



POTSDAM INSTITUTE FOR
CLIMATE IMPACT RESEARCH

Towards reproducible pluvial flood simulation in urban areas with TELEMAC-2D

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Hydrodynamic flood simulations for the megacity of Lagos

Recurrent pluvial flooding in the megacity of Lagos

- One of the largest cities in Africa
- Enhanced flood risk due to
 - insufficient / blocked drainage channels
 - illegal settlement
 - missing early warning systems
 - insufficient data
- Climate change → more extreme precipitation?



Source: Elena Ugrin, [The Watchers](#), CC BY-SA 4.0

Issues of hydrodynamic modelling

- Complex and complicated models
- High data demand
- Manual processing with different software tools necessary
- Limited reproducibility of simulations

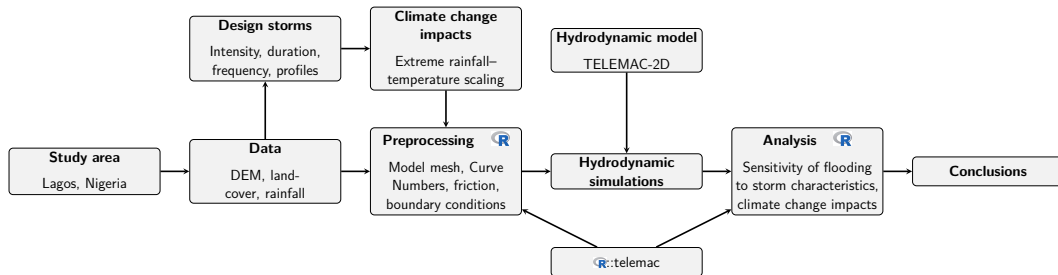
Reproducible workflow for hydrodynamic simulations

- How can we cope with limited data availability?
- Can we achieve a reproducible workflow with minimal manual interventions?

... to characterise the pluvial flood hazard for the megacity of Lagos

- How do storm characteristics influence pluvial flood hazard?
- In what way will climate change alter the current pluvial flood hazard?

Overview

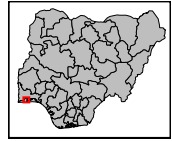


NOTE: This is an interactive presentation. Click on the boxes to learn more. Please view in presentation mode.

Study area: Lagos, Nigeria

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- 23 million inhabitants
- Tropical climate, rainy season with two peaks
- Recurrent pluvial floods
 - Ineffective regulations (blocked channels, illegal settlement)
 - No forecasting and early warning systems
 - Climate change (more extreme rainfall)
 - Insufficient data
- Study area  145 km², small watershed, limit computational burden, recurrent flooding



Lagos metropolitan area and surroundings. Source: Natural Earth, Bing.

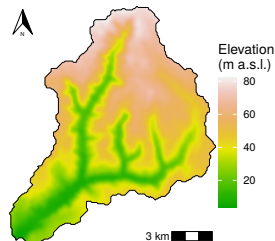


Drainage channel blocked by waste. Source: Google Street View.

Digital elevation model

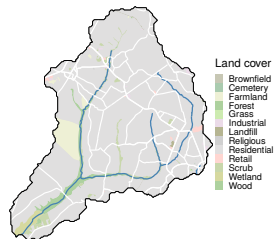
- MERIT DEM
- Based on SRTM and AW3D data
- 90 m resolution
- Good performance in *coarse-scale* hydrodynamic modelling

(McClean et al., 2020)



Landcover

- OpenStreetMap data 
- Curve Numbers (Cronshey et al., 1986, table 2) and soil hydrologic groups (Ross et al., 2018) to estimate infiltration
- Strickler friction values



Rainfall

TAHMO  station data

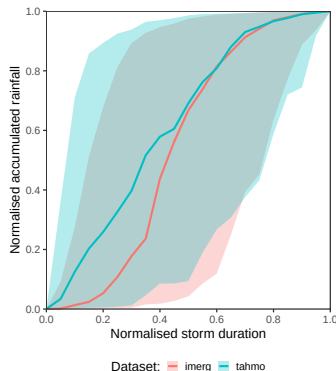
- Station-based measurement (tipping bucket)
- 5 minute resolution
- Only about 2 years available for Lagos

IMERG

- Gridded dataset, satellite- and observation-based
- Half-hourly resolution
- June 2000 to May 2020

Comparison of rainfall statistics over the period May 2018 to end of 2019.

