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A Question of development
Synthesis of AFD studies and research
APRIL 2024
N° 71

How to assess coastal flood risk in data-sparse coastal lowlands? Accurate information on land elevation is key

With rising sea level, the densely populated coastal lowlands in the world, many of them located in the Global South, face increasing flood risks and thus require reliable flood risk assessments. As these rely on land elevation information in relation to local sea level, both the accuracy and vertical reference of the data used strongly affect the reliability of such assessments. We therefore 1) provide an overview of the appropriate use of elevation data and considerations to be made, and 2) call for global public availability of high-accuracy elevation data.

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What needs to be considered – the problem of elevation inaccuracy

Global sea-level rise (SLR) triggered by human-driven global warming drives growing concerns on the future of coastal lowlands. While global mean sea level (MSL) increased by 0.2 m between 1901 and 2018, it is projected to be 0.5 m to 1.0 m higher in 2100 than in 1900, depending on the emission pathways (Intergovernmental Panel on Climate Change (IPCC), 2021). Given current deep uncertainties on the future behaviour of the polar ice sheets, much higher SLR values cannot be ruled out. On timescales of centuries to millennia, sea level is committed to rise further and could increase by several metres. As the impact of SLR and coastal hazards like storm surges and tsunamis is closely related to land elevation and coastal topography, flood risk assessments strongly depend on accurate elevation data, especially in low-lying river deltas and coastal plains. Recent studies have shown that globally 267 million people of 2020's population live on coastal land less than 2 m above MSL, tripling estimates based on less accurate datasets (Kulp and Strauss, 2019; Hooijer and Vernimmen, 2021).

Information on land elevation is obtained either by direct measurements through topographical levelling surveys and Global Navigation Satellite System (GNSS) measurements, or by exploiting remote sensing data from aircrafts or

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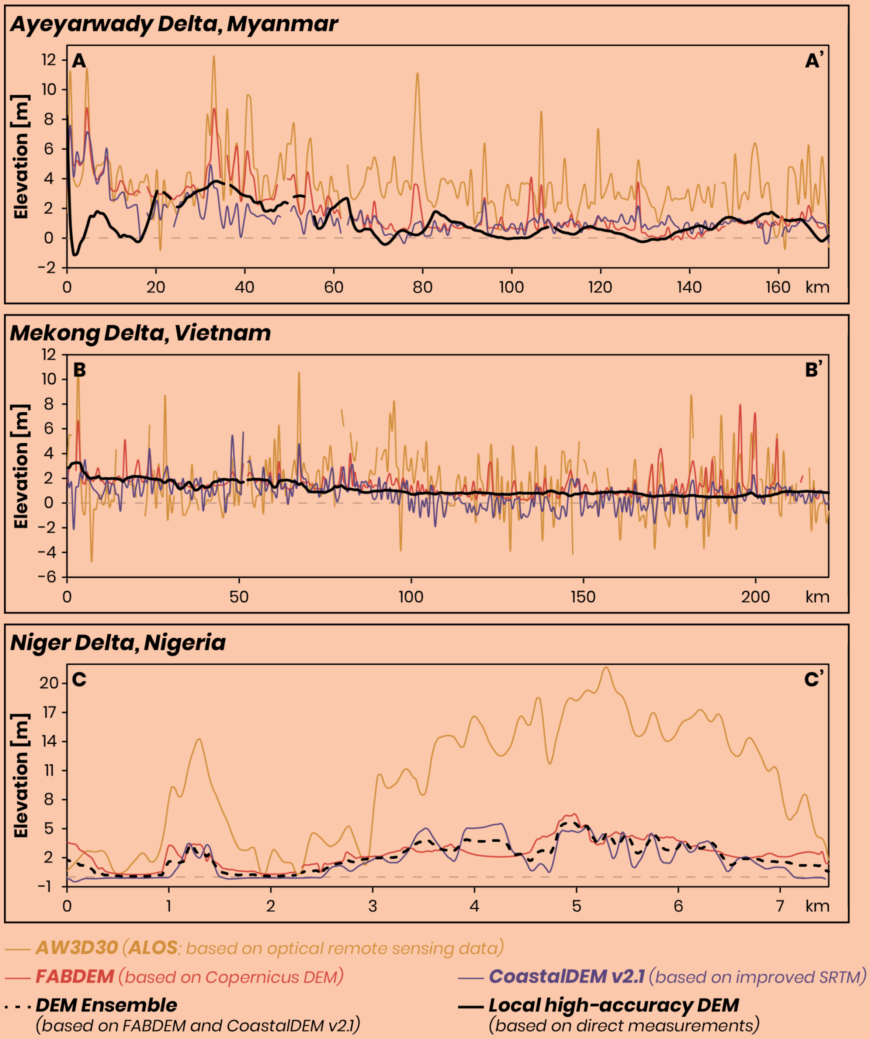
satellites (optical, radar, laser altimetry) to generate digital elevation models (DEMs) of the Earth's surface. The advancement of remote sensing in the 21st century has led to a variety of DEMs ranging from local to global scale, with different spatial resolution and accuracy related to the source data, processing techniques and the terrain itself. Elevation information is thus not a given thing but rather the result of a specific measurement or model, representing either *surface* elevation (including features like vegetation and buildings) or *terrain* elevation (i.e. at the level of bare ground). Consequently, the DEM type itself is of paramount importance when assessing flood risk. Furthermore, elevation may change over time, due to processes such as land subsidence[1] and sediment accumulation, particularly in river deltas. Hence, the actuality of DEMs becomes highly relevant in these landscapes to be considered before the data is used.

