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Modeling and Simulation of Data for the Identification and Prediction of the Behavior of Lake Sahambavy, Fianarantsoa, Madagascar

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Abstract

This study investigates the hydrodynamic behavior of Lake Sahambavy, located in Fianarantsoa, Madagascar, using the IRIC (International River Interface Cooperative) numerical simulation software. A two-dimensional hydrodynamic model was developed by integrating geo-hydrological, climatic, and land-use data to analyze water level variations, flow dynamics, and morphological processes within the lake.

The model incorporates transient boundary conditions, hydraulic roughness parameters, and stable numerical schemes. Simulation results reveal pronounced spatial variability in velocity, water depth, and free-surface elevation, controlled by bed topography and asymmetric channel geometry. Nonlinear hydrodynamic behavior between upstream and downstream areas highlights zones of flow concentration sensitive to erosion and sedimentation. Overall, the study confirms the relevance of IRIC as a decision-support tool for sustainable water resource management and hydrological risk mitigation in Malagasy lacustrine systems.

Keywords: Hydrodynamic modeling; Numerical simulation; IRIC; Lake Sahambavy

1. Introduction

Lake Sahambavy, located in the Fianarantsoa region of Madagascar, is an essential resource for water supply, agricultural activities, and local environmental balance, while being strongly influenced by climatic variability and anthropogenic pressures, particularly land-use changes. Alterations in the hydrological regime and lake morphology can lead to significant impacts on water levels, flow dynamics, and erosion and sedimentation processes. In this context, understanding and predicting the hydrodynamic behavior of the lake represents a major challenge for sustainable water resource management and hydrological risk prevention (Bader, J.-C. *et al.*). Numerical modeling constitutes a powerful tool for analyzing these complex dynamics, particularly through two-dimensional hydrodynamic models capable of representing the spatial variability of velocities, water depths, and free-surface elevations. This study relies on the IRIC software, recognized for its ability to simulate complex flows, to model the hydrodynamic behavior of Lake Sahambavy and to identify sensitive zones likely to influence its future evolution.

2. Materials and Methods

2.1. Geo-hydrological and climatic characterization of Lake Sahambavy

This study focuses on Lake Sahambavy, the only natural lake in the Haute Matsiatra region, southeastern Madagascar. The lake covers approximately 38 ha and is located near Fianarantsoa (21.4525° S, 47.2607° E), within a mountainous environment characterized by a tropical highland climate.

The region is marked by two contrasted climatic periods: a cyclonic season (November–April), associated with intense rainfall, strong winds, and flood events leading to rapid water-level fluctuations and increased sediment and nutrient inputs, and a non-cyclonic season (May–October), characterized by lower precipitation and reduced hydrological variability. These seasonal contrasts strongly influence the hydrological regime, ecological functioning, and socio-economic uses of the lake, including irrigation, fisheries, and recreational activities (Carré *et al.*, 2015) [2].
The analysis of Lake Sahambavy under these two seasonal contexts is therefore essential for understanding the response of tropical lacustrine systems to extreme climatic variability and for supporting sustainable water resource management and ecosystem conservation.

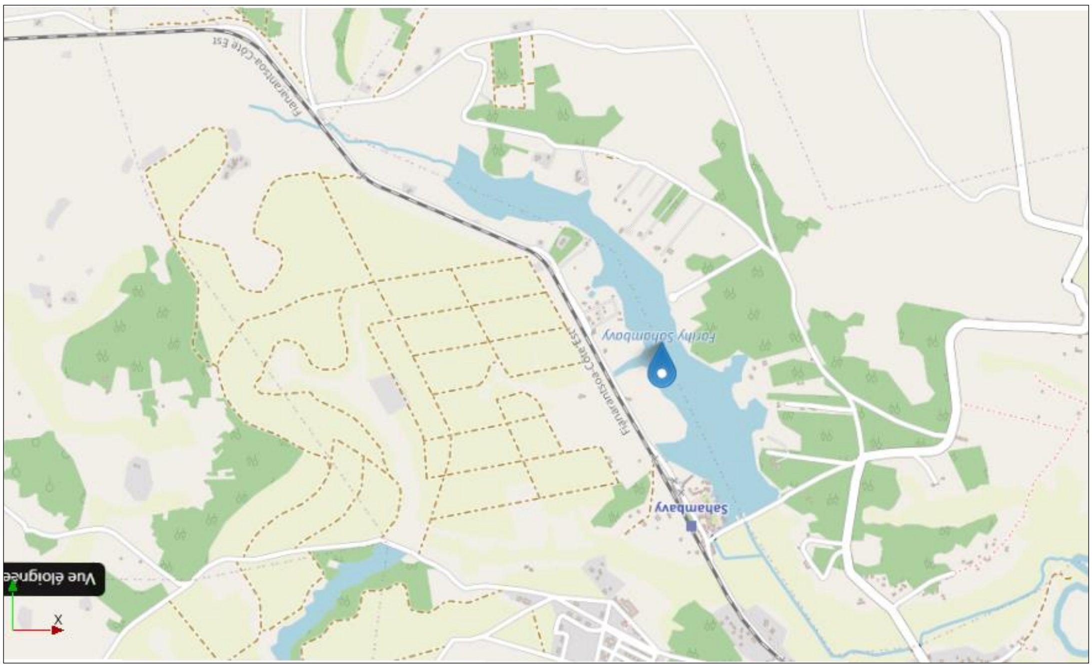


Fig 1 : Location map of Lake Sahambavy, Fianarantsoa

2.2. Analysis of land-use change (2018–2022) in the Lake Sahambavy area

Observed trends

Land-use analysis in the peripheral zone of Lake Sahambavy over the 2018–2022 period reveals significant transformations affecting the lacustrine ecosystem and its watershed. Satellite data and field observations indicate a marked expansion of agricultural areas, particularly rice cultivation, driven by demographic growth and food demand, leading to a reduction of natural and semi-natural vegetation around the lake (Codling *et al.*).
Concurrently, forest and natural vegetation cover has declined due to fuelwood extraction, agricultural expansion, and increasing urbanization, enhancing soil erosion and nutrient transfer toward the lake. Urban expansion around Fianarantsoa remains moderate but shows a gradual encroachment toward the lake margins. Peripheral wetlands have also been altered by agricultural drainage and diffuse pollution, reducing their filtration capacity and negatively affecting biodiversity (Cooper, M. J. *et al.*).
Overall, land-use changes reflect a progressive shift from natural to anthropogenic systems, mainly agricultural and urban, posing major challenges for erosion control, habitat conservation, and water quality management in Lake Sahambavy.

