International Journal of Maritime and Interdisciplinary Research
©2025 IJMIR/Volume 8(1) July-December | ISSN: 2734-3286.
Journal homepage: www.ijmir.edu.ng

Volumetric Analysis of the Niger-Benue River Basin using Surgical Dredging and Conceptual Sand Trap Design for Climate-Resilient Flood Management in Niger–Benue River Basin

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Abstract

Flooding in Nigeria's Niger-Benue River Basin has intensified due to climate change, siltation, and uncontrolled releases from dams, resulting in recurrent displacement of millions and extensive economic damage. This study analyzed bathymetric data from the Baro–Nun River section using Surfer and Rhinoceros 3D software. Findings revealed that dredging sand-filled islands can expand the basin's containment volume from 2.81 billion m³ to 4.42 billion m³, providing capacity to absorb extra 1.61 billion m³ emergency discharge. The work strengthened the need for surgical dredging as a sustainable intervention strategy and a way of minimizing ecological disturbance and reducing maintenance costs. It further proposed the application of Sand traps technology to further mitigate sediment re-accumulation, ensuring long-term performance. Implementation supports SDG 11 (sustainable cities and communities) by enhancing flood resilience, restoring navigation, and fostering blue economic opportunities. The work contributes to the growing need of methods for sustainable river navigation and transport management.

Keywords: River Niger, flash flood resilience, surgical dredging, sand traps, sustainable urban development

1. Introduction

The River Niger, Africa's third-longest river, remains a critical freshwater system supporting water supply, agriculture, fisheries, and transportation across West Africa. Within Nigeria, the Niger–Benue Basin forms the country's hydrological backbone, serving as the primary drainage route for extensive floodplains, farmlands, and settlements (UNEP, 2021). Despite its economic and ecological value, the basin is increasingly threatened by recurrent and severe flooding due to sedimentation, siltation, and climate-induced hydrological variability.

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Severe floods have been recorded across Nigeria in the past decade, with devastating impacts on lives and infrastructure. For instance, the 2012 flood event inundated 30 of Nigeria's 36 states, affected over seven million people, and caused economic losses exceeding ₦2.6 trillion (NEMA, 2013). When Lagdo releases entered the R. Niger in 2022, the event caused the worst flood disaster in West Africa, claiming 603 lives and injuring more than 2,400 people.

More recent events between 2022 and 2025 have demonstrated a worrying trend of increased flood frequency and magnitude, especially along the Niger–Benue flood-plains (NiMet, 2024). In June 2025 alone, extreme rainfall and reservoir releases submerged farmlands, destroyed homes, and displaced thousands of residents in Niger, Kogi, and Bayelsa States. Table 1 presents major recent flood events and their socio-economic impacts across the Niger–Benue Basin, emphasizing the need for sustainable flood-management engineering.

Table 1. Major flood events and socio-economic impacts in the Niger–Benue Basin (2012–2025)

Year	Fatalities	Displaced / Affected	Key Events / Locations
2022	612	1.4M displaced; 200,000 homes destroyed	National floods, Adamawa & Bayelsa worst hit. Lagdo Dam-related flooding in Adamawa region
2023	>33	Thousands displaced (Northeast)	Lagdo Dam-related flooding in Adamawa region
2024	1,237	1.24M displaced; 5.26M affected	Alau Dam collapse in Maiduguri; massive crop loss
2025 (so far)	>500	3,000 displaced; millions at risk	Mokwa catastrophe; multiple states at high risk

Source: Author (2025)

Earlier engineering studies on the Niger Basin have highlighted the importance of bathymetric restoration and hydraulic dredging in enhancing channel conveyance (Ibrahim & Sternberg 2021). These studies demonstrated that targeted dredging can improve flow-conditioning and reduce sediment deposition, contributing to long-term navigational and flood-resilience benefits. However, such interventions must be complemented with sediment-control mechanisms such as sand-trap installations to prevent rapid re-siltation and ensure hydraulic efficiency.

Dredging productivity depends primarily on sediment gradation, bed-material characteristics, and dredger type (Cheng et al., 2022; Bray et al., 1996). Cutter-suction dredgers and trailing-suction hopper dredgers are commonly selected for fine- to medium-grained sands, and under favourable working conditions, these machines can achieve high hourly removal rates (Cheng et al., 2022; Bray et al., 1996). Yet, continuous dredging without sediment-management measures is unsustainable because upstream sediment inputs rapidly refill cleared sections and operational impacts can increase resuspension (Mills & Kemps, 2017; Van Rijn, 1984).

The integration of sand-trap systems within dredged channels offers a more sustainable sediment-management solution. Sand traps function by creating zones of reduced velocity that allow heavier sediment particles to settle, while clearer water continues downstream. The effectiveness of a sand trap depends on its geometry, chamber length, flow velocity, and maintenance regime. Performance data from operational facilities in Ethiopia and Indonesia provided valuable insights into design optimization for the Niger–Benue context.

At the Wonji–Shoa Sugar Estate in Ethiopia, twin-chamber sand traps were constructed upstream of irrigation canals to intercept coarse sediments transported from volcanic terrain (Figure 1). The system operates by diverting flow through two parallel chambers, each designed with a length-to-width ratio of approximately 8:1, producing settling velocities sufficient to trap particles greater than 0.15 mm. As shown in Figure 2, field monitoring revealed retention efficiencies of 90–95%, significantly improving irrigation-water quality and reducing desilting frequency (Paulos et al., 2006).

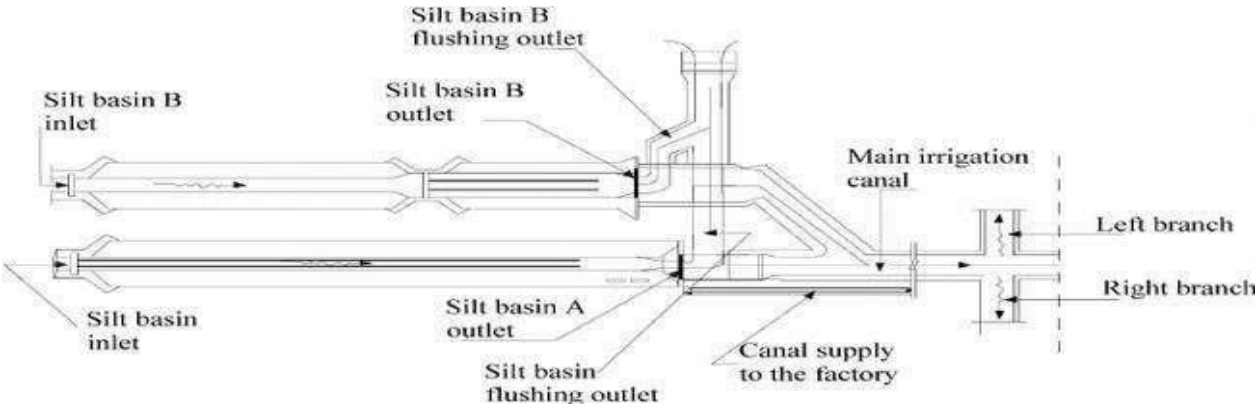


Figure 1. Schematic plan of the twin sand-trap layout at Wonji–Shoa Sugar Estate, Ethiopia (Paulos et al., 2006).

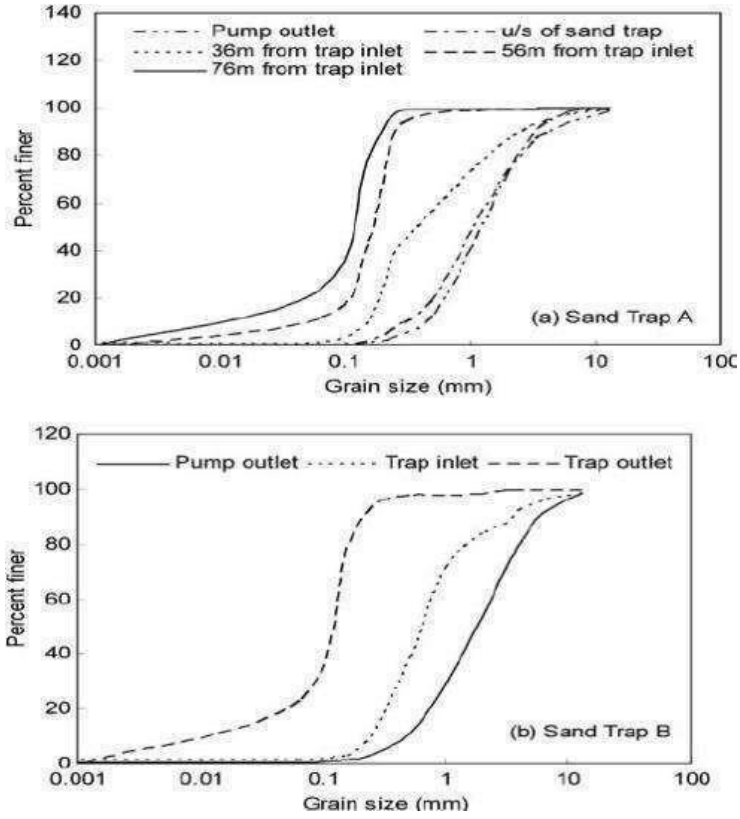


Figure 2. Bed-material grading curves showing particle-size distribution and sediment-retention efficiency at the Wonji–Shoa sand-traps (Paulos et al., 2006).

Similarly, in Indonesia's Pengasih Irrigation Network, a modular sand-trap system was integrated directly downstream of the intake to manage high sediment loads associated with monsoon flows (Figure 3). The trap design featured two sedimentation chambers and an automated flushing channel, allowing continuous operation during both irrigation and flushing cycles. As shown in Figure 4, the system's geometry permits sediment removal during the flushing phase while maintaining continuous flow through the irrigation channel. Efficiency tests revealed 65–90% sediment-removal rates, depending on maintenance intervals and sediment concentration (Pradipta et al., 2022).