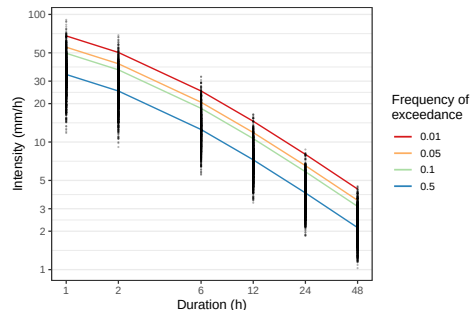
	TAHMO	IMERG
Raindepth (mm)	3876	3192
Wet days	186	239
No. of storms	112	155
Extreme 1-day rainfall, q ₉₅ (mm)	80.85	44.9
Wet-season storm duration, geom. mean (h)	5.78	14.5
Wet-season storm depth, geom. mean (mm)	15.82	13.25



⇒ **IMERG values smoothed:** more and longer storms but less rainfall, much lower extremes, slightly different intra-storm rainfall distribution

Approach (Koutsoyiannis et al., 1998)

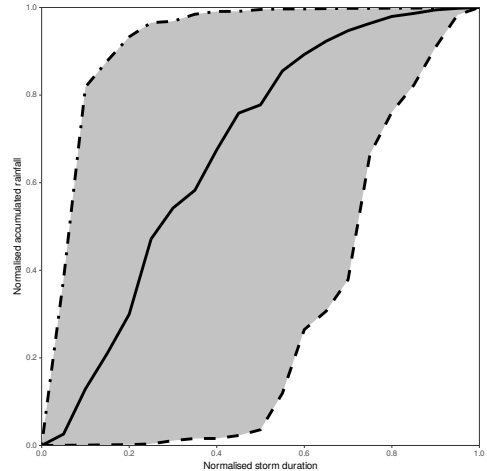
Take 20 years of IMERG data, fit annual rainfall maxima z of different duration aggregations d to duration-dependent Generalised Extreme Value distribution (d-GEV) and determine quantiles for different non-exceedance probabilities using **R::IDF**.



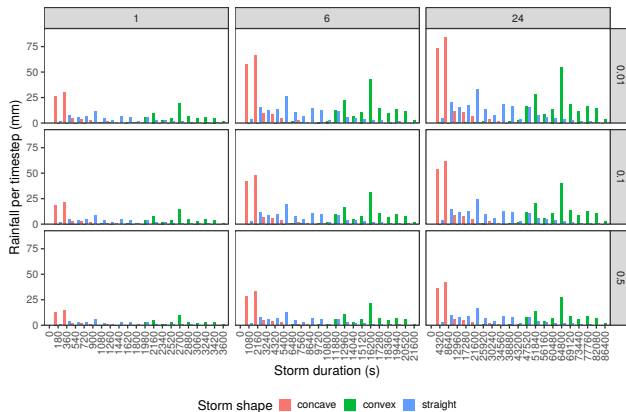
IDF relations derived from fitted d-GEV distribution. Dots are observations (IMERG). Note log scales.

$$\text{d-GEV}(z, d; \mu, \sigma, \xi, \theta, \eta) = \exp \left\{ - \left[1 + \xi \left(\frac{z}{\sigma(d+\theta)^{-\eta}} - \mu \right) \right]^{-1/\xi} \right\}$$

1. 2 years TAHMO rainfall data, 5 minutes resolution
2. 91 storm events of at least 1 hour and 10 mm
(algorithm of Restrepo-Posada and Eagleson, 1982)
3. Rainfall profiles: accumulated rainfall over storm duration, normalised to $[0, 1]$
4. Design profiles: 5th (convex), 50th (straight), and 95th (concave) percentiles of event profiles



Merge storm profiles with IDF relations to derive design storm events.