2.3. Numerical simulation setup

2.3.1. Grid generation and domain definition

2.3.1.1. Mesh structure and dimensions

The numerical domain of Lake Sahambavy (Fianarantsoa) was discretized using a structured curvilinear grid composed of 120 cells (3 longitudinal × 40 main divisions), with a single transverse level and no local refinement. The mesh density is moderate and adapted to the elongated morphology of the lake, with predominantly quadrilateral cells. Grid smoothing by relaxation (R = 0.15) and 30 optimization iterations ensured low distortion, acceptable aspect ratios, numerical stability, and reduced computational cost, making the grid suitable for global hydrodynamic and environmental simulations using IRIC.

2.3.1.2. Flow orientation

Flow orientation in the IRIC model follows the natural longitudinal axis of Lake Sahambavy, from upstream to downstream, in accordance with topography and observed circulation patterns. The curvilinear grid is aligned with this direction to minimize numerical errors and improve model stability.

2.3.1.3. Interface and model preparation

The pre-processing interface allows the import of geographic data (base maps, lake boundaries, obstacles), the definition of boundary conditions, roughness zones, and hydraulic parameters, as well as the visualization and quality control of the mesh. This model preparation phase is essential to ensure a faithful representation of Lake Sahambavy and to guarantee the reliability of the hydraulic and environmental simulations carried out using IRIC.

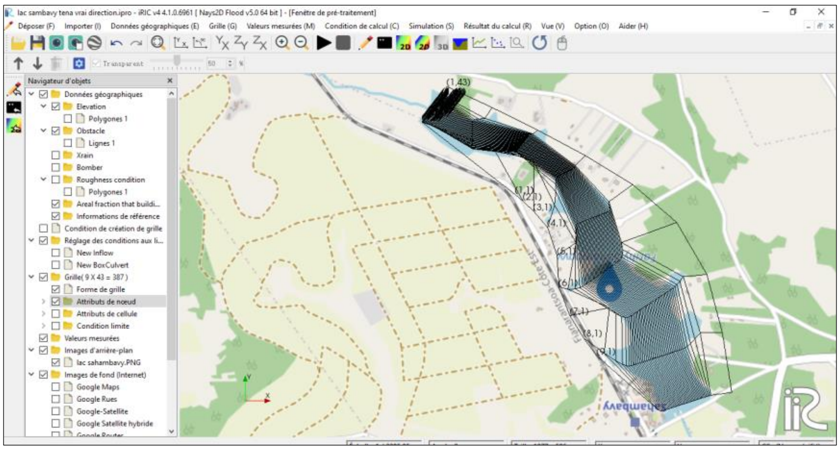


Fig 2 : Grid generation for the representation of Lake Sahambavy using IRIC

2.3.2. Boundary Conditions: definition of the transient hydrograph

Boundary conditions were defined in accordance with the domain geometry and flow direction. The upstream boundary corresponds to the lake inflow and is imposed as a transient discharge or prescribed water level using a hydrograph (Dadhich *et al.*). The downstream boundary represents the outlet of the domain and is defined by a water-level condition, a stage–discharge relationship, or a free-outflow condition, allowing water to leave the system without numerical disturbance. Lateral boundaries corresponding to lake shores are treated as impermeable walls with zero normal velocity, ensuring mass conservation and numerical stability of the IRIC model.

2.3.2.1. Interpretation of the hydrograph

The interpretation of the hydrograph makes it possible to analyze the hydrological response of the system (lake or river reach) to a given event. The rising limb of the hydrograph reflects the progressive increase in discharge associated with upstream inputs (rainfall, runoff, tributaries), while the peak discharge corresponds to the moment of maximum hydraulic loading within the domain. The falling limb represents the drainage and release phase toward downstream areas, controlled by the storage capacity of the lake and outlet conditions. The shape, magnitude, and temporal lag of the peak provide insights into the lake's regulatory role, system inertia, and the effectiveness of the upstream and downstream boundary conditions defined in the IRIC model.