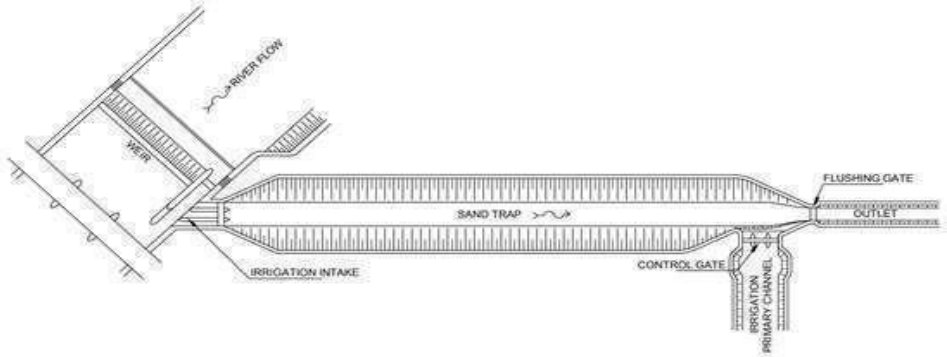


Figure 3. Sand-trap layout at the Pengasih irrigation network, Indonesia (Pradipta et al., 2022)

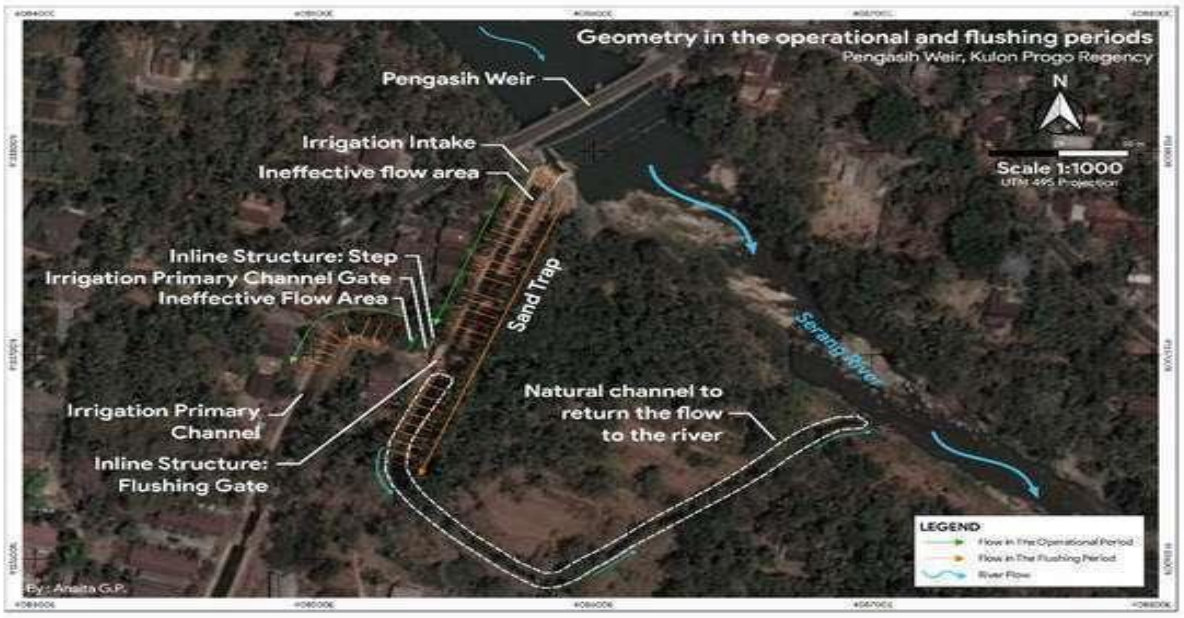


Figure 4. Geometry of the Pengasih sand-trap during operational and flushing periods (Pradipta et al., 2022).

These case studies demonstrate that well-engineered sand-trap systems can substantially reduce siltation rates and extend dredging intervals—an approach directly applicable to the Niger–Benue river. Integrating such systems within surgical dredging operations can improve river stability, flood resilience, and navigability while minimizing ecological disturbance. The morphological and sedimentological conditions of the Niger River, comprising fine- to medium-grained alluvial sands, are comparable to those of the Ethiopian and Indonesian sites, reinforcing the transferability of these solutions.

Therefore, this study applied an integrated engineering approach that combined surgical dredging with sand-trap technology to enhance channel capacity, mitigate flooding, and support sustainable inland navigation within the Baro–Nun reach of the Niger–Benue river basin.

The objectives of this study were to:

1. quantify, using Lagdo dam release as test case, the potential containment volume achievable through surgical dredging and selective sand-filling;

2. propose sand-trap design to sustain containment against sedimentation; and

3. explore how integrated dredging–sand-trap engineering can strengthen flood resilience and sustainable navigation in Nigeria's major river systems.

2. Materials and Methods

2.1 Study Area

The study focused on the Baro–Nun section of the Niger River, a flood-prone reach characterized by extensive sediment deposition and island formation (Garzanti et al., 2023; Lawal and Omosanya, 2023; Ozim, 2021). The section begins approximately at latitude 8° 36′ 25.50″ N and longitude 6° 24′ 49.18″ E, extending downstream toward the Nun River. This corridor represents a hydraulic transition zone between the Upper and Lower Niger basins, where channel aggradation and constricted flow have increasingly intensified over-bank flooding and navigation challenges. Figure 5 illustrates the geographical location and spatial context of the study area.



Figure 5. Section of the River Niger at Baro Town, Niger State (Study Area). Source: Google Earth Pro.

Hydrologically, the area lies within Nigeria's tropical wet-and-dry climate, receiving an average annual rainfall of 1,100–1,400 mm and mean temperatures between 24 °C and 32 °C. Peak discharge occurs between July and September, when combined inflows from the Benue River and occasional releases from the dams elevate water levels and flood-plain inundation.

Geospatial flood-modelling studies have identified this corridor as one of the most flood-vulnerable stretches within the Niger–Benue Basin (Ozim, 2021).

2.2 Data Collection

July 2022 bathymetric survey data were sourced from the Nigerian Inland Waterways Authority (NIWA), complemented by historical hydrological and flood records (Akinwale and Musa, 2024). The 43 survey sections encompassed approximately 11 km each, capturing critical variations in channel morphology and depth distribution along the Baro–Nun reach.

2.3 Analytical Tools

Surfer 16 and **Rhinoceros 3D** software were employed for three-dimensional bathymetric modeling and volumetric-capacity analysis.

SolidWorks was used to conceptualize sand-trap systems optimized for the Niger River's hydraulic conditions.

Similar use of 3-D and GIS technologies has been demonstrated by Ibrahim and Sternberg (2021) to enhance flood-hazard visualization and policy design in Nigeria.

2.4 Mathematical Basis of the Analysis

The computations performed with Surfer and Rhinoceros 3D are founded on standard numerical methods.

(a) Surface interpolation

(i) Inverse Distance Weighted (IDW) Method

According to Qaraghuli et al. (2021), the bathymetric elevation at an unsampled point can be obtained by the inverse-distance-weighted average of measured depths:

$$Z(sS_0) = \sum_{i=1}^{n} W_i Z(S_i) \quad (1)$$

$$W_i = \frac{\frac{1}{d_i^k}}{(\sum_{i=1}^{n} \frac{1}{d_i^k})} \qquad i = 1,2,\ldots,n, \quad (2)$$

where $Z(sS_0)$ is the interpolated elevation at the predicted location, $Z(S_i)$ is the observed value at sampled point i. The W_i is the weight assigned to point i. The d_i is the distance between S_0 and S_i. The k is the power parameter controlling distance decay (usually 1-3).

The IDW interpolation was applied to generate a continuous depth surface from discrete sounding data for all 43 cross-sections, allowing identification of siltation zones and quantification of containment volumes.

(ii) Ordinary Kriging

Following Isaaks and Srivastava (1989), the kriging estimator of an unknown point is a linear combination of neighbouring observations:

$$Z(S_0) = \sum_{i=1}^{n} \lambda_i Z(Si) \quad (3)$$

where the weights λ_i were obtained by solving the kriging system using a semi variogram model that minimizes estimation variance.

Kriging served as a comparative statistical interpolation to validate the IDW results, providing error-variance maps that confirm spatial reliability of the interpolated bathymetric surfaces.

(b) Cross-Sectional Area

The cross-sectional area of each surveyed river transect was computed following the trapezoidal integration procedure described in Chow et al. (1988). If a transect contains N lateral sampling points with horizontal coordinates $x_1, x_2 \ldots, x_N\ (m)$ and corresponding water depths $y_1, y_2 \ldots, y_N\ (m)$, the wetted area A is given by the discrete trapezoidal rule:

$$A = \sum_{i=1}^{N-1} \frac{(y_i + y_{i+1})}{2} \Delta x_i \quad (4)$$

Where y_i is the measured depth (m) at lateral station i, $\Delta x_i = x_{i+1} - x_i$ is the lateral spacing (m) between adjacent measurement points, and A is expressed in square metres (m^2).

This formulation integrates the depth profile across each cross-section and is the standard method recommended in Chow et al. (1988) for river geometry computations. Where sampling intervals were uniform, Δx_i reduces to a constant lateral increment.

The equation was used in Rhinoceros 3D to compute wetted-sectional areas automatically from the 3-D bathymetric mesh.

(c) Channel Volume Integration

The channel volume between consecutive river cross-sections was also computed using trapezoidal integration as outlined in Chow et al. (1988). For M surveyed transects located at

longitudinal distances $L_1, L_2 \ldots, L_M$ (m) along the river, with corresponding cross-sectional areas $A_1, A_2 \ldots, A_M$ (m^2), the volume V is:

$$V = \sum_{j=1}^{M-1} \frac{(A_j + A_{j+1})}{2} \Delta L_j \quad (5)$$

Where A_j and A_{j+1} are cross-sectional areas (m^2) at transects j and $j+1$, $\Delta L_j = L_{j+1} + L_j$ is the longitudinal spacing(m) between the two transects, and V is expressed in cubic metres (m^3),

This equation provides the containment volume of each river segment and follows the hydrologic geometry procedures documented by Chow et al. (1988).

