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Special Series

Nature-based solutions for improving navigation reliability on the Madeira River, Brazil

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EDITOR'S NOTE:

This article is part of the special series "Incorporating Nature-based Solutions to the Built Environment." The series documents the way in which the United Nations Sustainable Development Goal (SDG) targets can be addressed when nature-based solutions (NBS) are incorporated into the built environment. This series presents cutting-edge environmental research and policy solutions that promote sustainability from the perspective of how the science community contributes to SDG implementation through new technologies, assessment and monitoring methods, management best practices, and scientific research.

Abstract

The Madeira River Navigation and Improvement Project provides a unique opportunity to incorporate nature-based solutions (NbS) into the built environment to promote sustainable communities and water resources infrastructure. The Madeira River has no major physical interventions (river training structures, navigation locks and dams, etc.) to improve navigation, and so is one of the world's last remaining undeveloped megarivers that exhibits natural morphological processes. The objective of this study is to create a safe, reliable, and sustainable navigation channel in the Madeira River. This is being accomplished by designing navigation improvement measures that leverage natural geomorphic processes of the river while minimizing conventional engineering practices that alter the river's morphology. To meet this objective, fluvial geomorphology analysis and hydrodynamic modeling studies have been performed to improve understanding of the morphological behavior of the system. Measures that incorporate beneficial reuse of dredged sediment within the system are being prioritized and incorporated into the study's design. Natural processes are being leveraged through the implementation of an adaptive management process to shape the navigation channel by incorporating the use of dynamic structures using natural local materials (e.g., large woody debris already in the system), a direct application of NbS in practice. This process includes extensive stakeholder collaboration and utilizing nature's energy to balance navigation, ecological, and social benefits along the Madeira River. This project demonstrates that nature-based approaches not only provide navigation benefits but can also provide ecological and social benefits in ways that are sustainable in the long term, consistent with United Nations Sustainable Development Goals (SDGs) and the International Union for the Conservation of Nature's global standard for NbS. *Integr Environ Assess Manag* 2021;00:1–8. © 2021 SETAC. This article has been contributed to by US Government employees and their work is in the public domain in the USA.

KEYWORDS: Adaptive management, Engineering with Nature, Madeira river, Nature-based solutions, Navigation

INTRODUCTION

The Madeira River is one of the world's last remaining undeveloped megarivers and exhibits natural morphological processes including avulsions, lateral migration within a Holocene valley, formation and erosion of islands, downstream migration of meanders, among other natural riverine processes (Gibson et al., 2019; Latrubesse, 2008). Unlike many navigation channels in developed countries, the 1080-km Madeira River has no major physical interventions (river training structures, navigation locks and dams, canals, dredging, revetments, or rock excavation) to improve navigation for shipping over 10 million tonnes of commodities annually (e.g., corn, soy, and petroleum; ANTAQ, 2019).

The Madeira River is the Amazon River's largest tributary in terms of average annual discharge (Q_{avg} =

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FIGURE 1 Barge strike observed at Baianos, Brazil in 2016 illustrates the current hazards to navigation on the Madeira River

19 000–25 000 m^3/s), sediment load ($Q_{sed(annual)} = 450–600$ million tonnes), and contributing drainage area (1.45 million km^2). The river is typically 1200 m wide bank-to-bank and is geologically incised—accessing its floodplain only in events that exceed a 50-year recurrence interval (Gibson et al., 2019). The Madeira River provides year-round shallow draft navigation, yet there are several reaches that currently have inadequate channel depth during the low flow season or have rocky outcrops that create a navigational hazard (-Figure 1). Currently, dredging is the primary measure used to improve navigation, but this measure alone has been expensive and largely ineffective due to the dynamic nature of the system. During low water levels, navigation depths are limited at these reaches and barge companies must reduce volumes of commodities transported in each barge convoy via a reduced number of barges and reduced volume of cargo in each barge (a term called light-loading; Creech et al., 2018). The current state of light-loading results in higher emissions and costs to the navigators due to the increased number of round trips necessary to transport commodities during the low-water conditions.