2.3.3. Roughness conditions and simulation duration

2.3.3.1. Hydraulic roughness parameter

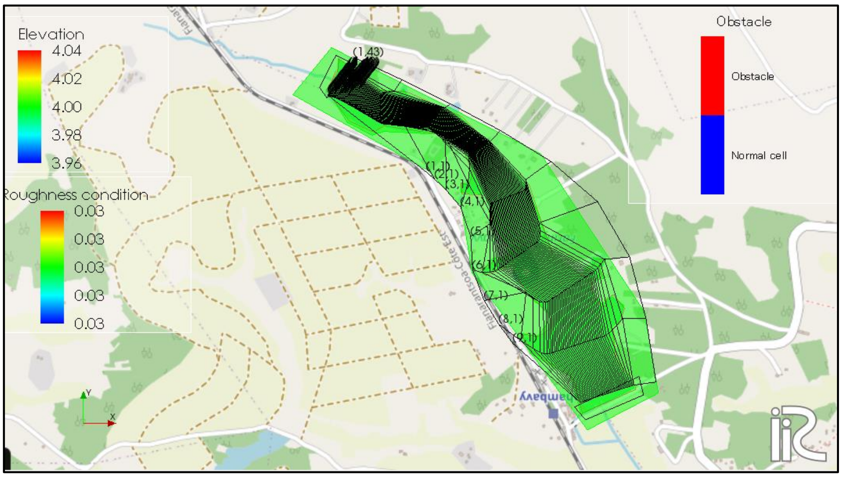


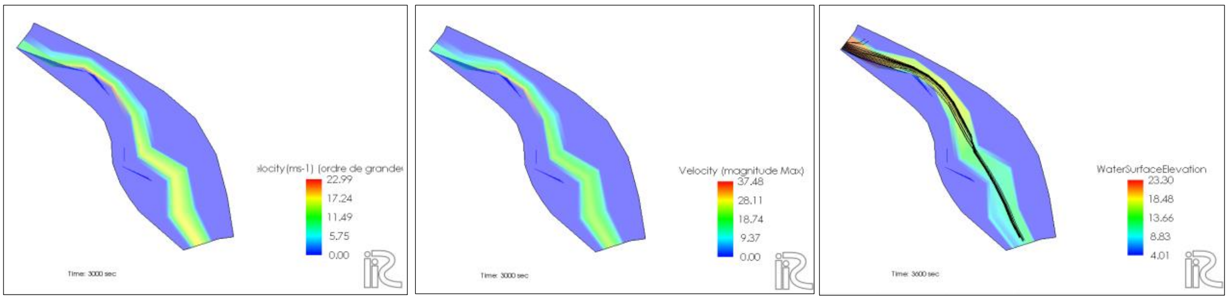
Fig 3 : Obstacles and roughness condition values in Lake Sahambavy

2.3.3.2. Temporal domain

The interpretation of the hydrograph enables analysis of the hydrological response of the system (lake or river reach) to a given event. The rising limb represents the progressive increase in discharge due to upstream inputs such as rainfall, runoff, and tributaries, while the peak discharge corresponds to the maximum hydraulic load within the domain. The falling limb describes the drainage and downstream release phase, controlled by lake storage capacity and outlet conditions. The hydrograph shape, peak magnitude, and time lag provide key information on the lake's regulatory role, system inertia, and the effectiveness of the upstream and downstream boundary conditions implemented in the IRIC model.

2.3.4. Numerical computation conditions

Analysis of computational parameters



(a) Velocity by Order of Magnitude **(b) Maximum Velocity** **(c) Representative (Mean/Rational)**

Fig 4: Velocity fields in the analytical data of Lake Sahambavy

Figure 2.4 illustrates the spatial distribution of hydrodynamic velocities in Lake Sahambavy. The order-of-magnitude velocity map (Figure 2.4a) reveals strong spatial heterogeneity, with higher velocities concentrated along the central axis of the lake, while peripheral zones exhibit markedly lower values, indicating preferential circulation controlled by the elongated lake morphology. The maximum velocity map (Figure 2.4b) confirms the presence of fast-flow corridors, likely related to inflow–outflow zones and the combined influence of bathymetry and hydrodynamic forcing, which play a key role in sediment and nutrient transport. The representative (rational) velocity map (Figure 2.4c) shows a smoother and more structured flow regime, reflecting average lake dynamics while preserving the main spatial patterns. Overall, these results highlight the combined control of lake geometry and hydrodynamic conditions on velocity distribution, with implications for mixing, sedimentation, and water quality in Lake Sahambavy.

2.3.5. Numerical computation parameters of the IRIC model

2.3.5.1. Numerical scheme and stability control

The hydrodynamic modeling of Lake Sahambavy is based on an explicit numerical scheme implemented in IRIC, solving the depth-averaged two-dimensional Saint-Venant equations. This approach ensures accurate representation of spatial and temporal variations in velocity and water level while conserving mass and momentum. Numerical stability is controlled through adaptive time stepping in strict compliance with the CFL condition. Sensitivity tests on time step and numerical diffusion confirmed model robustness and the absence of non-physical oscillations.

2.3.5.2. Viscosity, parallelization, and domain options

An effective numerical and turbulent viscosity adapted to the lacustrine flow regime was applied to ensure energy dissipation and smooth velocity fields while preserving physical flow structures. Large-scale turbulence effects were thus represented without using computationally intensive three-dimensional models. Parallel computation was enabled to reduce simulation time, particularly for transient conditions, and domain options were configured to minimize artificial boundary effects, improving overall model stability and accuracy.

2.3.6. Roughness conditions and grid generation parameters

2.3.6.1. Domain definition and obstacle representation

The computational domain was defined to accurately represent the spatial extent and morphology of Lake Sahambavy, using geographic data integrated into the IRIC environment (Munawar, H. S. *et al.*). Natural and anthropogenic obstacles, including vegetation zones and shoals, were represented through specific roughness values or geometric constraints, allowing realistic simulation of flow retardation and deflection effects.

2.3.6.2. Uniform hydraulic roughness

A uniform hydraulic roughness was applied over the entire domain to limit model complexity while maintaining realistic hydrodynamic behavior. This assumption reflects the relative homogeneity of the silty–sandy lakebed and the lack of detailed spatial roughness data (Moriasi, D. N. *et al.*). The selected roughness value adequately reproduces friction losses at the lake scale and is appropriate for global analysis of Lake Sahambavy, despite known limitations in shallow and vegetated areas (Nash, D. J. *et al.*).

2.3.6.3. Usefulness of the simulation

Hydrodynamic simulation provides a spatially integrated representation of flow processes in Lake Sahambavy, enabling analysis of velocity, depth, and elevation gradients that are difficult to capture through field measurements alone. It also allows the evaluation of contrasted hydrological scenarios, including variations in inflow, water levels, and bed morphology. As such, the model constitutes a key prospective tool for anticipating hydro-sedimentary evolution, identifying erosion- and sedimentation-prone areas, and supporting sustainable water resource management of Lake Sahambavy.