This yielded the pre- and post-dredging containment capacities used to assess storage gain.

(d) Hydraulic Flow Capacity

$$Q = \frac{AR^{2/3}S^{1/2}}{n} \quad (6)$$

Where Q is discharge (m^3/s), A is the flow area (m^2), $R = {}^{A}/_{P}$ is the hydraulic radius, S is the channel slope, and n is Manning's roughness coefficient.

Flow-capacity simulations provided insight into the improvement in conveyance after surgical dredging.

(e) Sediment Transport for sand-Trap Design

Sediment load was estimated using the Meyer-Peter and Müller (1948) bed-load transport equation:

$$q_b = 8(\Upsilon_* - \Upsilon_{*c})^{1.5} \sqrt{(s-1)g{d_{50}}^3} \quad (7)$$

Where q_b is sediment transport rate(m^2/s), Υ_* dimensionless shear stress, Υ_{*c} is critical Shields parameter, s is sediment specific gravity ratio, g is gravitational acceleration, d_{50} is median grain diameter.

This was used in the SolidWorks 2021 to size the sand-trap chamber and determine optimal settling velocities for the Niger's sediment characteristics.

2.5 Engineering Interventions

The engineering intervention for this study was conceived as a conceptual design, integrating surgical dredging with sand-trap technology to mitigate flood impacts and sediment accumulation within the Baro–Nun reach of the Niger River. The approach targets the removal of sediment-laden islands occupying approximately 10 % of the river width, thereby restoring hydraulic conveyance and navigation depth. Only islands with zero social-economic value were considered for the surgical dredging.

3. Results and Discussions

3.1 Current Containment Capacity

The initial modeled containment volume across all 43 survey sections was 2.81 $billion\ m^3$, reflecting significant sediment infill, island formation, and reduced channel depth.

These features substantially limit discharge conveyance and increase flood susceptibility within the Baro–Nun reach.

3.2 Capacity After Surgical Dredging

Selective removal of sand-filled islands increased the basin's total capacity to 4.42 $billion\ m^3$, representing a net gain of 1.6 $billion\ m^3$, adequate to absorb the full emergency discharge from Cameroon's Lagdo Dam, representing possible largest potential inflow to the Niger Basin.

Figures 2 to 11 present the pre- and post-dredging cross-sections of the first ten surveyed reaches; remaining sections are available on request.

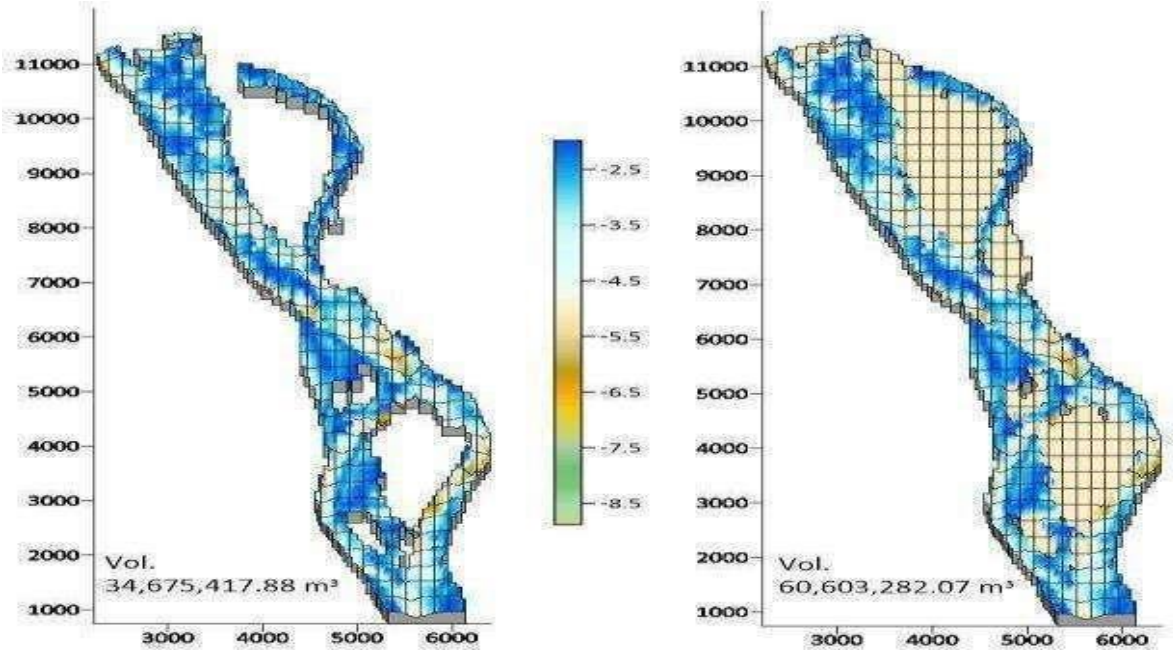


Figure 2: Section 1 indicating before and after removal of sandy islands by dredging

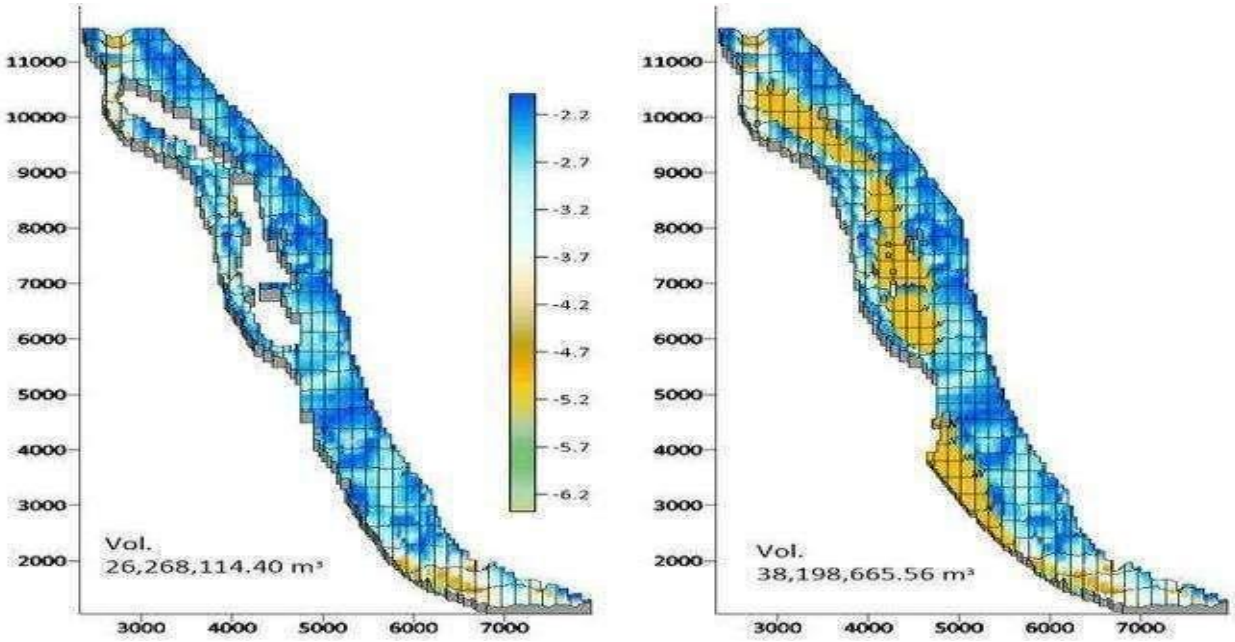


Figure 3: Section 2 indicating before and after removal of sandy islands by dredging

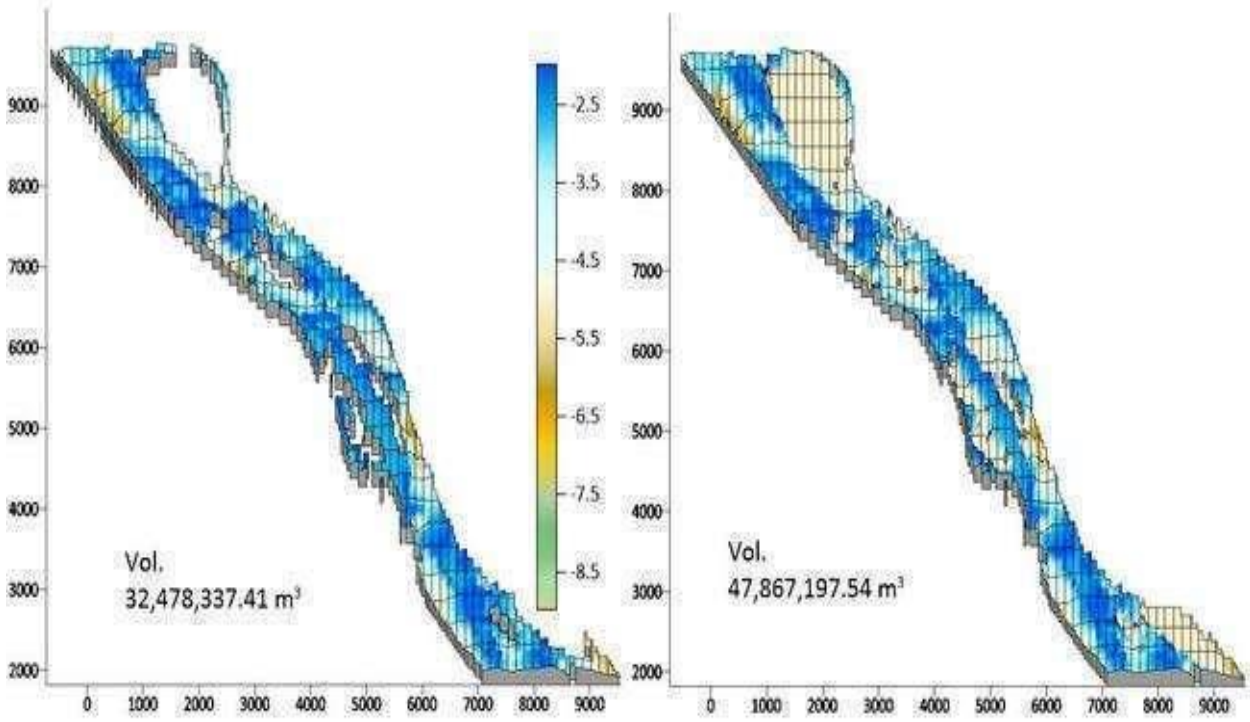


Figure 4: Section 3 indicating before and after removal of sandy islands by dredging