To address this challenge, the overall goal of the Madeira River Navigation Improvement Project is to design and implement measures that improve navigation sustainability between Porto Velho, Rondônia and the confluence with the Amazon River near Itacoatiara, Amazon as—a distance of 1080 km (Figure 2). A partnership between the Brazilian Department of Transportation Infrastructure (DNIT) and the US Army Corps of Engineers (USACE) was developed in 2016 to incorporate international expertise in this project. The approach leverages the natural geomorphic processes (working with nature, rather than resisting these processes), while providing increased economic opportunities along the river. This is being accomplished through a variety of hydrodynamic modeling studies to first understand the morphological behavior of the system (Creech et al., 2018). Measures that incorporate nature-based solutions (NbS) include opportunities for beneficial reuse of both large woody debris and sediment within the system are being prioritized and incorporated into the study. Innovative river training structures are being incorporated into the design process to harness the river's energy while reducing overall impacts to its natural state and incorporating habitat features. In addition, the project goals were accomplished through a proactive and meaningful stakeholder engagement process and leveraging an adaptive management strategy that will allow natural evolution processes and the implemented measures to shape the navigation channel well into the future.

There is growing evidence for how NbS strategies produce economic, environmental, and social benefits while reducing the impacts of anthropogenic stresses imposed on the natural environment (Oen, 2019). In one of the few relevant studies found that addressed an application of NbS in free-flowing rivers (FFRs), Corum et al. (2019) combined a high river flow reconnaissance and results from a literature review to evaluate the impacts of large wood (LW) on Madeira River ecology and navigation. The authors found that the forest-river edge is heavily utilized by fish and wildlife. Trees and LW, originating both locally and from upstream sources, are fundamental components of this aquatic terrestrial transition zone (Junk et al., 2012), contributing meaningfully in bank erosion, island, and floodplain building processes. Corum et al. concluded that attempts to limit the amount of LW in the river or the river's ability to migrate LW over long reaches would be cost prohibitive and have incalculable ecological impacts, highlighting the need to implement NbS rather than conventional aids to navigation in this FFR.

A FFR has been defined as "rivers where ecosystem functions and services are largely unaffected by changes to the fluvial connectivity, allowing unobstructed movement and exchange of water, energy, material, and species within the river system and with surrounding landscapes" (Grill et al., 2019). Fluvial connectivity encompasses longitudinal (river channel), lateral (floodplains), vertical (groundwater and atmosphere) and temporal (intermittency) components. These elements can be compromised by physical infrastructure in the river channel, along riparian zones or in adjacent floodplains (consistent with findings of Corum et al., 2019); hydrological alterations of river flow due to water abstractions or regulation; and changes to water quality that lead to ecological impacts caused by pollution or altered water temperatures (Grill et al., 2019). These factors were considered when developing NbS for the Madeira River project.

The project team is integrating NbS into the design of the navigation infrastructure elements as discussed in the previous paragraph, consistent with the Working with Nature (WwN) philosophy created to foster development of sustainable inland waterways. WwN promotes an integrated planning and design process, seeking to utilize the ecosystem's natural processes to produce positive environmental outcomes, while supporting the delivery of navigation project goals (PIANC, 2008). Applying WwN principles produces