2.4. Data analysis
2.4.1. Analysis of the simulated velocity field
2.4.1.1. Flow direction and momentum

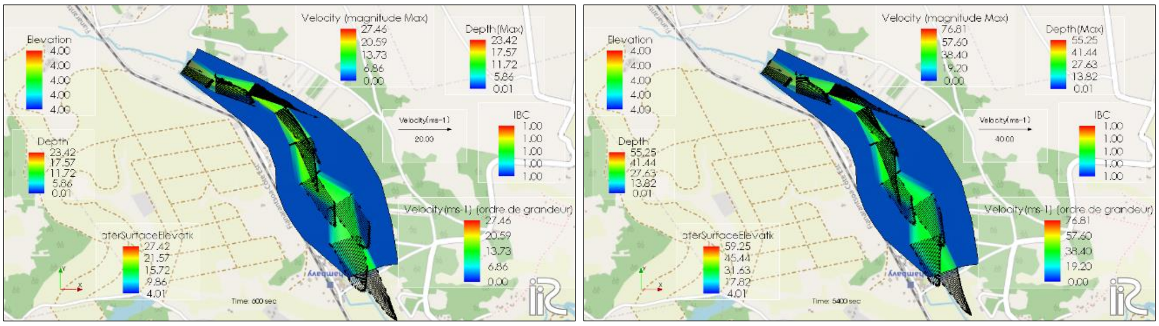
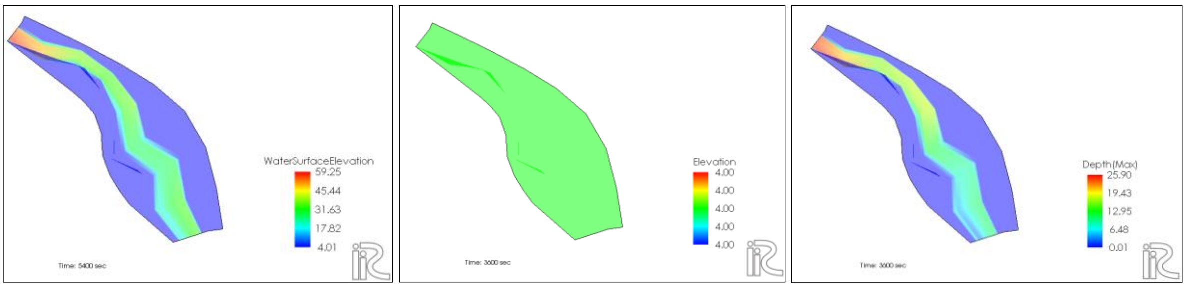


Fig 5 : Flow direction and momentum distribution

Figure 2.5 illustrates the flow direction and spatial distribution of momentum in Lake Sahambavy. Velocity vectors show a circulation mainly oriented along the longitudinal axis of the lake, reflecting preferential flow controlled by the elongated morphology and by inflow and outlet conditions. Momentum values are higher in the central and longitudinal zones, where velocities are maximal, indicating greater kinetic energy transfer that favors suspended sediment transport and limits local deposition. In contrast, peripheral and wider zones exhibit lower momentum, corresponding to calmer conditions conducive to fine sediment settling. Spatial variations in momentum intensity reflect the combined influence of bathymetry, friction, and hydrodynamic forcing, highlighting gradients that influence mixing processes and nutrient distribution. Overall, lake circulation is dominated by a structured axial flow with marked contrasts between the central channel and marginal zones, with direct implications for hydro-sedimentary processes and water quality.

2.4.2. Analysis of Elevation and Depth
2.4.2.1. Analysis of Water Surface Elevation



(a) Water Surface Elevation **(b) Bed Elevation** **(c) Maximum Depth**

Fig 6 : Elevation and depth values in Lake Sahambavy

Amplitude and elevation gradient

Figure 2.6 shows the spatial distribution of water surface elevation and depth in Lake Sahambavy. Water surface elevation (Figure 2.6a) exhibits low spatial variability, indicating a limited elevation amplitude and a globally stable hydraulic regime. However, moderate longitudinal elevation gradients along the lake axis generate sufficient hydraulic head to sustain internal circulation. Bed elevation patterns (Figure 2.6b) are consistent with basin morphology, while maximum depth (Figure 2.6c) is concentrated in the central longitudinal zone, with shallower marginal areas. This bathymetric configuration locally controls elevation gradients and velocity fields, influencing circulation, sedimentation, and nutrient distribution in Lake Sahambavy.

Flow dynamics and hydraulic behavior

The combined analysis of elevation and depth indicates a hydraulic behavior dominated by preferential longitudinal flow in Lake Sahambavy. Deeper central zones exhibit more active circulation driven by elevation gradients, whereas shallow peripheral areas show weaker gradients and reduced dynamics, functioning as energy dissipation and sediment deposition zones. This configuration typifies a slow-circulation lacustrine system, with direct implications for mixing processes, nutrient distribution, and morpho-sedimentary evolution.

2.4.2.2. Analysis of bed elevation

Amplitude and elevation gradient

Bed elevation in Lake Sahambavy shows low overall amplitude but perceptible longitudinal gradients aligned with the main lake axis. These moderate gradients act as the primary hydraulic driver of internal circulation, with local amplification controlled by basin geometry, thereby structuring observed velocity fields.

Channel topography and morphodynamics
The alternation of deep central zones and shallow marginal areas reflects an elongated and sinuous lake morphology. High-energy central zones favor erosion and channel maintenance, while low-energy margins promote sediment accumulation, indicating an active morphodynamic balance between longitudinal erosion and lateral deposition.