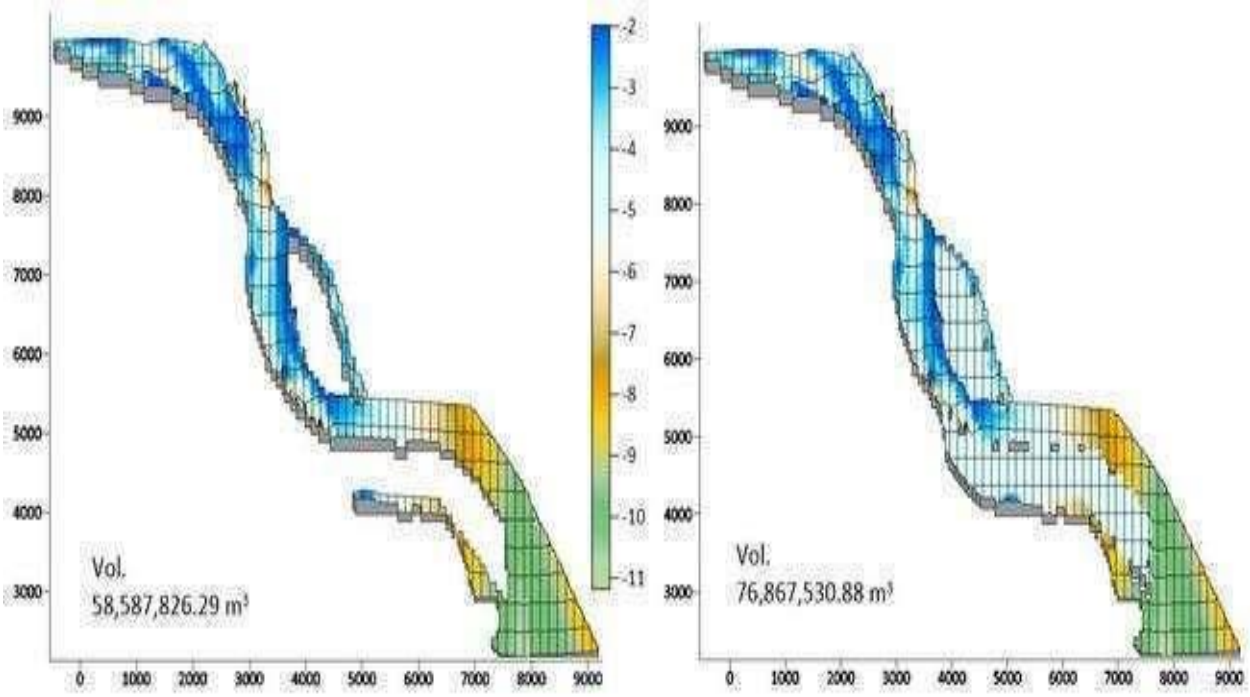


Figure 5: Section 4 indicating before and after removal of sandy islands by dredging

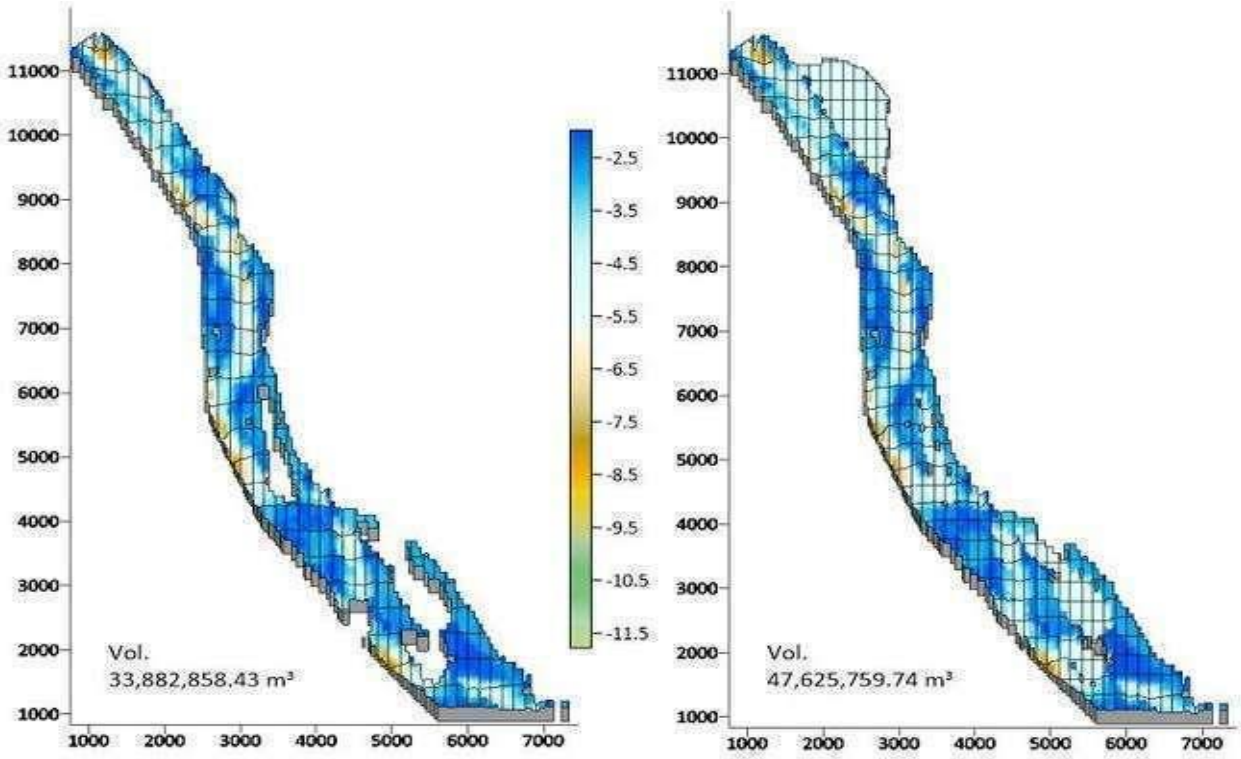


Figure 6: Section 5 indicating before and after removal of sandy islands by dredging

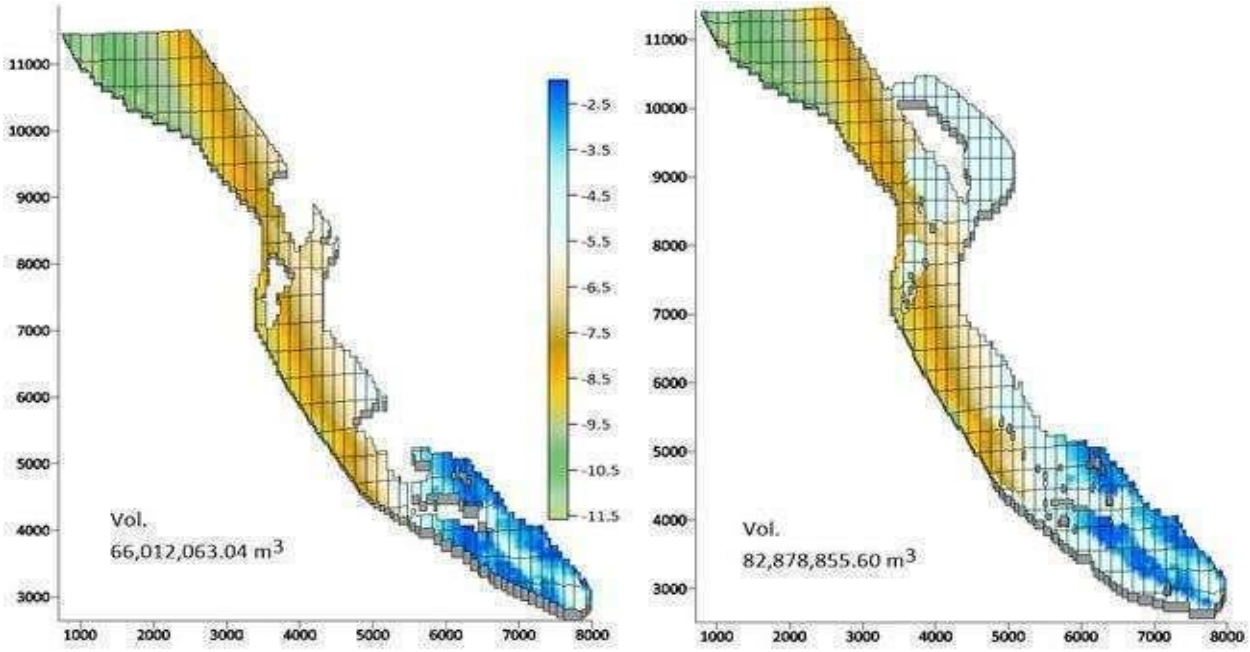


Figure 7: Section 6 indicating before and after removal of sandy islands by dredging