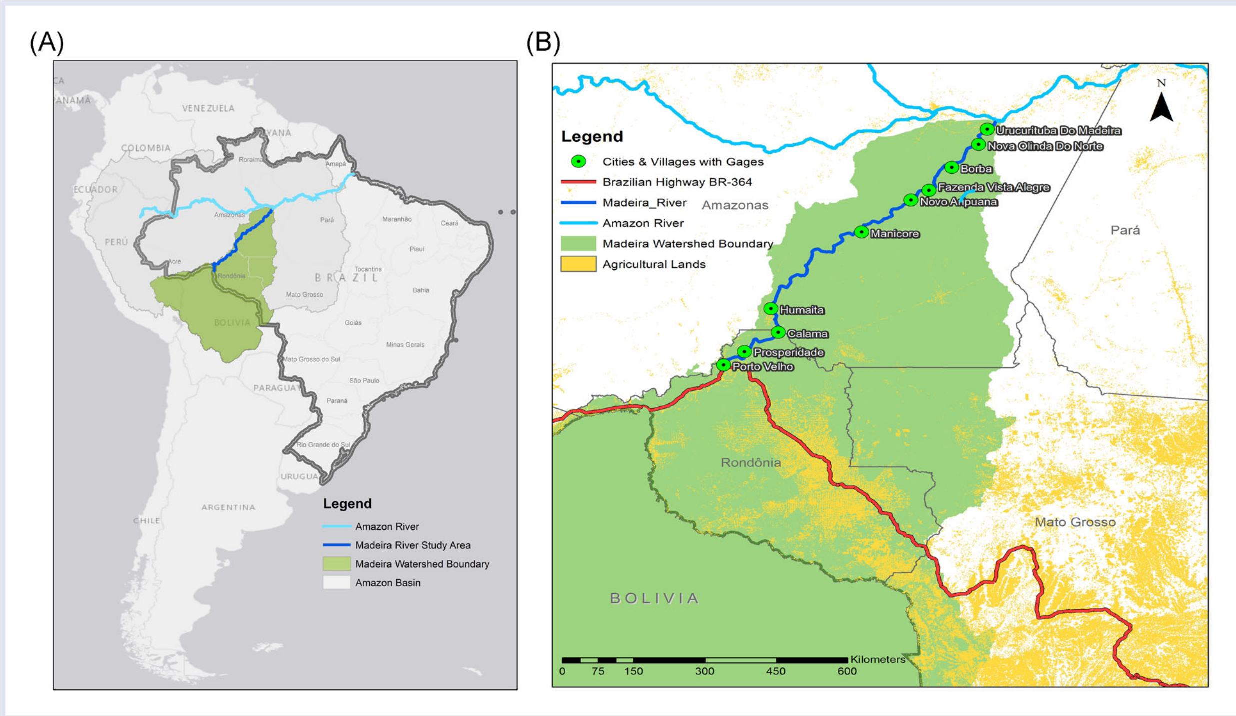

FIGURE 2 Location of the Madeira River within South America and the Amazon Basin (left) and the study area between Porto Velho and the Amazon River (right)

project outcomes that are designed to contribute to ecosystem enhancement. Specifically, WwN considers project objectives in the context of the ecosystem and intentionally designs the project to use natural processes to achieve project goals while yielding multiple economic, social, and environmental benefits. Building with Nature (BwN), managed by the public–private innovation program EcoShape in The Netherlands and the Engineering with Nature® (EWN®) initiative launched by the USACE are applying approaches that are consistent with the WwN philosophy (Bridges et al., 2014, 2018, 2021; de Vriend & van Koningsveld, 2012; Foran et al., 2018; IADC, 2010; PIANC, 2008, 2018).

The overall objective of this paper is to document how NbS are being incorporated into the planning and design phases of the Madeira River project, so that sustainable measures can be effectively implemented during the project construction and monitoring phases. Such implementation will help preserve the free-flowing aspects of the river, maintain current environmental benefits, and enhance the region's economy.

INTEGRATING NBS INTO PROJECT PLANNING AND DESIGN

Stakeholder engagement

Stakeholder involvement was an integral part of the infrastructure planning process from the outset to work towards providing solutions to address shallow draft navigation challenges on the Madeira River. A key part of this process was to host a 3-day charette with stakeholders representing various interests of the Madeira River. The charette brought together stakeholders to identify and discuss navigation challenges on the Madeira River, to identify potential solutions to address them, to build a shared understating of the issues and an understanding of the path forward. River engineering experts from the United States and Brazil collaborated with the navigators of the Madeira River to confirm the critical navigation locations in the system. The critical navigation locations were prioritized based on size, level of restriction (is the navigation shoal creating the need to light-load during the low-water season) and navigation safety. The information gained during the charette improved the overall project as the values and opinions expressed by the participants were included in the overall infrastructure project design. Participating stakeholders included the transportation ministry, dredging contractors, navigation contractors, private company consortium, transportation companies, and river engineering experts from the USACE.

The goals and expectations of the charette as articulated by the 30 participants included: Identifying both short- and long-term innovative solutions; implementing solutions that enable productive navigation year-round while ensuring navigation safety; improving planning, coordination, and communication among stakeholders; and developing solutions that are implementable, broadly applicable, and that work with nature.

The approach for developing innovative solutions was constrained by several factors, including achieving environmental regulator acceptance and maintaining or enhancing existing

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transportation of local residents. Taken together, these factors shaped the planning and design phases of the project.

The next step in the charette consisted of identifying several measures that could be implemented by the Brazilian National DNIT to develop several alternative plan solutions that met project objectives. The selected plan solution consists of constructing dynamic river training structures, dredging all remaining sand shoal sites annually, excavating rock at select reaches, and installing aids to navigation along the entire navigation channel. Through the stakeholder engagement process the team was able to identify and subsequently implement the recommended infrastructure designs to advance the overall planning study for the purpose of improving navigation reliability and safety on the Madeira River waterway.

