A Staged, Uncertainty-Aware Digital Twin for Relative Sea-Level Rise in Data-Scarce Coastal Cities

STAR-Twin: a review-based design for Lagos, Nigeria

A. I. Hamid-Mosaku, Adewale I. Adewuyi, Ibrahim O. Shittu, Theophilus O. Attah, T. A. Ojeniran

Department of Surveying and Geoinformatics, University of Lagos | FEIC 2026, 7–9 October 2026

Cities feel relative sea-level rise

267 M

people live on land less than 2 m above sea level, with greatest vulnerability in the tropics

~3×

improved elevation data roughly tripled earlier estimates of exposed population

−11.4 mm/yr

fastest Lagos subsidence rate (10th percentile) from Sentinel-1 InSAR, 2015–2025

Relative sea level = ocean change + vertical land motion (VLM). Elevation error decides what is called flooded.

Sources: [2], [4]–[7]

The gap and the research questions

The mismatch

Earth-system twins assume dense gauges, lidar-grade terrain and cloud-scale computing.

Lagos has few gauges, metre-scale DEM error, and intermittent power and connectivity.

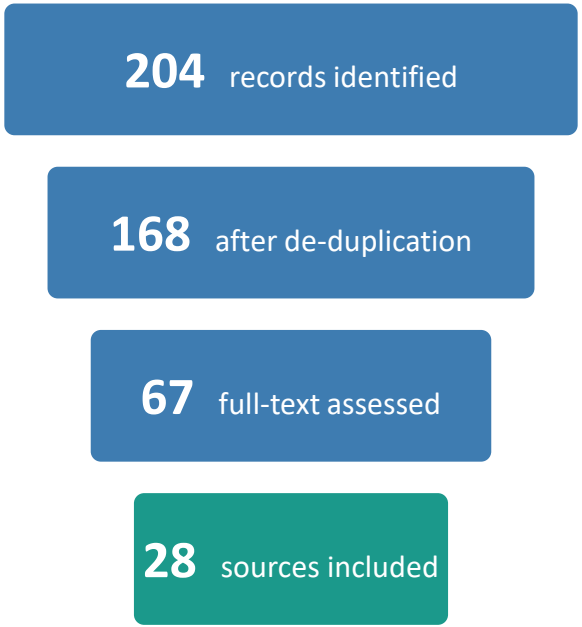
RQ1 How are coastal and sea-level-rise twins conceptualised, and at what level of twinning?

RQ2 Which data and model constraints dominate reliability in data-scarce settings?

RQ3 What design requirements follow, and how are they assembled into a staged framework?

Sources: [10]–[12], [14], [20], [21], [26], [27]

A structured narrative review of 28 sources



How it was done

- Eight open-access platforms, six Boolean search strings
- Coded on a common twinning scale: digital model, shadow or twin
- Design-science logic; PRISMA-style transparency
- **Purposive and single-coder: indicative patterns, not systematic evidence**

Sources: [15]–[17]

What the retrieved sources show

1 Mostly models and shadows

Coastal twin proposals are conceptual or Earth-system scale. Few city-scale implementations exist in the Global South.

2 Key errors seldom propagated

DEM vertical error and omitted VLM are well documented, yet rarely carried through to outputs.

3 “Twin” is used loosely

Many systems labelled twins lack automated two-way data flow.

Sources: [3], [14], [17], [18], [20], [21]

Six design requirements

R1 **Model relative sea level**

VLM as a spatial state variable

R2 **Carry vertical uncertainty**

Exceedance probabilities, not flood lines

R3 **Tier model fidelity**

Escalate by decision relevance

R4 **Accept sparse observations**

Fidelity registry, datum harmonisation

R5 **Stage the twin honestly**

Testable entry and exit gates

R6 **Interoperable and governed**

Open standards, human approval

Sources: R1 [2], [3], [6], [7] · R2 [4], [5], [21]–[24] · R3 [7], [19], [25] · R4 [14], [26], [27] · R5 [17], [18] · R6 [12], [14], [20], [30]

STAR-Twin: five layers, one ledger

L5 Decision and governance
roles, human approval, local ownership

L4 Synchronisation and stage control
stage gates S0–S2, return channel

L3 Model and uncertainty engine
T0–T2 tiers, Monte Carlo

L2 Data and provenance
datum harmonisation, FAIR records

L1 Observation
gauges, InSAR, GNSS, DEM

Uncertainty ledger

Every layer writes its error terms here, so each output shows its dominant uncertainty source.

Data flow is manual at S0 and automated from S1. The return channel (L4 to L1) is active only at S2.

Sources: [12], [14], [17], [20]

Core idea: ocean rise minus land rise

$$\Delta h(x, t) = \Delta\eta(t; s) - v(x)\cdot(t - t_0)$$

$$WL(x, t; q) = MSL_0 + \Delta h(x, t) + Eq$$

$$Pexc = Pr[\, zD(x) + \varepsilon z(x) < WL(x, t; q) \,]$$

$v < 0$ is subsidence. Eq is the q-year return level. εz is DEM error.