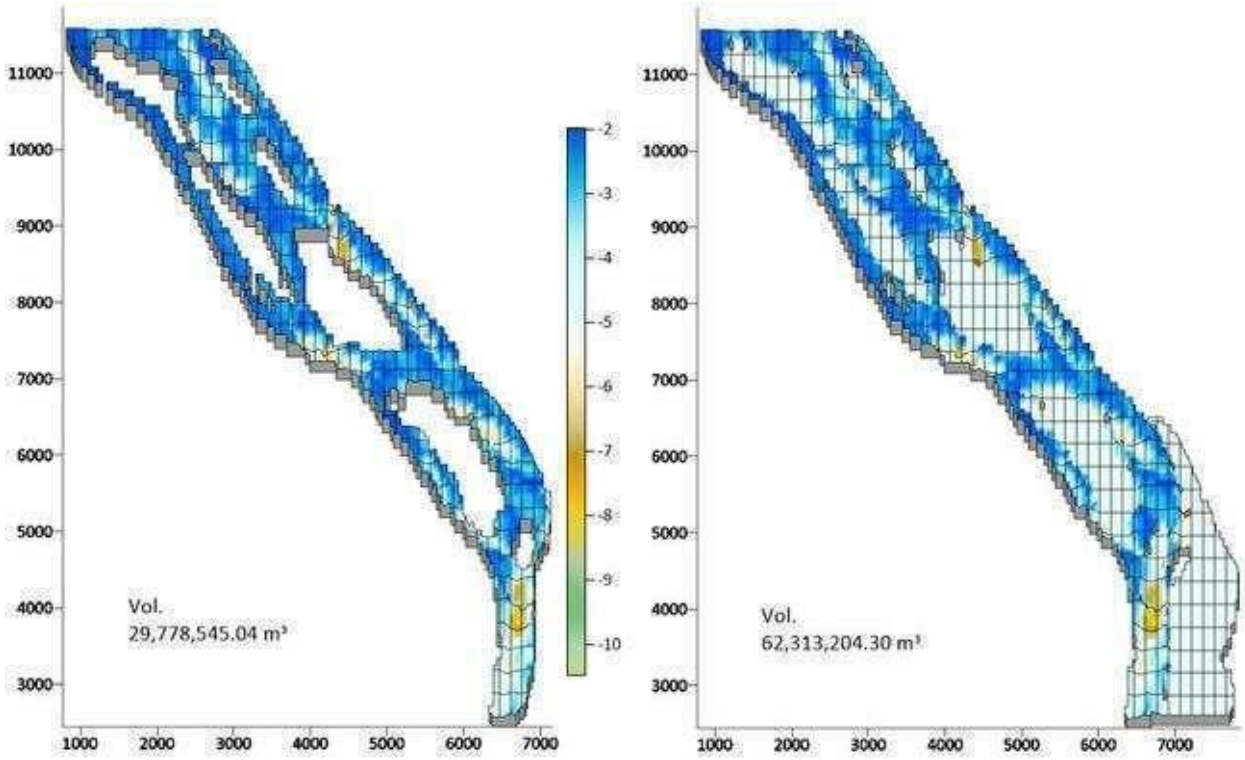


Figure 8: Section 7 indicating before and after removal of sandy islands by dredging

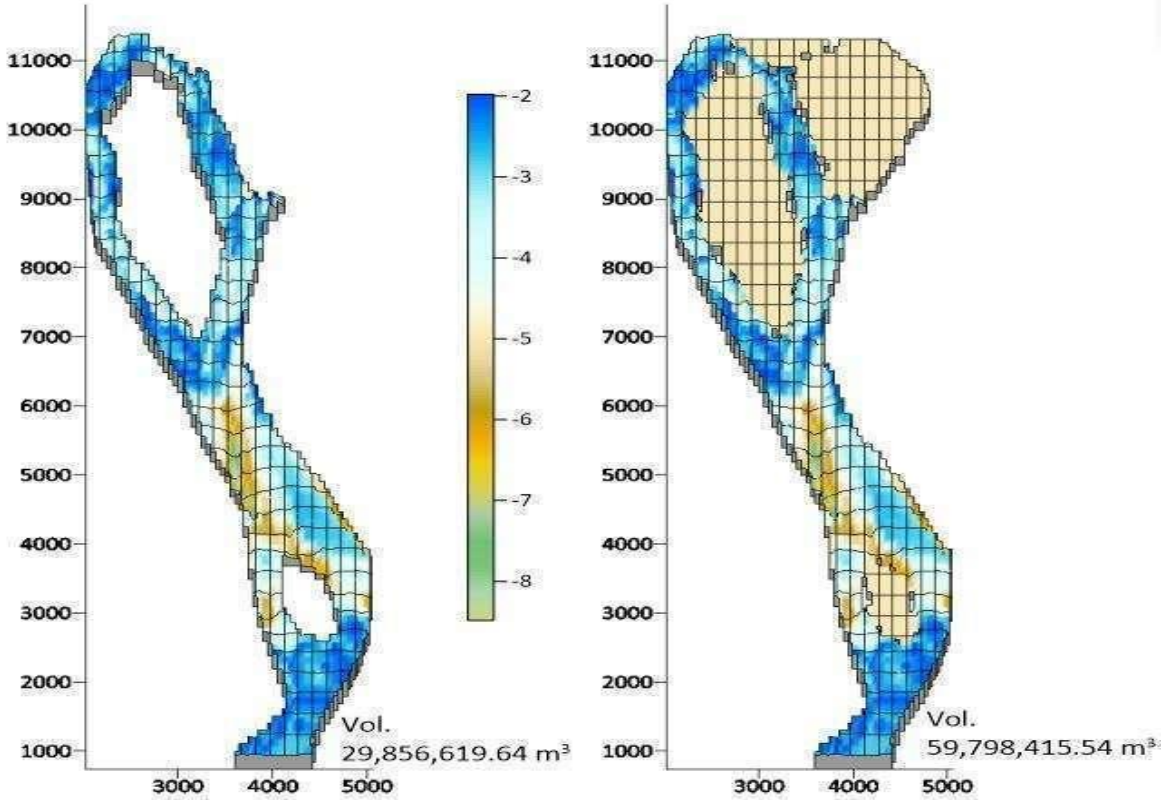


Figure 9: Section 8 indicating before and after removal of sandy islands by dredging

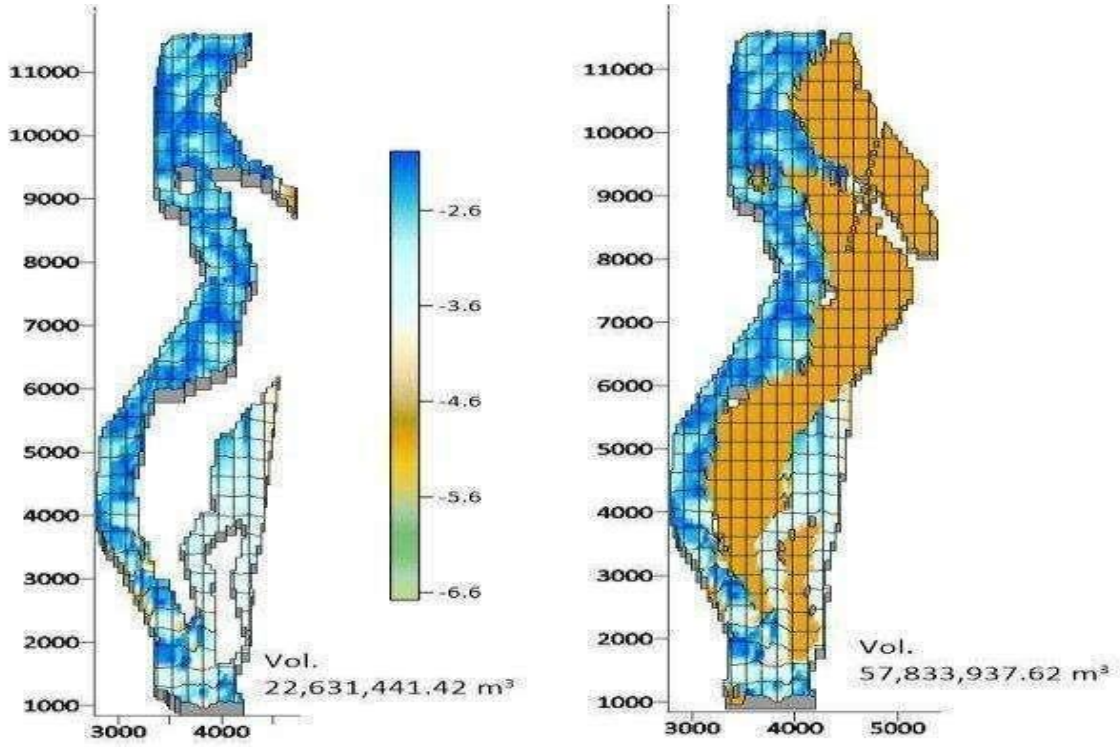


Figure 10: Section 9 indicating before and after removal of sandy islands by dredging