This process included extensive stakeholder collaboration in Porto Velho (local scale), Manaus (regional scale), and Brasília (national scale). Through this engagement the implementation of natural and nature-based features was prioritized into the design. These features utilize nature's energy to balance navigation, ecological, and social benefits along the Madeira River. This project demonstrates that nature-based approaches not only provide the needed navigation benefit but can also provide ecological and social benefits in ways that are sustainable in the long term, consistent with United Nations Sustainable Development Goals (SDGs; SDG 6 Clean Water and Sanitation; UN 2019) and the International Union for the Conservation of Nature (IUCN) standard for implementing NbS (IUCN, 2020).

Working with Nature

A reconnaissance trip of the Madeira River was conducted by the Brazilian Navy, DNIT, USACE, and the Brazilian Geological Survey (CPRM) to perform an initial evaluation of the conditions of the river by navigating the length of the authorized navigation channel from Porto Velho to the Amazon River (Corum et al., 2019). The site reconnaissance team was afforded the opportunity to observe firsthand the variety of navigation challenges including eroding banklines, areas of sediment deposition in the channel, and unreliable navigation channel aids. This information greatly improved both the understanding of the system and the designed measures to improve the reliability of the navigation channel.

Armed with this information, hydraulic modeling was conducted using the one-dimensional hydraulic model (Hydrologic Engineering Center–River Analysis System) (Creech et al., 2019; HEC, 2016) that was used as input into two one-dimensional sediment transport models: One to inventory existing sediment conditions and forecast future without project conditions; and a second to analyze physical responses of the Madeira River to proposed alternatives aimed to improve navigation reliability (Table 1). A multidimensional hydrodynamic model of built structural features (river training structures, etc.) was developed at site-specific locations to analyze alternative designs identified during the charette and sediment transport modeling results to improve navigation reliability (see e.g., Figure 3). The hydrodynamic model was used to refine alternatives by optimizing alternative structure layouts in the river, and to evaluate hydrodynamic impacts associated with the proposed river training structures. In addition to the structural alternatives, the hydrodynamic simulation results were compared to the existing conditions to determine benefits to maneuverability and navigation conditions due to the proposed improvements to the system.

The output from the model runs were critical to informing ways in which the project team could pursue opportunities

TABLE 1 Approaches used in the two Hydrologic Engineering Center–River Analysis System (HEC-RAS) models to calculate the low water reference plane for the Madeira River, Brazil

Component	Porto Velho to Manicoré	Manicoré to Amazon River
Software	HEC-RAS	HEC-RAS
Modeling approach	Steady	Unsteady
Length (km)	640	430
Downstream boundary condition	Manicoré rating curve	Daily stage at Iracemá Gage (15042200) on the Amazon River
Upstream discharge	90% exceedance discharge at Porto Velho (4308 cms)	Daily discharge record at Manicoré
Period of record	1961–2019 for statistical hydrology (discharge). 2010–2019 for rating curve at Manicoré. Only recent data used in rating curve due to trend of aggradation at the downstream gage	2014–2019
Tributary inflows	Three major tributaries. Differences between low flows at gages assigned to tributaries	One major tributary (Aripuanã River). Daily difference between Fazenda Vista Alegre and Manicoré applied to tributary location
Manning's n	0.028 (channel)/0.080 (overbanks)	0.026 to 0.028 (channel)/0.080 (overbanks)
Model time step	Not applicable	15 min

