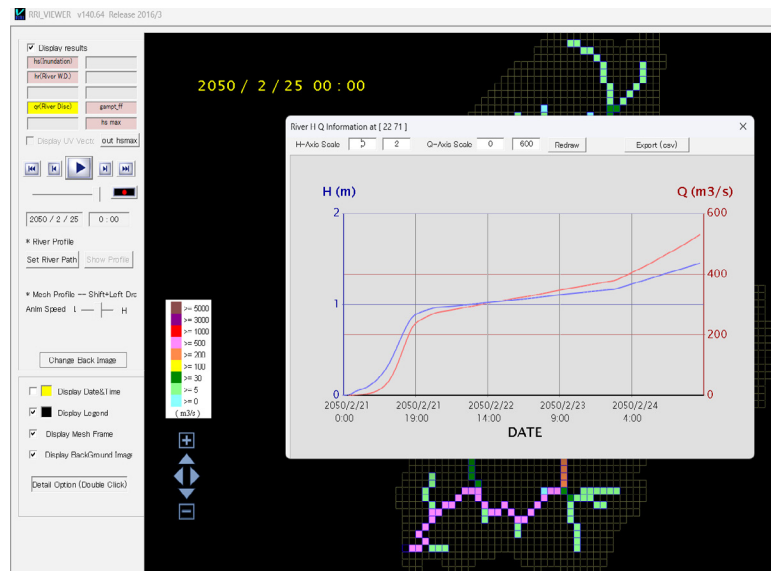


Figure 6: River Water Depth (blue) and River discharge (red) Hydrograph 2050.

Discussion

Hydrological indicators (hs, hr, qr) reveal a clear intensification of flooding in both magnitude and duration.

- **2007:** moderate, short-duration flooding
- **2020:** extreme, multi-peak flooding
- **2050:** persistent, long-duration flooding

This evolution reflects a transition toward system-wide saturation under climate change and urban pressure²⁻⁴.

Uncertainties associated with satellite rainfall products are consistent with previous studies on GSMaP performance⁴⁻⁶.

Practical sponge city applications

To enhance urban resilience, practical measures include:

- Conversion of flood-prone areas into retention basins
- Installation of permeable pavements
- Development of green corridors along rivers
- Wetland restoration for natural storage
- Rainwater harvesting systems

These strategies align with Sponge City principles and contribute to sustainable flood mitigation¹.

Implications for Practice and Policy

Future flood management should prioritize integrated, nature-based approaches, including permeable infrastructure, infiltration zones, and retention systems.

Enhancing hydrometeorological monitoring and improving rainfall data accuracy are also essential to ensure reliable flood modeling and informed planning⁷.

Conclusions

Urban flooding in Antananarivo is intensifying due to climate variability, cyclone activity, and rapid urbanization¹⁻³.

RRI simulations demonstrate a progression from moderate flooding (2007) to extreme flooding (2020), and ultimately to persistent flooding conditions projected for 2050.

Key indicators (hs, hr, qr) confirm increasing flood magnitude, duration, and recurrence.

The 2050 scenario highlights a critical shift toward a saturated system with no recovery between rainfall events.

These findings confirm that conventional drainage systems are insufficient and that nature-based solutions aligned with Sponge City principles are essential for future resilience^{7,8}.

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