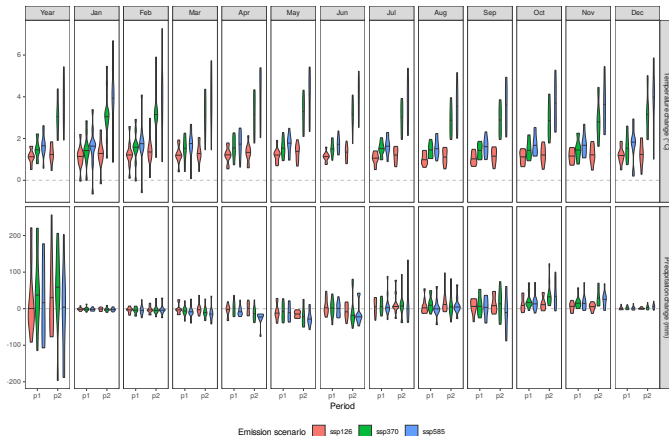


Design storm events of different shape (colour), duration (columns, in hours), and frequency (rows).

Frequency	Raindepth (mm) for storm duration		
	1 hour	6 hours	24 hours
0.01	68	151	192
0.10	50	110	140
0.50	34	75	96

Projections derived from [ISIMIP3b](#): 10 CMIP6 models, 3 emission scenarios (SSP1-RCP2.6, SSP3-RCP7.0, SSP5-RCP8.5), [bias corrected](#), statistically downscaled towards corrected ERA5 data ([W5E5](#)).

- Temperature increase
 - Up to 4 °C (far future, high emissions), mostly <2 °C
 - GCM uncertainty higher than seasonal variation
- Rainfall projections
 - High GCM uncertainty, often different signs of change
 - March to May (beginning of the first rainy season) projections mostly negative
 - October and November (end of the second rainy season) projections mostly positive



Violin plots of projected rainfall and temperature changes for future periods 2035 to 2064 (p1) and 2071 to 2100 (p2) relative to 1985 to 2014. Each violin plot consists of 10 GCM projections; their median is shown as horizontal line.

⇒ What about sub-daily rainstorm intensities?

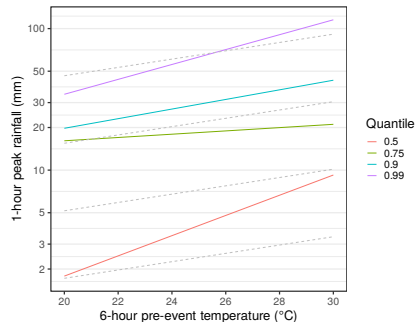
1. Determine storm events from observations: continuous wet time steps, at least 15 min, event intensity ≥ 0.2 mm/h, peak intensity ≥ 1 mm/h (Visser et al., 2020)
2. Associate maximum hourly rainfall intensity per storm event with 6-hour pre-event temperature (Visser et al., 2020)
3. Quantify sensitivity of rainfall intensity to temperature increase for extreme quantile (e.g. 0.99) using quantile regression, `R::quantreg` (Wasko and Sharma, 2014)
4. Multiply scaling with expected temperature increase and adapt design storm depths accordingly

In this case

Limited data availability → Large range of scaling for different quantiles, very wide confidence intervals (not shown) → 7 %/°C scaling assumed (Clausius–Clapeyron relation)

100-year design storm depth under different warming scenarios.

ΔT	Raindepth (mm) for storm duration		
	1 hour	6 hours	24 hours
1 °C	73	161	206
2 °C	77	172	219
3 °C	82	182	232
4 °C	87	193	246



Peak rainfall–temperature scaling. Dashed gray lines show the Clausius–Clapeyron scaling.

- TELEMAC-MASCARET system for computational fluid dynamics
- Modular framework for different tasks (sediment, hydrodynamics, waves, water quality, etc.)
- TELEMAC-2D: 2-D Hydrodynamic model
- Free and open source since 2010
- Solves the full Shallow Water (Saint Venant) equations in two dimensions
- Computations based on an irregular triangular mesh
- Supports finite-element and finite-volume schemes
- Rainfall–runoff module based on the Curve Number (CN) approach
- Fields of application: coastal and maritime water flows, waves, river flows, floods, dam breaks, transport of tracers, etc.
- Contains only the solver, no pre- and post-processing software or GUI

`tin()` creates a triangulated irregular network (TIN)

`geo()` mesh object with all information for the geometry file

`cli()` object with boundary conditions

`cas()` organises the steering parameters

`optionals()` handles optional input

`t2d()` initialises a full TELEMAC setup

`write_t2d` writes all input files of a TELEMAC setup

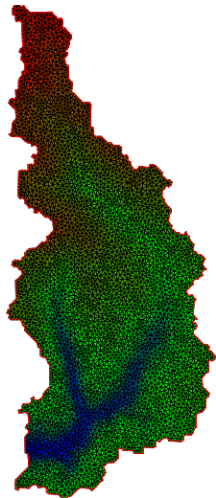
`results()` imports results file of a TELEMAC simulation

Additional functions for `plot()` ing, interpolation of TIN values to a regular grid

(`tin2grid()`), etc.