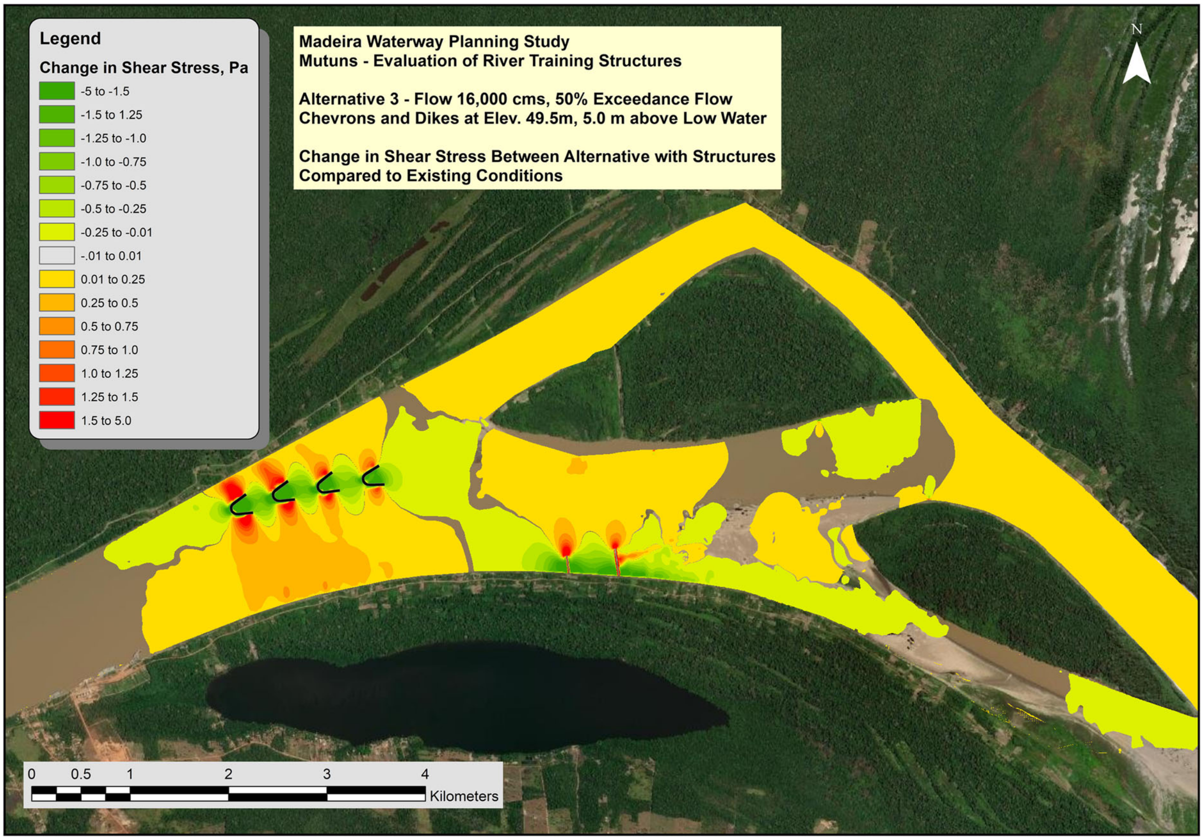

FIGURE 3 Illustrative example of the use of innovative river training structures to provide for a more sustainable navigation channel at Mutuns reach of the Madeira River. The series of chevrons pointed upstream concentrate the river flow into the main channel while reducing erosion along the bankline. The structures also create bottom relief, thereby enhancing fishery habitat downstream

to work with nature by leveraging natural geomorphic processes (Creech et al., 2021). Measures identified included the use of large woody debris that is in natural abundance in the river for the construction of palisades and temporary training structures, the beneficial use of sediments dredged to maintain the navigation channel, utilizing rocks excavated to reduce underwater strike hazards, and the use of innovative river training structures (Figure 3).

Large wood. The Madeira River is known for its large amounts of wood being naturally transported in the river (the word "madeira" is Portuguese for "wood"). Multiple reaches of the Madeira River occur in a Pleistocene era valley that is sufficiently wide to allow a high sinuosity of the river and high bank erosion rates, resulting in an active river evolution and navigation challenges during low water levels. This offers multiple opportunities to engineer with nature, as LW readily available in the river can be used to construct wooden pile dikes or palisades to reduce flow, thereby transforming erosional zones into depositional zones, or to stabilize the banks where erosion threatens the resiliency of the communities residing behind them. As noted by Corum et al. (2019), LW plays a meaningful role in the ecology of the river so sustainable solutions inherently utilize the LW as a natural resource. This design approach is proposed at the largest critical navigation site known as Curicacas near the village of Prosperidade (Figure 2).

Beneficial use of dredged material. Sediments depositing in the navigation channel due to shoaling may be used beneficially during dredging to create island habitat. Alternatively, plans include placing dredged sediment at a given location, configuration, and elevation to serve as a berm or sill restrict or direct flow where desired. The beneficial use options being considered share the common sustainability objective of keeping the sediment in the system, a NbS and a key element of EwN (see Bridges et al., 2018, pp. 86–89 and 90–93).