Hydrodynamic interpretation in meanders
In meander sectors, elevation and depth asymmetry induces flow acceleration along outer banks and reduced velocities along inner banks. This promotes lateral sediment transfer, with erosion on outer banks and deposition on inner banks, driving the morphological evolution of Lake Sahambavy.

Implications for water level
Overall low elevation amplitudes indicate a globally stable water level in Lake Sahambavy. However, channel constrictions and meanders may induce localized water-level increases, influencing riparian inundation, bank submergence, habitat distribution, and hydraulic management.

2.4.2.3. Analysis of flow depth

Depth amplitude and spatial distribution
Lake Sahambavy bathymetry exhibits strong spatial heterogeneity, with maximum depths along the central longitudinal channel and shallower peripheral zones. Depth variations are accentuated in constricted and curved sections, reflecting direct hydrodynamic control.

Hydro-morphological correlation
Depth, elevation, and velocity fields are strongly correlated: deep zones coincide with higher velocities and momentum, indicating enhanced erosive capacity, while shallow areas favor sediment accumulation. This reflects a dynamic equilibrium between flow, sediment transport, and channel geometry.

Flow dynamics and meander evolution
In meanders, deeper outer-bank zones are associated with higher velocities and erosion, whereas shallow inner banks favor sedimentation. This asymmetric organization suggests slow meander migration and continuous sediment redistribution, influencing bank stability, channel configuration, and ecological dynamics in Lake Sahambavy.

2.4.3. Upstream velocity conditions

2.4.3.1. Nonlinear hydrodynamic relationship

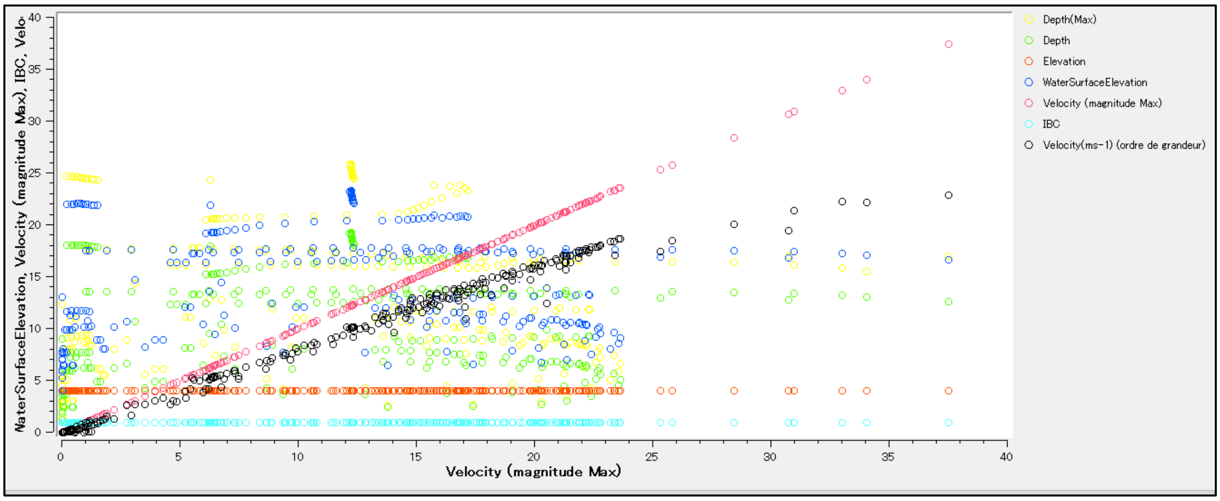


Fig 7 : Nonlinear relationship between velocity and depth, actual velocity, and spatial overlay of Lake Sahambavy

Figure 2.7 shows a nonlinear relationship between flow velocity and depth in Lake Sahambavy. Maximum velocities occur at intermediate depths, reflecting a balance between bottom friction in shallow zones and energy dissipation in deeper areas. Shallow zones exhibit low velocities, while the deepest zones show velocity attenuation due to stratification effects. Discrepancies between theoretical and simulated velocities confirm the nonlinear, spatially variable influence of bathymetry, channel geometry, and meanders. This behavior controls sediment transport, mixing processes, and the localization of erosion and deposition zones in Lake Sahambavy.

2.4.3.2. Data aggregation and model validation

Model validation was performed by jointly analyzing simulated velocity, depth, and elevation fields and comparing them with available observations from Lake Sahambavy (Rabotovao, D. S. *et al.*). The results show satisfactory agreement between simulations and field trends, confirming the ability of the IRIC model to reproduce the main hydrodynamic characteristics of the lake. This validation supports the use of the model as a reliable decision-support tool for hydro-sedimentary analysis and sustainable lake management.

2.4.4. Analysis of downstream velocity conditions

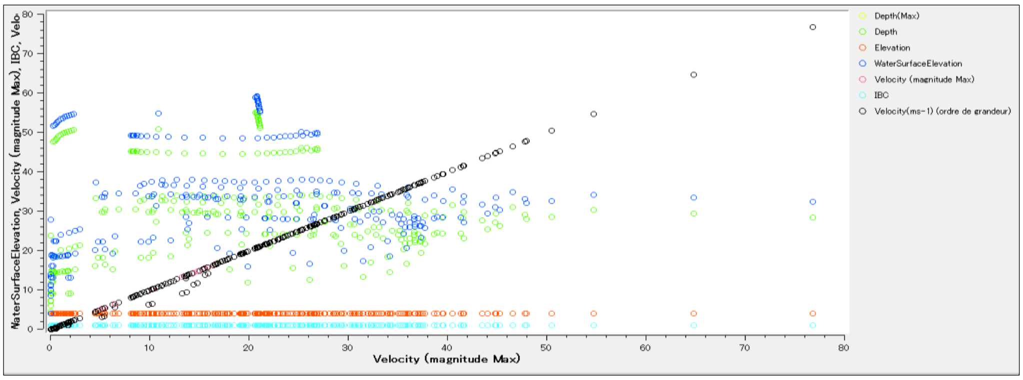


Fig 8: Downstream velocity conditions of Lake Sahambavy

Figure 2.8 shows a marked increase in flow velocities downstream of Lake Sahambavy, reflecting the transition from a lacustrine to a fluvial regime at the lake outlet. Flow acceleration is controlled by channel narrowing and increased hydraulic gradient, with high velocities concentrated along the central axis and lower velocities near the banks. Shear zones near the margins indicate potential erosion areas. Overall, the lake acts as an upstream energy dissipation zone followed by rapid hydrodynamic reorganization, with implications for sediment transport, downstream morphology, and flood and erosion risk management.