Package (with documentation and examples) available on [CRAN!](#)

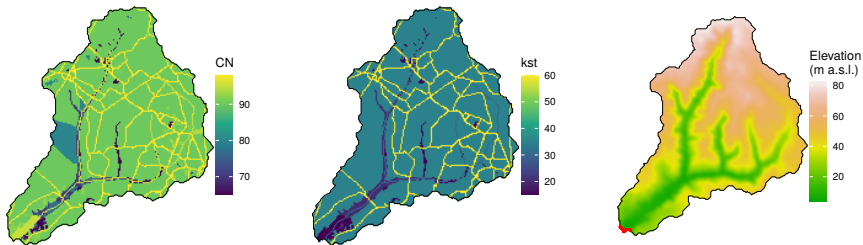
Installation: `install.packages("telemac")`



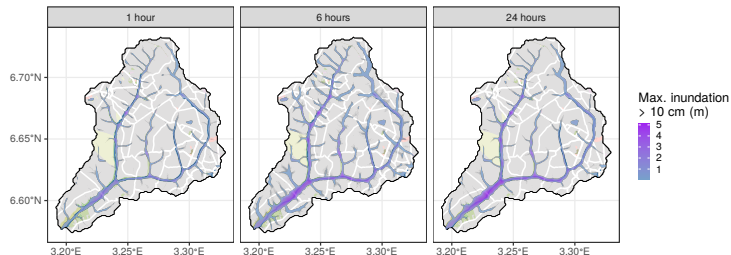
Pre-processing and analyses fully realisable within R!

TELEMAC-2D setup

1. TIN with 1.2 million mesh points
2. CN from landcover and look-up table for parametrisation of rainfall-runoff module
3. Strickler (kst) values from landcover and look-up table for surface roughness parametrisation
4. Closed boundary with free flow boundary at the watershed outlet



- Simulation of individual design storms using prepared setup
 - 27 reference storms (3 shapes X 3 durations X 3 frequencies/return periods)
 - 36 under climate change impacts (3 shapes X 3 durations X 4 warming scenarios)
- Finite volume solver with adaptive time steps
- Tracking of water levels of each mesh element to determine maximum inundation
- Simulations on High Performance Cluster
 - 8 cores in parallel for each simulation
 - Runtimes between 2 and 24 hours



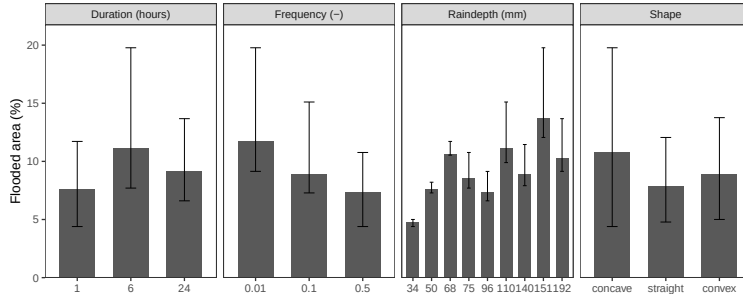
Maximum inundation generated by a 100-year design storm of concave shape and different durations.

Share of flooded area generated by a 100-year design storm of concave shape and different durations.