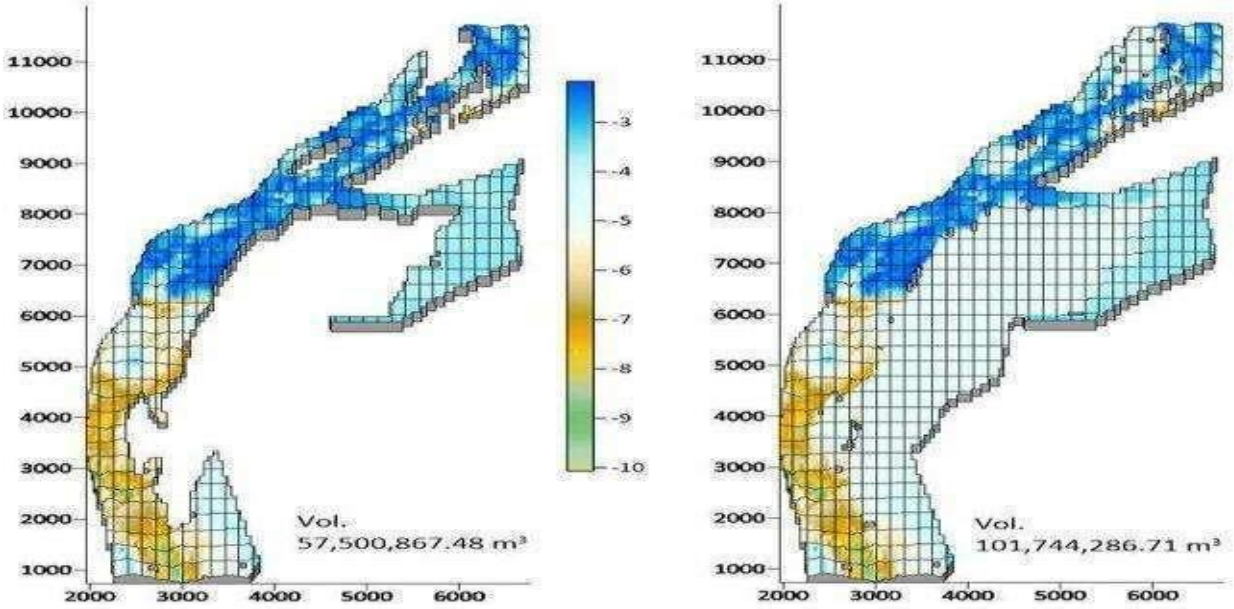


Figure 11: Section 10 indicating before and after removal of sandy islands by dredging

Table 2 shows all the 43 Sections of the river indicating the respective water containment volume capacity before and after implementation of the surgical dredging of the river. It is interesting to notice that the difference in volume is more than $1.6\ billion\ m^3$, about more than the total volume of water in the Lagdo dam. Note that Alau dam that largely caused the recent havoc in June 2025 is only about $112\ million\ m^3$, a 'mini' of Lagdo dam. Recall that emptying of this dam in the river Niger in 2022 led to the worst flood disaster in the West African continent and in Nigeria alone killed over 603 persons and injured over 2400 persons.

The implication of the volume capacity enlargement in the tune of over 1.6 billion cubic meter is that depending on the flowrate and velocities, there is a good prospect that the increased capacity will largely provide a cushion and therefore resilience against incident of flood such as the one that happened in 2022.

Table 2: Volume containment for each section before and after dredging

Section	Initial volume	New volume after dredging		Section	Initial volume	New volume after dredging
1	34,675,417.88	60,603,282.07		**22**	70,387,254.49	115,486,676.09
2	26,268,114.40	38,198,665.56		**23**	65,356,753.00	93,880,225.60
3	32,478,337.41	47,867,197.54		**24**	79,568,394.08	117,824,004.18
4	58,587,826.29	76,867,530.88		**25**	68,954,729.06	131,802,416.76
5	66,012,063.04	82,878,855.60		**26**	69,884,664.45	113,039,883.75
6	33,882,858.43	47,625,759.74		**27**	84,319,852.99	102,090,728.39
7	29,778,545.04	62,313,204.30		**28**	116,607,291.18	214,461,481.08
8	29,856,619.64	59,798,415.54		**29**	112,107,826.31	172,095,751.21
9	22,631,441.42	57,833,937.62		**30**	72,257,809.45	148,493,388.15
10	57,500,867.48	101,744,286.71		**31**	84,318,651.57	155,735,447.17
11	87,439,928.22	114,516,253.42		**32**	87,612,854.70	186,875,906.70
12	91,055,608.55	102,759,694.25		**33**	87,378,714.14	130,419,532.84
13	85,174,752.98	125,668,239.28		**34**	79,704,919.87	167,026,102.97
14	62,464,213.76	87,085,150.76		**35**	58,430,144.49	88,395,912.19
15	47,832,939.86	148,208,812.86		**36**	66,558,309.09	87,104,868.99
16	74,705,834.56	138,385,521.56		**37**	59,016,672.95	84,692,991.85
17	72,151,853.22	142,590,582.52		**38**	34,207,694.48	41,468,978.79
18	84,039,310.21	113,181,238.51		**39**	60,728,330.27	70,020,775.22
19	105,894,125.76	142,642,867.76		**40**	83,606,911.39	102,887,481.69
20	75,011,685.53	101,508,225.53		**41**	63,916,778.15	64,112,740.62
21	41,710,439.57	97,826,341.27		**42**	75,511,877.76	75,511,877.76
	TOTAL VOLUME CONTAINMENT			**43**	10,526,853.23	10,526,853.23
	Initial Basin/m^3	Dredged Basin/m^3			**DIFFERENCE**//m^3	
	2,810,116,070.33	**4,424,058,088.48**			**1,613,942,018.15**	**The difference can take 100% Lagdo's dam release!**

Fig.12 indicates the add-up of all the sections (sections 1 to 43). It is observed that dredging operations also contributed to clearing of the ox-bowing and over-meandering sections of the river (especially at the tail end toward Nun River). Meandering and ox-bowing of rivers are ageing processes with its attendant consequences of island formation, oxbow lake formation and discharge rate reductions. The implementation of surgical dredging of the river Niger is tantamount to revitalization of Niger river for not only flood mitigation but also navigation (Osuji and Agbakwuru, 2023).

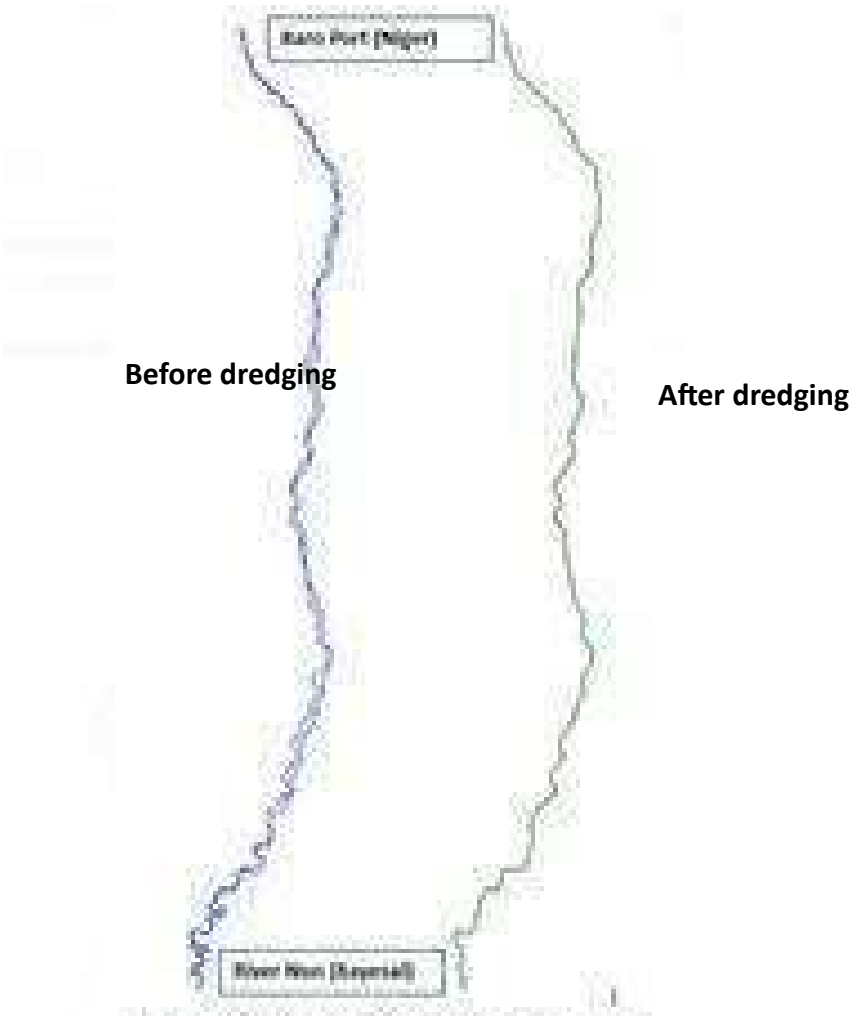


Figure. 12: Channel from Baro to river Nun of river Niger

3.3 Impact on Flood Resilience

The volumetric increase enhances the river's ability to buffer high inflows, reducing the likelihood of catastrophic overbank flooding.

3.4 Navigational Benefits

Dredging simplifies the river's morphology by reducing meandering and oxbow lake formation, restoring navigability and supporting inland waterway transport (Osuji and Agbakwuru, 2023).

3.5 Sediment Management via Sand Traps

The idea of employing sand traps to capture sediment is not a new one. Parshall's early model-and-prototype studies established the concept and scaling of trap behaviour in open channels (Parshall, 1952). Subsequent field and prototype studies have demonstrated how sand traps can significantly decrease sedimentation in irrigation and power canals and preserve flow capacity (Paulos, Yilma and Ketema, 2006; Pradipta et al., 2020). Sand trap systems are effective at intercepting upstream sediment transport, thereby slowing re-siltation rates and extending dredging intervals. This system minimizes operational and economic burdens of regular dredging. A proportional sand-trap system was conceptualized in SolidWorks 2021, drawing inspiration from the Wonji–Shoa (Ethiopia) and Pengasih (Indonesia) applications (Paulos et al., 2006; Pradipta et al., 2022), included an innovation of pumping out sediments at regular interval but adapted to the Niger River's hydro morphological context. The proposed trap basin is embedded below the main channel bed, designed to induce localized flow deceleration, enabling sediments to settle. A conceptual layout of the proposed sand-trap system is presented in Fig. 13 showing the circuitry of the sand trap (de-sanding) using hydraulic pumps



Figure 13 Circuit diagram of the sand trap system

Each sand-trap basin is connected to a pipeline system leading to a mobile sediment pumping unit (see Fig. 13), which periodically extracts deposited materials and conveys them to the riverbank for reuse as construction sand. This closed-loop mechanism ensures continuous flow, minimizes channel disturbance, and extends dredging intervals compared to traditional methods. The concept also allows easy replication at other strategic points (or sedimentation hotspots) along the Niger–Benue basin.