Worked example

10 mm/yr × 30 yr
= −0.30 m land motion

$\Delta\eta = 0.15$ m

$\Delta h = +0.45$ m

Sources: [1], [3], [29]; worked example from Sec. 3.2 of the paper

Tiered engine with Monte Carlo uncertainty

T0 **Bathtub + DEM error**

City-wide screening

T1 **Connectivity-filtered**

Drops cells disconnected from the sea

T2 **2D hydrodynamic**

Priority zones and critical assets

Escalate a tier only where an asset's exceedance probability sits between 0.10 and 0.90 (provisional).

- ≥ 10 000 realisations, extended until standard error of Pexc ≤ 0.005
- Inputs: scenario, VLM field, DEM error, datum offset, event level
- Sobol' indices rank uncertainty sources; aleatory and epistemic parts reported separately

Sources: [1], [7], [19], [25], [28], [29]

Stage gates tie the “twin” label to data flow

S0

Digital model

Manual flow both ways

Exit test: Reproducible on a second machine; control-network misclosure ≤ 5 cm

S1

Digital shadow

Automated, physical to digital

Exit test: ≥ 90 days: hourly RMSE ≤ 10 cm, ingest uptime ≥ 95 %

S2

Digital twin

Automated both ways

Exit test: Brier skill score > 0; zero actions outside the whitelist

Sources: [17], [18]; thresholds are provisional design values (Table 4)

Proposed Lagos instantiation

Candidate data sources

- VLM: Sentinel-1 InSAR products, checked against GNSS or levelling
- Terrain: CoastalDEM or FABDEM plus local control
- Scenarios: IPCC AR6 geocentric projections
- Water level: existing gauges, altimetry, pilot low-cost nodes
- Pilot district chosen from the three regions of the Johnson et al. study

S0 feasibility check

- ≥ 20 control points per terrain class (≥ 60 in total)
- Vertical standard uncertainty ≤ 5 cm
- Levelled ties to ≥ 2 benchmarks and each gauge zero
- Coherent InSAR over ≥ 70 % of the district

If unmet, outputs are labelled “screening only”.

Sources: [1], [6], [7], [21], [23], [24], [26], [27]

Four falsifiable hypotheses

H1 **VLM matters**

Exposed area with vs. without VLM; 5th percentile of the difference must be positive

H2 **Tier bias is estimable**

T0/T2 area ratio with a 90 % interval of width ≤ 0.25

H3 **Frugal sensing works**

95 % of errors ≤ 3 cm, bias ≤ 1 cm, drift ≤ 1 cm per 30 days

H4 **Probabilities are calibrated**

Positive Brier skill score; reliability slope 0.8–1.2

All thresholds are provisional and will be fixed in a dated analysis plan before testing.

Sources: H1: [2], [3], [7] | H2: [19], [25] | H3: [26], [27] | H4: [28], [29]; thresholds provisional (Table 6)

Conclusion and next steps

- An ordering and an obligation: build the twin in gated stages, and make every output carry its uncertainty.
- Conceptual only: not implemented or empirically validated; the review is purposive, not systematic.
- Next: confirm data access and datums, run S0 on a pilot district, then test H1 and H2 (no new hardware).

Thank you. Questions?

adewuyiadewaleisaiah@gmail.com

Sources: [17], [21]

References (1 of 2)

[1] Fox-Kemper et al., IPCC AR6 WG1, ch. 9, 2021

[2] Nicholls et al., Nat. Clim. Change, 2021

[3] Shirzaei et al., Nat. Rev. Earth Environ., 2021

[4] Kulp & Strauss, Nat. Commun., 2019

[5] Hooijer & Vernimmen, Nat. Commun., 2021

[6] Ohenhen & Shirzaei, Earth's Future, 2022

[7] Johnson et al., npj Nat. Hazards, 2026

[8] Grieves & Vickers, Springer, 2017

[9] Tao et al., IEEE Trans. Ind. Informat., 2019

[10] Bauer et al., Nat. Clim. Change, 2021

[11] Nativi et al., Remote Sens., 2021

[12] Kollert et al., EGU General Assembly, 2023

[13] Ryabinin et al., Front. Mar. Sci., 2019

[14] Yu et al., Fundam. Res., 2024

[15] Peffers et al., J. Manage. Inf. Syst., 2007

Sources: numbering follows the reference list in the paper; full details with DOIs are in the paper

References (2 of 2)

[16] Page et al., BMJ, 2021

[17] Kritzinger et al., IFAC-PapersOnLine, 2018

[18] VanDerHorn & Mahadevan, Decis. Support Syst., 2021

[19] Silva et al., Nat. Hazards Earth Syst. Sci., 2026

[20] Hlal et al., Remote Sens., 2025

[21] Gesch, Front. Earth Sci., 2018

[22] Kulp & Strauss, Front. Earth Sci., 2016

[23] Kulp & Strauss, Remote Sens. Environ., 2018

[24] Hawker et al., Environ. Res. Lett., 2022

[25] Seenath et al., Ocean Coast. Manage., 2016

[26] Woodworth et al., Afr. J. Mar. Sci., 2007

[27] Almar et al., Surv. Geophys., 2023

[28] Kapteyn et al., Nat. Comput. Sci., 2021

[29] Vousdoukas et al., Nat. Commun., 2018

[30] Hinkel & Klein, Glob. Environ. Change, 2009

Sources: numbering follows the reference list in the paper; full details with DOIs are in the paper