2.4.4.1. Correlation between hydraulic variables

Joint analysis of velocity, depth, free-surface elevation, and momentum in Lake Sahambavy reveals predominantly nonlinear relationships. Velocity is positively correlated with momentum, especially along the central channel and constricted zones. Maximum velocities occur at intermediate depths, highlighting the influence of channel geometry and meanders. Elevation gradients act as the main hydraulic driver of flow acceleration, particularly at the outlet. High-energy zones coincide with deeper, morphologically stable areas, while low-energy zones favor sediment accumulation (Rabotovao, D. S. *et al.*).

2.4.4.2. Model performance and verification of boundary conditions

Model evaluation shows good agreement between simulated and observed velocities, depths, and water surface elevations in Lake Sahambavy, confirming reliable reproduction of overall hydrodynamic behavior (FAO, 2022). Verification of inflow, outflow, and lateral boundary conditions indicates coherent energy transfer without numerical artifacts. These results confirm the robustness of the model for analyzing velocity distribution, momentum, and morphodynamic processes.

2.4.5. Depth conditions: interrelationship with velocity and elevation

Depth plays a key role in controlling hydrodynamic behavior in Lake Sahambavy by regulating velocity distribution, elevation gradients, and sediment transport capacity. The combined analysis of depth, velocity, and free-surface elevation highlights strong interactions between bed morphology and flow dynamics, enabling identification of zones with pronounced hydraulic contrasts and implications for morphodynamic stability (Yuen, K. W., Hanh *et al.*).

2.4.5.1. Depth–velocity correlation

2.4.5.1. Depth–velocity correlation

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2. harmonize terminology across all figures and sections, or
3. prepare a strong Conclusion & Perspectives section aligned with your results.

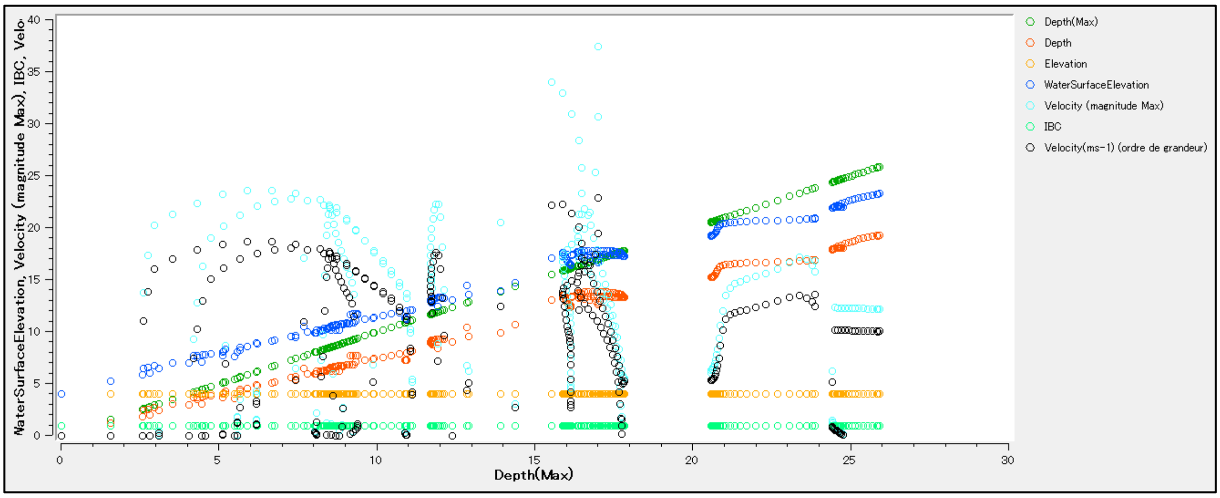

Fig 9 : Distribution of depth and velocity in Lake Sahambavy

Figure 2.9 shows that maximum velocities in Lake Sahambavy occur mainly at intermediate depths rather than in the deepest zones, confirming a nonlinear depth–velocity relationship. Shallow areas exhibit low velocities due to strong friction, while deeper zones show moderated velocities, reflecting a more regulated flow regime. This pattern highlights the dominant control of channel morphology on flow dynamics and hydraulic energy distribution at the lake scale.

2.4.5.2. Consistency between water surface elevation and boundary conditions

Simulated water surface elevations in Lake Sahambavy are consistent with inflow, outflow, and lateral boundary conditions, accurately reproducing hydraulic head gradients without numerical artifacts. This consistency confirms that the boundary conditions reliably represent lake functioning and allow robust analysis of hydrodynamic and morphodynamic processes, including water-level variations and momentum transfer.

3. Results and Discussion

3.1. Hydrodynamic modeling for sustainable water resource management in Lake Sahambavy

Hydrodynamic modeling successfully reproduces the spatial distribution of velocity, depth, free-surface elevation, and momentum in Lake Sahambavy, highlighting high-energy zones, sedimentation areas, and gradients controlling sediment and nutrient transport. The integration of these results into management strategies supports anticipation of water-level changes, erosion control, and optimization of aquatic uses. Overall, the model provides a robust decision-support framework for sustainable water resource management, balancing ecological conservation, resource use, and hydrological risk prevention.