4.1 Conceptual Design and Quantification of the Proposed Sand Trap System

Sediment accumulation remains a major constraint to navigability and hydraulic efficiency within the Niger–Benue River system, particularly along throttled reaches where flow constriction promotes deposition. To complement surgical dredging operations, a conceptual sand trap system is proposed as a sediment management solution for critical sections of the river.

The proposed sand trap is conceptually located at Section 1 of the study area, identified from the volumetric and bathymetric assessment as a sediment-prone throttling zone. The system is positioned along the throttling side of the channel, where sediment concentration and deposition potential are highest. Fig. 14 presents a conceptual SolidWorks representation showing the location of the proposed sand trap relative to the channel alignment and the identified throttling zone.

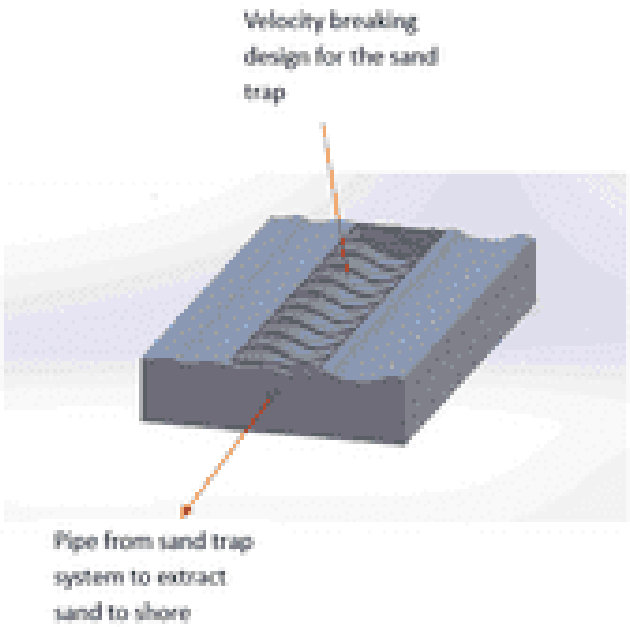


Figure 14: Conceptual SolidWorks model showing the proposed placement of the sand trap along the throttling side of Section 1 of the Niger–Benue River system

Based on lateral (width) characterization of Section 1, an effective design length of the sand-trap chamber is approximately 500 m. The trap is configured as an off-channel retention chamber with an assumed effective width of 30 m, allowing partial diversion of sediment-laden flow while maintaining the main navigation channel. The semi-cylindrical geometry of the chamber is intended to promote flow expansion and reduce internal flow velocity. The geometric configuration and longitudinal extent of the sand trap chamber (with the velocity breakers mounted on top of the chambers) are illustrated in Fig. 15.

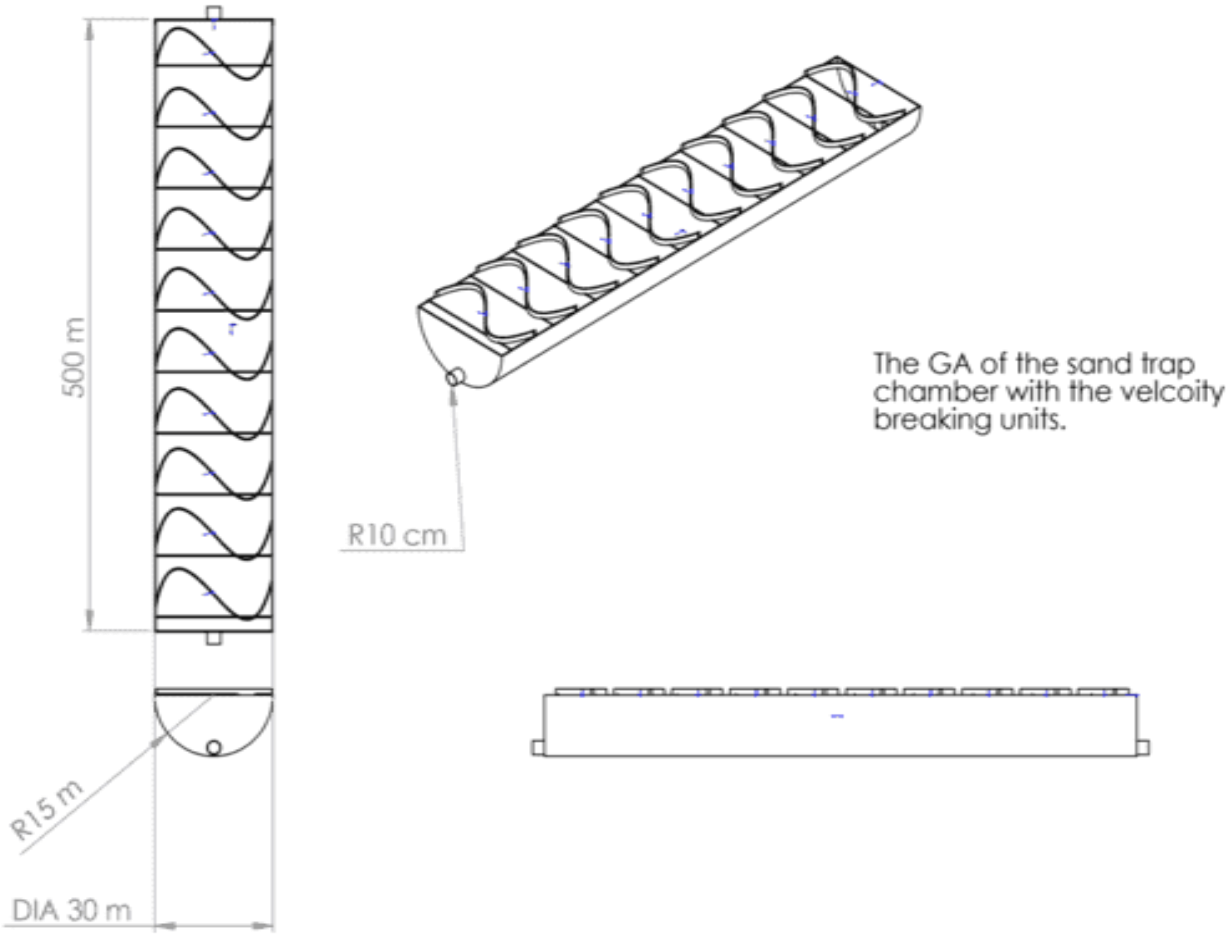


Figure 15: SolidWorks representation of the proposed sand trap chamber geometry, illustrating the semi-cylindrical configuration and longitudinal extent adopted for the conceptual design.

To enhance sediment deposition within the chamber, the proposed system incorporates an internal flow-conditioning component referred to as a Velocity Breaking Unit (VBU). The primary function of the VBU is to diffuse the incoming river velocity (v_o) and reduce it to a lower internal velocity referred to as sand settling velocity (v_s), thereby increasing residence time and creating favourable conditions for sediment settling. Conceptually, the VBU consists of S-shaped flow-deflecting plates arranged within the chamber to dissipate kinetic energy and

reduce sediment transport capacity. The conceptual configuration and positioning of the Velocity Breaking Unit within the sand trap chamber are shown in Fig.16

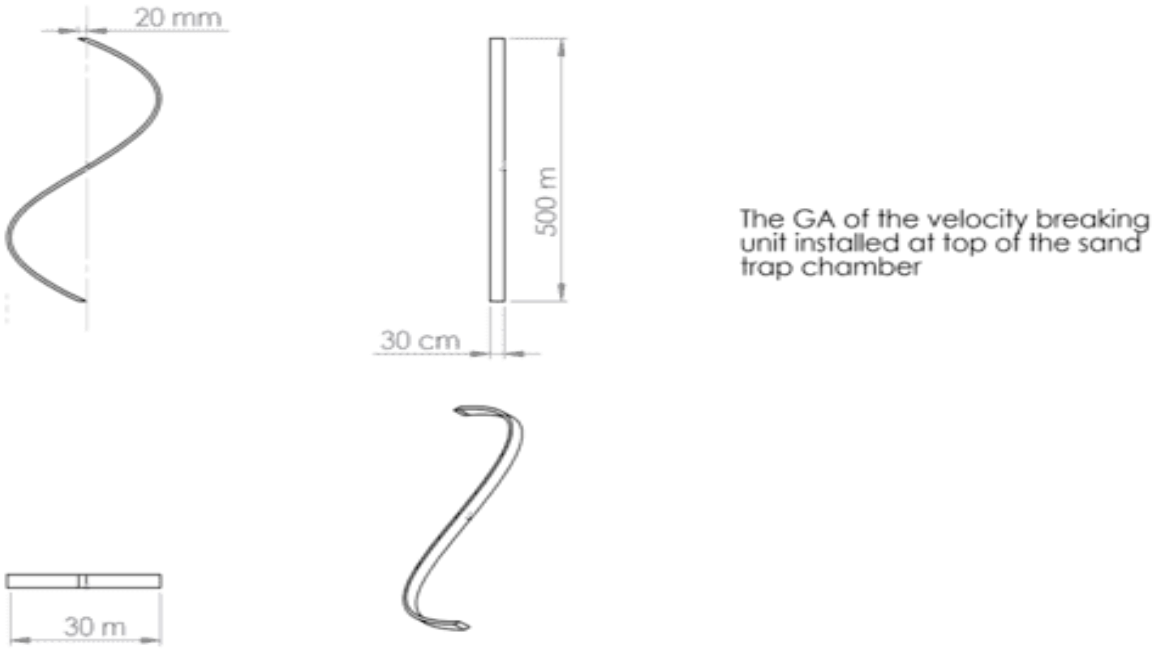


Figure 16: SolidWorks schematic of the Velocity Breaking Unit (VBU) integrated within the sand trap chamber for flow diffusion and reduction of internal flow velocity.