While high-quality DEMs (derived from airborne Light Detection and Ranging - LiDAR) representing elevation at spatial resolutions and vertical accuracies at decimetre scale are available for regions in the United States, Australia, New Zealand, and Europe, such data cannot be accessed or does not exist for major parts of the Earth's coasts. Particularly for the densely populated Asian and African coastal lowlands or Small Island Development States this creates major issues. Here, often flood risk assessments still rely on global satellite-based DEMs which suffer from large vertical errors, up to several metres, and artefacts such as stripes (Figures 1 and 2), thereby severely impacting the quality of flood and SLR exposure assessments (Minderhoud *et al.*, 2019; Hauser *et al.*, 2023; Seeger *et al.*, 2023).

Some of the shortcomings originally present in global DEMs (e.g. SRTM, ACE, ASTER, AW3D (ALOS)) have been partly addressed in recently published, corrected global DEMs (e.g. MERITDEM, CoastalDEM, FABDEM), but also in these latter, elevation discrepancies are still present. In addition, a crucial processing step, referencing the global data to a local vertical datum such as *local* MSL is often omitted or forgotten. By default, when acquired from online repositories, global DEMs are referenced to a global ellipsoid (e.g. WGS84), i.e. a smooth, flattened spheric model of the Earth, or a geoid model (e.g. EGM96, EGM2008), i.e. the shape that the ocean surface would have under the sole influence of Earth's gravity, thus not taking into account the impacts of water temperature, winds, tides and currents. Assuming geoid or ellipsoid elevation to match local sea level is fundamentally incorrect and problematic since local MSL can differ up to several metres.

[1] i.e. the gradual lowering of the land surface itself, contributing to SLR in coastal regions.

Figure 1 - DEM comparison for data-sparse coastal regions using elevation profiles.



For A and B, the difference of the DEMs to the more reliable 'local high-accuracy DEM' shows the large vertical mismatches. For C, no local DEM is available, the dashed line shows an ensemble average (A: Seeger *et al.*, 2023; B: Minderhoud *et al.*, 2019 (modified); C: Hauser *et al.*, 2023).