Flooded by	Flooded area (%) for storm duration		
	1 hour	6 hours	24 hours
> 10 cm	10.66	19.77	13.67
> 50 cm	4.27	8.38	7.95
> 100 cm	2.23	6.10	5.93

Sensitivity of design storm characteristics on flood extent

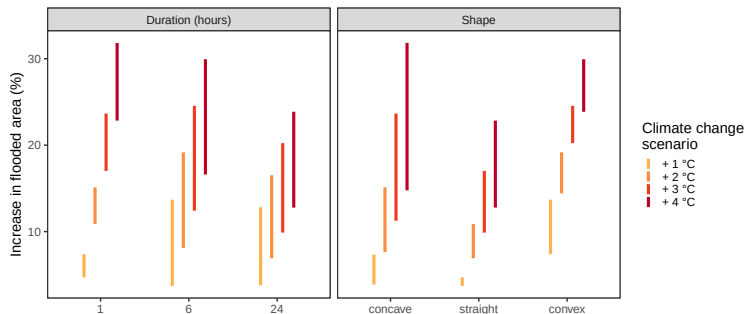
- 6-hour storm duration: highest inundation
- Higher frequency → less inundation
- High rainfall depth not always associated with higher inundation
- Storm shape: large dependence on other characteristics
- Large variation → complex relation between storm characteristics and flood extent



Sensitivity analysis of storm characteristics on flood extent. Each characteristic varied one at a time. Bars show the median, errorbars the range of flood extent when varying the other characteristics.

Impact of temperature increase on flood extent of a 100-year design storm

- Up to 30 % increase in flooded area
- Highest impact on events of short duration and storms with convex profile (highest intensities at storm onset)
- Higher variation for longer storms and other profiles causes less clear but still significant impact



Impacts of temperature increase on flood extent of a 100-year design storm. Each bar shows the span of 3 values induced by the other characteristic.

Limited data availability

- Freely available DEMs → limited use due to coarse resolution, artefacts and flow barriers
- OpenStreetMap data → valuable source of landcover information but still some gaps in Lagos
- Satellite-based meteo data → high resolution with station-based corrections but smoothed in comparison to TAHMO data

⇒ **Shown results are preliminary until more reliable data is available!**

Reproducible workflow

New  package [telemac](#) enables automation and reproducibility of pre- and post-processing of TELEMAC simulations!

Influence of design storm characteristics on flood extent

Frequency / return period and storm duration determine flood extent while intra-storm rainfall distribution depends more on the other characteristics.

Climate change impacts on pluvial flood hazard

Climate change may increase flood extent by up to 30 % for the high 4 °C temperature scenario; the impact is higher for events of shorter duration and storms that start with high intensities.



Cronshey, R., R. H. McCuen, N. Miller, W. Rawls, S. Robbins, and D. Woodward (1986). *Urban Hydrology for Small Watersheds*. Technical Release TR-55. Washington, DC, USA: United States Department of Agriculture. URL: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf.



Koutsoyiannis, D., D. Kozonis, and A. Manetas (1998). "A mathematical framework for studying rainfall intensity-duration-frequency relationships". In: *Journal of Hydrology* 206.1, pp. 118–135. DOI: [10.1016/S0022-1694\(98\)00097-3](https://doi.org/10.1016/S0022-1694(98)00097-3).



McClean, F., R. Dawson, and C. Kilsby (2020). "Implications of using Global Digital Elevation Models for Flood Risk Analysis in Cities". In: *Water Resources Research* 56.10, e2020WR028241. DOI: [10.1029/2020WR028241](https://doi.org/10.1029/2020WR028241).



Restrepo-Posada, P. J. and P. S. Eagleson (1982). "Identification of independent rainstorms". In: *Journal of Hydrology* 55.1, pp. 303–319. DOI: [10.1016/0022-1694\(82\)90136-6](https://doi.org/10.1016/0022-1694(82)90136-6).



Ross, C. W., L. Prihodko, J. Anchang, S. Kumar, W. Ji, and N. P. Hanan (2018). "HYSOGs250m, global gridded hydrologic soil groups for curve-number-based runoff modeling". In: *Scientific Data* 5, p. 180091. DOI: [10.1038/sdata.2018.91](https://doi.org/10.1038/sdata.2018.91).



Visser, J. B., C. Wasko, A. Sharma, and R. Nathan (2020). "Resolving Inconsistencies in Extreme Precipitation-Temperature Sensitivities". In: *Geophysical Research Letters* 47.18, e2020GL089723. DOI: [10.1029/2020GL089723](https://doi.org/10.1029/2020GL089723).



Wasko, C. and A. Sharma (2014). "Quantile regression for investigating scaling of extreme precipitation with temperature". In: *Water Resources Research* 50.4, pp. 3608–3614. DOI: [10.1002/2013WR015194](https://doi.org/10.1002/2013WR015194).