Innovative river training and stabilization structures. These structures are being designed and constructed to reduce shoaling in select reaches in a manner that does not adversely affect bankline stability nearby. One example would be a notched closure structure (e.g., dike) that includes an open section within the structure to allow continuous passage of river flow, thereby maintaining aquatic habitat with sufficient flushing in the secondary channel. Another example would be constructing a series of chevron training structures (see e.g., Figure 3). These structures utilize the river's energy to maintain navigable depths in the main channel, divert some flow from the main channel towards the wet bankline, and deposit sediment downstream of the chevrons for increased environmental diversity in the reach, which ultimately reduces future dredging requirements. In addition, these structures can be made more sustainable by using local materials to construct them. Such structures have been designed and constructed in the Mississippi River, USA, that sustain the navigation channel while maximizing social and economic benefits and creating diverse natural habitat (see e.g., Bridges et al., 2021, pp. 272–275).

Rock excavation. Rocks as navigation hazards can be safely removed from the bottom of the navigation channel and subsequently reused in the system to stabilize banks or safely placed outside the channel where they can serve as habitat for aquatic species. If rock properties permit, they can be used as construction material for river training structures such as a weir, sill, or dike. Local rock sources such as these have been used to construct permeable structures to split river flow, creating a shallow bench with variable depths and flows to create diverse aquatic habitat (see e.g., Bridges et al., 2021, pp. 152–155).

Using these sustainable measures, the project is employing a clear "win–win" process, as these designs are consistent with the WwN philosophy, creating habitat using locally sourced materials while improving the reliability and sustainability of the navigation channel.

Adaptive management

Maintaining a sustainable navigation project requires incorporating a management approach that is adaptive, that is, builds on lessons learned. These lessons learned are informed by monitoring and data collection program for the system, the specific reach, and other open water rivers. The lessons learned from applying EWN approaches consistent with the WwN philosophy in open rivers in the United States were well-documented so that what was learned, how it was learned, and how the new knowledge can be applied was available knowledge to the project team. Specifically, lessons learned are being integrated into the project by partnership agreement between the DNIT and the USACE and the years of knowledge gained by the USACE incorporating EWN into their river engineering designs. This knowledge is being applied to the Madeira River study so that the multiple benefits of a natural open river combined with enhanced sustainable and reliable navigation can be realized.

The first example of the adaptive management in this project is associated with the prioritization of a waterway

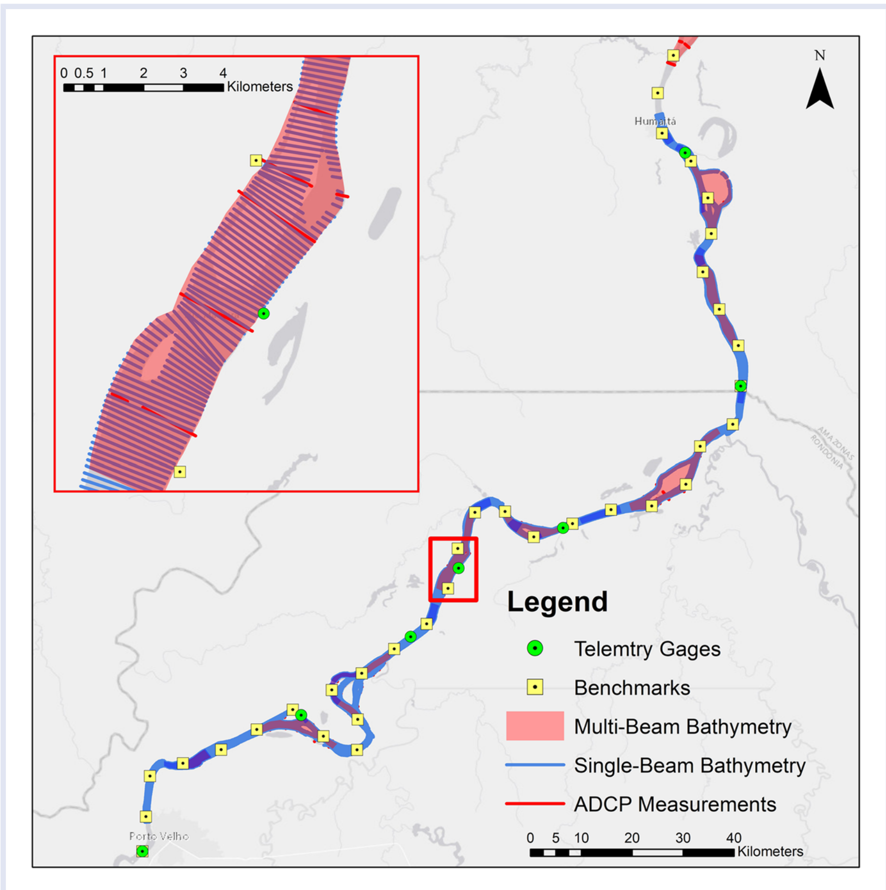

FIGURE 4 Proposed Madeira River waterway monitoring plan between Porto Velho and Humaitá. Monitoring continues downstream to the confluence with the Amazon River