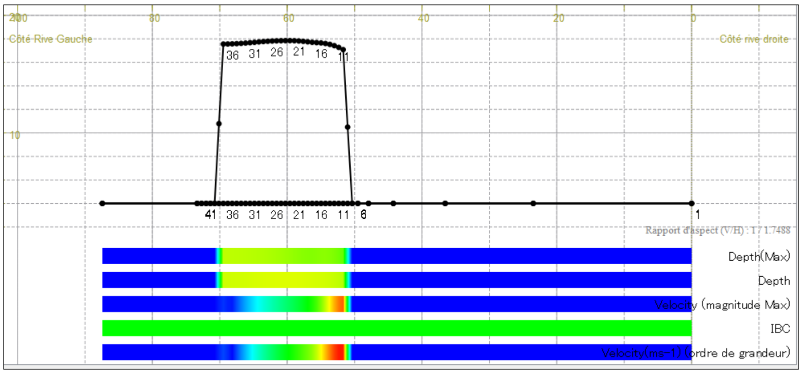

Fig 10 : Physical variables along a cross section of Lake Sahambavy

The transverse section of Lake Sahambavy reveals a deep central channel bordered by shallow lateral zones. Maximum depth is concentrated along the central thalweg, while flow velocity is highest in this zone and decreases toward the banks due to increased friction and reduced depth. This configuration concentrates kinetic energy and suspended sediment transport in the central channel, whereas peripheral zones act as low-energy areas favoring sediment deposition and distinct aquatic habitats, underscoring the structuring role of bathymetry in lake hydrodynamics.

3.1.2. Model limitations and adaptive strategy

The model is limited by its two-dimensional, quasi-stationary formulation, which may underestimate three-dimensional processes such as thermal stratification and secondary circulations, and by uncertainties in bathymetry, boundary conditions, and friction parameters (Rajeshkumar *et al.*). To address these limitations, an adaptive approach combining numerical modeling with regular field measurements and sensitivity analyses is proposed. Progressive data integration and scenario testing enhance model robustness and support sustainable management of Lake Sahambavy.

3.2. Analysis of asymmetric channel topography and hydraulic concentration

3.2.1. Asymmetric channel geometry

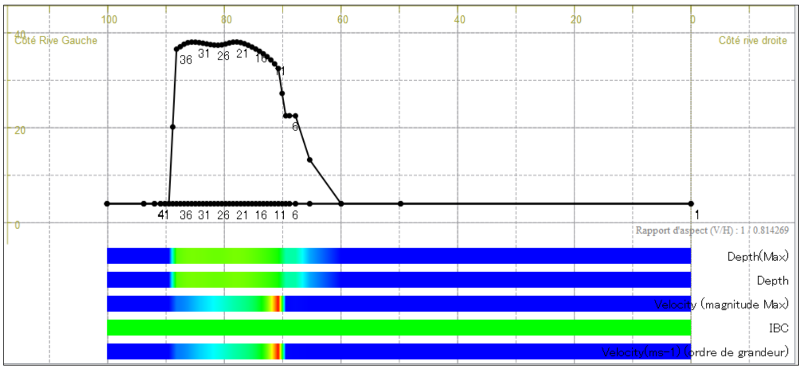

Fig 11 : Topographic profiles of the left and right banks of Lake Sahambavy

3.2.1. Asymmetric channel geometry

The transverse topographic profile of Lake Sahambavy shows a strongly asymmetric channel, with a steep left bank and a gentler right bank. The thalweg is shifted toward the left bank, indicating preferential concentration of hydraulic energy. This asymmetry reflects uneven erosion and sedimentation processes controlled by flow dynamics and bank morphology. High velocities and fine sediment transport dominate the left-bank deep zone, while the right bank forms a low-energy area favorable to sediment deposition and aquatic habitat development.

3.2.2. Hydraulic distribution and flow concentration

Hydraulic distribution in Lake Sahambavy is governed by channel asymmetry, with flow concentrated along the deep left-bank thalweg where velocities and hydraulic energy are highest. Peripheral zones, especially along the gently sloping right bank, exhibit lower velocities due to increased friction and reduced depth. This contrast promotes erosion and depth maintenance in the central channel, while lateral areas favor sediment deposition, nutrient accumulation, and habitat differentiation.

3.2.3. Usefulness of the simulation

Hydrodynamic simulation provides a spatially explicit representation of depth and velocity patterns in Lake Sahambavy, highlighting flow concentration zones, low-energy sectors, and hydraulic gradients linked to asymmetric morphology (Neal, J. C., Shustikova *et al.*). It supports scenario analysis of water-level changes, hydrological inputs, and shoreline modifications, making it a key decision-support tool for anticipating system evolution and ensuring sustainable lake management.

3.3. Analysis of channel cross section and bed elevation

Cross-sectional analysis is essential for linking bed morphology and flow dynamics in Lake Sahambavy. It characterizes channel geometry, depth distribution, and transverse hydraulic contrasts, helping to identify flow concentration mechanisms, bank asymmetry, and their role in the morphodynamic evolution and overall functioning of the lake.