Required steps when using elevation data in the absence of ground-truthing possibilities

Especially in data-poor regions, flood risk assessment requires careful investigations and processing of elevation data beforehand:

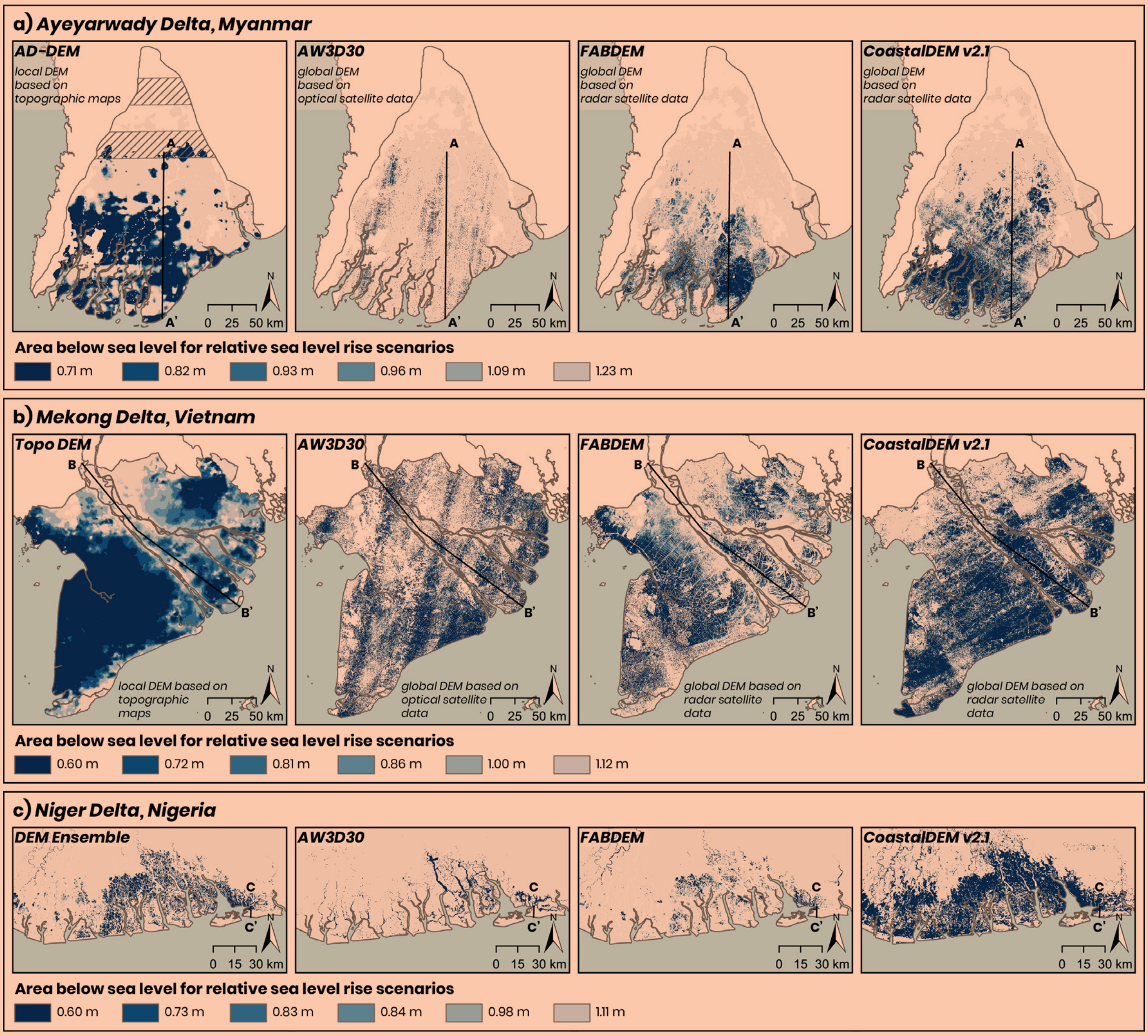
(i) **Collection of available datasets.** Information on data generation, status of processing, vertical reference system, spatial resolution and DEM type (surface or terrain) need to be considered.

(ii) **Vertical datum conversion to local MSL.** While tide gauges provide highly local information on sea level, they may be inadequate in capturing sea level in larger coastal areas under study, or if time-series is incomplete, too short or outdated. Satellite-altimetry-derived mean dynamic topography serves as an open-accessible substitute.

(iii) **Accuracy assessment through validation with local elevation data.** In the absence of ground measurements, indirect validation allows for assessing the relative differences between the DEMs, e.g. in terms of relations between topography and geomorphology and/or areas drowned during floods. Evaluating the DEMs against diverse criteria and using a wide range of statistics will give the most complete insight into their performance and enable to select the most appropriate elevation data for flood risk assessment in the area of interest.