monitoring plan. The limited historic bathymetric, geomorphic, and sediment data resulted in risk to effectively implement permanent solutions that may not optimize cost or environmental benefits. As a result, DNIT developed a 5-year monitoring plan to improve understanding of the permanency of the critical shoals, and to improve understanding of the fluvial geomorphology dynamics in the system. The monitoring plan data collection began in 2021. There are five different types of data being collected: single-beam bathymetry, multibeam bathymetry, Acoustic Doppler Current Profiler (ADCP) measurements, telemetric gages to included stage readings every 15 min, and benchmarks (see Figure 4). As a result, only the low-cost temporary measures associated with the proposed masterplan (including dredging and temporary native materials to provide short term benefits) are currently being implemented in the Madeira River.

The natural processes of the system are being leveraged into an adaptive management process to shape the navigation channel, and incorporates the use of dynamic structures using natural local materials (i.e., large woody debris, rocks, and sediments already in the system), rather than utilizing conventional structures that work against nature—a direct application of implementing NbS in practice. Design plans include a variety of NbS that will retain the natural integrity of the river and create habitat value, while enhancing navigation reliability. Adaptive management is a key to the design phase where continued monitoring of proposed conditions is used to inform proposed implementation of temporary training structures to address morphologically active sites. These locations do not require revetments or permanent structures, and applying natural solutions improved overall efficiency of navigation, reduces construction schedules, and drastically reduces costs.

Incorporating EWN approaches that utilize natural processes consistent with WwN comes with inherent uncertainties, although this project demonstrates how these uncertainties can be managed through application of sound engineering, meaningful stakeholder involvement, and adaptive management principles. The Madeira River project is promoting successful and sustainable outcomes by applying WwN principles in practice, by considering and incorporating WwN at the earliest stages of project development, being consistent with local and regional regulations, combining ecological with social and economic benefits, and seeking broad support from a variety of stakeholders. The Madeira River project is a demonstration of how an open river's natural character is being sustained, while increasing both the navigation reliability and supporting positive economic, social, and environmental values of the region.

CONCLUSIONS

The Madeira River being one of the world's last remaining undeveloped megarivers, exhibits natural morphological processes with no major physical interventions to improve navigation. Though year-round navigation occurs on the Madeira River, navigation is substantially less efficient during the low water conditions due to sand shoals and rock outcrops, necessitating commercial navigators to implement various measures that increase travel time and costs. To address this concern, the Brazilian government initiated studies to identify sustainable solutions for improving navigation reliability on the Madeira River.

The planning process developed for the Madeira River project combines several engineering and technical studies and adaptive management to evaluate the feasibility of implementing various alternative measures. The studies used for evaluating the success of the designs were a statistical hydrology study to define the statistical reliability of channel conditions, a hydraulic model to calculate dredging volumes under a range of scenarios, a fluvial geomorphology study to determine navigation maneuverability for various hydrologic conditions and barge configurations, and a sediment transport model to demonstrate the effectiveness of the river training structure design and to calculate long term maintenance dredging needs. This process involved extensive stakeholder collaboration to identify ways in which the river's natural geomorphology could be used to balance navigation, ecological, and social benefits along the river. NbS identified include use of large wood, innovative river training and stabilization structures, sediment beneficial use, and reuse of rocks obstructing the channel. The results of this study are being used to identify candidate locations for constructing features in future phases of the Madeira River project that will substantially limit dredging needs, while enhancing economic benefits and sustaining the river's ecology in the long term, consistent with United Nations SDGs and the IUCN global standard for NbS.

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CONFLICT OF INTEREST

The authors declare that there are no conflict of interests.

DISCLAIMER

The views and opinions expressed in this paper are those of the individual authors and not those of the US Army Corps of Engineers, US Army Engineer Research and Development Center, or other sponsor organizations. The peer review process for this article was managed by the

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DATA AVAILABILITY STATEMENT

Data available upon request from author Calvin Creech at Calvin.T.Creech@usace.army.mil.

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