3.3.1. Geometric profile and hydraulic representation

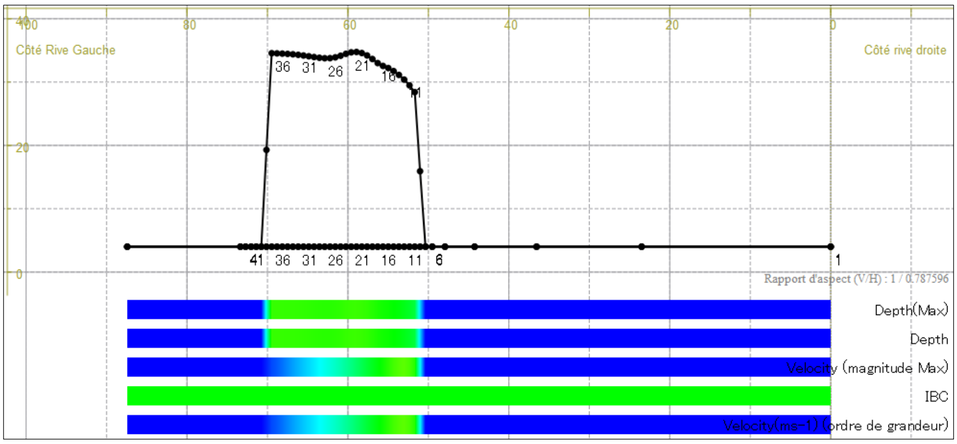

Fig 12 : Transverse cross section of the watercourse and bed elevation in Lake Sahambavy

The transverse cross section of Lake Sahambavy shows an asymmetric geometry with a well-defined central channel marked by minimum bed elevation and maximum depth, while the margins display steeper slopes toward shallower areas. This morphology reflects a preferential flow axis maintained by erosion in the central channel, whereas lateral zones are dominated by sediment deposition. Hydraulic variables are consistent with this structure: highest velocities occur in the deepest central zone, indicating enhanced sediment transport capacity, while reduced velocities near the banks favor fine sediment settling and lateral bed aggradation. This coupling between bed geometry and flow dynamics is characteristic of fluvio-lacustrine hydrosedimentary systems.

3.3.2. Bed morphology and flow dynamics

Bed morphology in Lake Sahambavy is controlled by the balance between erosion in the deep central channel, where flow energy and velocities are highest, and sedimentation along the margins, where flow decelerates. This configuration promotes channel depth maintenance in the center and progressive elevation of lateral beds, governing the spatial and temporal evolution of flow dynamics and sediment distribution within the lake.

4. Lake management policy for agricultural efficiency

The discharge structures at Lake Sahambavy artificially regulate the hydrological regime to support agricultural water supply, but their performance is highly sensitive to extreme climatic conditions. During the cyclonic season, intense rainfall and runoff induce rapid changes in water levels, discharges, and erosion–sedimentation dynamics, increasing the risk of overtopping and structural failure. Hydraulic and hydrological simulations, particularly under cyclonic flood scenarios, are therefore essential to anticipate system response, optimize discharge management, and ensure a balance between infrastructure safety, agricultural productivity, and the ecological stability of Lake Sahambavy.

Fig 13 : Water discharge management toward agricultural land

Fig 14 : Water dam system for storage in Lake Sahambavy

The dam system at Lake Sahambavy regulates water storage and stabilizes lake levels for downstream agricultural supply but modifies the natural flow regime by increasing water residence time, thereby enhancing sedimentation and hydraulic stratification. During intense rainfall and cyclonic floods, inadequate control of storage capacity may lead to overtopping or structural stress, making hydrological and hydraulic simulations under extreme-event scenarios essential to optimize management rules, anticipate flood peaks, ensure dam safety, and support the long-term sustainability of the lake.

Fig 15 : Water level of Lake Sahambavy during normal season and rainy period

The images show seasonal water-level variations in Lake Sahambavy, with higher levels during the rainy period due to increased direct precipitation and watershed runoff, altering the balance between storage, evaporation, and controlled discharge. While this variability is natural, intense or cyclonic rainfall can raise overtopping and shoreline inundation risks, highlighting the need for hydrological water-level modeling to anticipate critical thresholds, optimize dam operation, and ensure safe and effective lake regulation.

Fig 16 : Potential lake expansion areas of Lake Sahambavy

The identified areas represent potential expansion zones of Lake Sahambavy, functioning as natural hydrological buffers during seasonal water-level rise. These zones temporarily store excess water during the rainy season, dissipate hydraulic energy, and influence infiltration and sedimentation, thereby limiting rapid lake-level increase and overtopping risk. However, their buffering capacity under intense or cyclonic rainfall remains uncertain, underscoring the need for hydrodynamic simulations integrating topography, floodable areas, and extreme-event scenarios to support safe and sustainable lake management.

Fig 17 : Current cultivated land with the three existing drainage outlets

The images depict the cultivated areas surrounding Lake Sahambavy, organized around three drainage structures that regulate soil moisture in agricultural plots. Hydrological and climatic simulations enable anticipation of flooding and water deficits, optimization of drainage according to crop stages, and reduction of flood-related losses during intense rainy or cyclonic periods. By integrating extreme-event scenarios, modeling supports yield security, limits soil degradation, and promotes sustainable agricultural land management around the lake.

5. Conclusion

This study highlights the contribution of two-dimensional hydrodynamic modeling to understanding and predicting the behavior of Lake Sahambavy, located in Fianarantsoa, Madagascar. Using the IRIC numerical simulation software, the analysis integrated the geo-hydrological, climatic, and morphological characteristics of the lake, as well as the effects of transient boundary conditions and hydraulic roughness parameters. The simulations enabled a detailed representation of the spatial distribution of velocities, depths, and water surface elevations, revealing strong hydrodynamic heterogeneity related to bed topography, asymmetric channel geometry, and meandering zones.

The results reveal nonlinear hydrodynamic behavior between upstream and downstream areas, with flow concentration zones particularly sensitive to erosion and sedimentation processes. Analysis of transverse sections and bed elevation highlights the decisive influence of morphology on flow dynamics and lake water-level variations. Despite certain limitations related to data availability and modeling assumptions, this study demonstrates the relevance of the IRIC software as a decision-support tool for the sustainable management of Lake Sahambavy. It opens perspectives for improving water resource management strategies, enhancing hydrological risk prevention, and integrating future scenarios of climate variability and land-use change.

6. References

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