For example, Minderhoud *et al.* (2019) and Seeger *et al.* (2023) used directly measured elevation data from local topographic maps to generate DEMs for the Mekong and the Ayeyarwady Delta, respectively. The comparison between these local DEMs, vertically accurate at decimetre scale and tied to local MSL, and global ones such as widely used SRTM or AW3D reveals differences of several metres, with the global models overestimating elevations compared to the local ones (Figure 1). Consequently, these discrepancies are transferred when area, population and assets at risk of SLR and flooding are assessed and different DEMs may indicate substantially different estimates (Figure 2). In the Ayeyarwady Delta, currently available elevation data indicates a deltaic area of ~1 to 68 % and a present-day (2020) population of ~65,000 to 5 million people living in areas likely to fall below sea level following ~2.2 m SLR (Seeger *et al.*, 2023). Using more advanced, processed DEMs with the most robust performance, these large uncertainties can be narrowed down, in the case of the Ayeyarwady Delta to ~53 to 68 % of the deltaic area and ~3.6 to 5 million people. Still, these uncertainties are comparably large to initiate appropriate adaptation strategies on small spatial scale and underscore the need for local elevation data of higher quality to become publicly available.

Figure 2 - Area below future mean sea level according to local and global DEMs (a) Seeger *et al.*, 2023; b) Minderhoud *et al.*, 2019 (modified); c) Hauser *et al.*, 2023).



Towards the decision for and use of specific elevation data for assessing flood risk in coastal regions

So far, data paucity and the lack of adequate consideration of DEM uncertainties and vertical datum conversion challenge the reliability of flood risk assessment and mitigation strategies for many coastal lowlands, and people and assets at risk of coastal hazards may be larger than thought so far. To improve future assessments, we provide the following recommendations for the use of elevation data:

- **Elevation data should be carefully selected and their quality checked:** Compare available elevation datasets, consider their contextual information and clarify the relations between their vertical references. The evaluation should be based on a wide range of criteria and statistics. Indeed, the selection of an elevation dataset that fits best the intended application very much depends on the geomorphological setting of the area of interest, quantity and quality of local data, as well as the array of datasets and investigations involved into the quality assessment itself. Greater complexity coupled with limitations in data availability may challenge the identification of one single DEM outperforming the others. Combining the most accurate DEMs to delineate low-lying flood-prone areas, provides a balanced approach that is less sensitive to error in individual products and can capture low-lying zones overlooked by individual products alone. Additionally, when local, accurate elevation data is present (e.g. point measurements), this can be used to correct and further improve the best performing global DEM(s) locally. Observed uncertainties should be clearly stated and communicated in a transparent manner.

- **Acquisition of high-accuracy elevation data and its actuality should be prioritised:** Nevertheless, the above options are all intermediate solutions as the public availability of high-accuracy elevation data referenced to tidal level should be prioritised for coastal lowlands globally and especially for countries in the Global South. Regular updates of DEMs are needed to ensure the data's actuality, especially in view of processes contributing to elevation in the coastal lowlands. By conducting field and LiDAR campaigns, elevation data accurate in the range of centimetres to decimetres and up to 25 cm spatial resolution can be generated.

- **Open access:** Such high-quality data products should be actively communicated in the related scientific, practical, and technical community. They should be made freely accessible for research purposes on commonly known, open-access databases, accompanied by necessary metadata and documentation detailing data sources, processing, uncertainties, and vertical reference information (tidal datums, location and timing of establishment will be key). Only then can coastal experts provide assessments of SLR impact and flood risk in high quality and resolution, which will form a solid information basis for policy makers and agencies to design and implement adaptation and mitigation strategies.

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Agence française de développement (AFD)
5, rue Roland Barthes | 75012 Paris | France
Publication Director Rémy Rioux
Editor-in-chief Thomas Mélonio
Graphic design MeMo, Juliegilles, D. Cazeils
Design and production eDeo-design.com

Legal deposit 2nd quarter 2024 | **ISSN** 2428-8926
Credits and authorizations

Printed by the AFD Reprographics Department.