Sediment samples obtained from the Patani reach of the Niger–Benue River system indicate that the transported material is predominantly fine to medium alluvial sand, with particle sizes ranging from 0.3 mm to 1.5 mm. The settling behaviour of these particles under low-velocity conditions may be described using Stokes' settling velocity relationship:

$$V_s = \frac{(\rho_s - \rho) g d^2}{18\mu} \quad (8)$$

Where V_s is the particle settling velocity, ρ_s and ρ represent sediment and fluid densities respectively, g is gravitational acceleration, d is particle diameter, and μ is the dynamic viscosity of water. In this conceptual framework, the design objective of the sand trap system is to reduce the incoming river velocity V_r such that the internal chamber velocity satisfies $V_r \leq V_s$, enabling effective sediment deposition.

Assuming a semi-cylindrical chamber geometry, the potential sediment retention capacity of the sand trap is estimated using:

$$A = \pi r^2 L \quad (9)$$

where $r = 15m$ and $L = 500m$. This yields an estimated storage volume on the order of $3.5 \times 10^5 m^3$. At an assumed operational efficiency of 50%, the system is capable of retaining sediment equivalent to approximately 10,000 standards $18m^3$ haulage trucks, demonstrating the significant sediment management potential of the proposed design.

A complete three-dimensional SolidWorks model integrating the sand trap chamber and the Velocity Breaking Unit is presented in Figure 18, illustrating the overall conceptual configuration and interaction of system components.

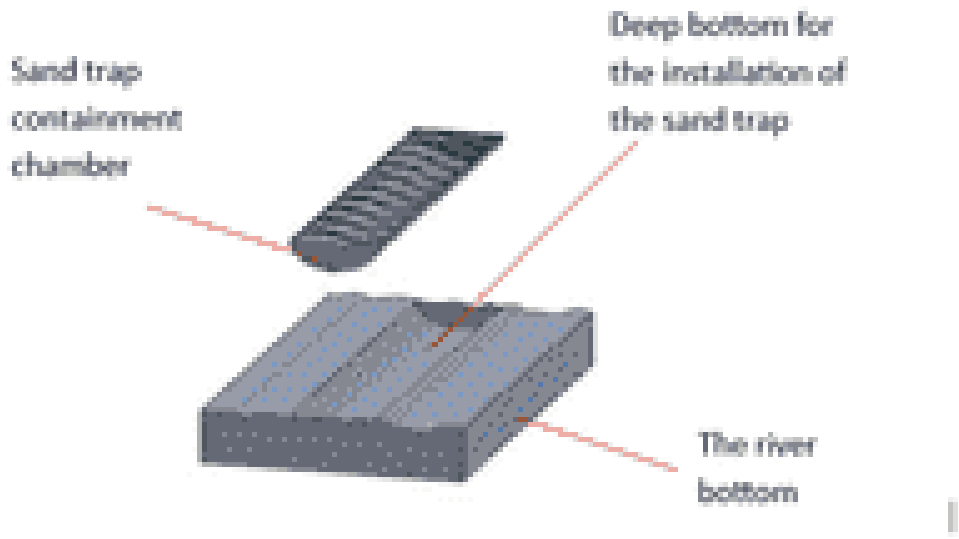


Figure 18: Three-dimensional SolidWorks model of the complete conceptual sand trap system showing the chamber layout and internal flow-conditioning components.

The proposed sand trap system represents a conceptual engineering solution, intended to demonstrate feasibility rather than provide a fully validated hydraulic design. Further refinement through field measurements, hydraulic analysis, and numerical modelling is required to optimize system performance and validate sediment capture efficiency.

4.2 Integration Framework and Application

The integration framework combined bathymetric restoration through surgical dredging with sediment management using sand traps, providing a sustainable flood-mitigation model for the Niger–Benue Basin. The conceptual workflow involves three major components:

I. Channel Restoration: Selective dredging at critical aggraded zones identified from bathymetric modeling improves hydraulic conveyance and floodwater storage capacity.

II. Sediment Retention: Sand-trap basins positioned downstream of dredged segments capture inflowing sediments, preventing re-siltation and maintaining navigable depths.

III. Operational Flexibility: Mobile dredging units linked to the sand-trap discharge pipelines allow for scheduled sediment removal without interrupting river flow or navigation.

Unlike conventional full-scale dredging, this surgical approach reduces cost, environmental impact, and maintenance frequency while promoting adaptive river management. It also supports Nigeria's flood-risk-reduction and inland-navigation goals under the Sustainable Development Goal (SDG) 11 framework for resilient infrastructure.

The model is conceptual and designed for numerical validation in future research phases. Nevertheless, it provides a replicable engineering template for sustainable sediment management across Nigeria's major river basins.

4.3 Flood Mitigation and Climate Adaptation

Enhancing the Niger Basin's capacity directly mitigates flood damage in densely populated floodplains. This intervention provides resilience against both climate-induced heavy rainfall and sudden dam discharges, addressing recurrent disasters in Nigeria.

Flood frequency analyses have shown that precise statistical modeling of flood return periods is essential for estimating design floods, planning infrastructure, and developing early warning systems (Ibeje, 2020). Combining these models with sediment control measures increases the effectiveness of flood mitigation.

A recent frequency analysis at the Shintaku Station of the Niger River applied various statistical models to long-term flood data, identifying Log-Pearson Type III as suitable for predicting extreme discharge events and producing return period estimates that underscore the urgency for engineered flood resilience (Ibeje, 2020). This supports the present study's call for increasing the containment capacity through dredging to absorb such projected peak flows.

Additionally, sediment traps like those used in Cirata Dam in Indonesia may also be recommended as effective flood protection measures by reducing sedimentation-induced capacity loss (Soekarno, 2024).

4.4 Urban and Regional Planning Implications

Increased storage capacity protects critical infrastructure, housing, and farmland, aligning with SDG 11's mandate for resilient urban settlements. It supports sustainable growth in riverside communities and enhances disaster preparedness. Geological studies at dam sites in the Niger Basin provide background on site stability and the importance of resilience planning (Malomo and Olawole, 1984).

Moreover, the integration of sediment traps in irrigation schemes demonstrates how sediment control infrastructure supports long-term land use stability and agricultural productivity (Paulos, Yilma and Ketema, 2006; Pradipta et al., 2020).

4.5 Economic and Social Benefits

Restored navigability promotes trade, transportation, and employment in Nigeria's "blue economy." Sediment removal through sand traps offers secondary economic opportunities, including construction material sourcing. Studies have shown high trap efficiencies under proper maintenance regimes (Paulos, Yilma and Ketema, 2006).

This aligns with findings from regional geotechnical studies highlighting the need for foundation stabilization where high-plasticity soils exist (Malomo and Olawole, 1984).

4.6 Sustainability and Cost Efficiency

Surgical dredging targets the most critical zones, reducing operational scope and associated costs compared with full-scale dredging. Sand traps reduce sediment load sustainably, minimizing long-term maintenance expenses. This approach is supported by empirical evidence from Cirata Dam and others where localized sediment management extended reservoir life (Soekarno, 2024). Additionally, controlled dredging, when paired with predictive sediment transport models (e.g., Van Rijn, 1993; Meyer-Peter & Müller formulations), enables precision planning (Van Rijn, 1993).

It is noted that environmental research warns that dredging, if not properly evaluated, can increase suspended solids and disturb estuarine ecosystems, as observed in well-documented studies on dredging impacts in coastal and estuarine systems (Van Maren et al., 2015).

5.0 Conclusions

The Niger–Benue River Basin's reduced containment capacity remains a central factor behind Nigeria's escalating flood crises. Findings from this study demonstrated that targeted surgical dredging, when integrated with sand-trap technology, provided a technically feasible, economically sustainable, and environmentally responsible strategy for enhancing flood resilience. A review of field and laboratory studies indicated that well-designed sand-trap installations can achieve sediment-removal efficiencies typically ranging from 65% to 90%, depending on sediment type, flow velocity, and maintenance practice. Integrating such traps within dredged reaches is expected to reduce downstream siltation and prolong channel stability.

The modeled capacity gain of approximately 1.6 billion m^3 exceeding the Lagdo Dam's maximum discharge volume indicates that selective dredging and sediment-control interventions can safeguard millions of lives, protect infrastructure, and restore inland-waterway navigability.

Broader implementation of these combined measures will substantially strengthen Nigeria's preparedness for climate-driven hydrological extremes while simultaneously unlocking economic, social, and environmental benefits consistent with Sustainable Development Goal 11 on resilient and sustainable communities.

It is suggested that R. Niger River bedload estimation should be investigated to support optimal volume design of the sand trap system. Further work is also required to advance the proposed system beyond the conceptual stage. Field measurements of river velocity, discharge, and sediment concentration are necessary to validate the assumed hydraulic conditions. Detailed hydraulic and computational fluid dynamics (CFD) modelling should be conducted to optimize the geometry and configuration of the Velocity Breaking Unit and to assess flow behaviour within the sand trap chamber. In addition, pilot-scale implementation and monitoring are recommended to evaluate sediment capture efficiency, operational performance, and maintenance requirements under real flow conditions.

The integration of such validated systems into national inland waterway management strategies could support sustainable navigation, reduce flooding risks, and enhance the overall resilience of inland water transport infrastructure in Nigeria.

Acknowledgement

The authors acknowledge the contribution of Nigeria Inland Waterway Authority in providing the bathymetric data. Engr Smith Akpere and Johnny Edet Ubaha in the software application.

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