Development of a Navigation Channel Coincident Probability Method for Improving Navigation Reliability in a Reservoir Backwater Influenced River, Tocantins, Brazil

Will Veatch, Hydrologist, US Army Corps of Engineers, New Orleans, LA, William.C.Veatch@usace.army.mil
Matt Dircksen, Civil Engineer, US Army Corps of Engineers, Chicago, IL, Matthew.S.Dircksen@usace.army.mil
Ana Luisa Osorio, Engineer, DNIT, Brasília, Brazil, ana.nunes@dnit.gov.br
Renato Amorim, Engineer, DNIT, Brasília, Brazil, renato.amorim@dnit.gov.br
Calvin Creech, PhD, PE, Lead Interdisciplinary Engineer, USACE, Brasília, Brazil, Calvin.T.Creech@usace.army.mil

Abstract

A spatially distributed coincident frequency analysis was developed and applied to determine a project reference plane at a 96% level of navigational reliability for a proposed navigation project on the Tocantins River in Northern Brazil. A rock outcrop navigation impedance, known as the Pedral do Lourenço, is located approximately 50 km downstream of the city of Marabá, in the state of Pará, and 110 km upstream of the Tucuruí Dam. The study reach is a 35 kilometer long section of river influenced by reservoir backwater. Water levels are influenced by the flow from upstream and the reservoir level downstream. Temporal coincidence of low reservoir levels and low river flow result in shallow depths throughout the study reach. The reach of the river where rock outcrops impede navigation includes a subsection where the flow is the dominant variable and reservoir stage is a clear secondary variable, and a subsection where the reservoir level is the dominant variable and the flow is a clear secondary variable. The total probability method and calibrated numerical hydraulic models were used to determine longitudinal water surface profiles for several stage duration targets, e.g. 1%, 4%, 10% of the days exceeded in a year. Then, various recurrence intervals were computed for these duration series, including a 2-year, 10-year, and 25-year recurrence intervals using the normal and Gumbel distributions. Daily reservoir stage records and daily river flow records were used for the corresponding duration and frequency analyses. A calibrated hydraulic model was used to determine the response at selected locations throughout the study area to changing flows and reservoir levels. The coincident frequency analysis determined the water surface profile and required rock removal volumes for desired levels of exceedance and probabilities. The analysis informed decision makers of the relationships between rock removal volumes and probability of desired navigation conditions being met during a year. The method developed and demonstrated here offers a design approach for situations where the relative importance of two coincident variables reverses over the project domain. This is believed to be the first application of this method to a navigation (i.e., low-flow) project design.

Introduction

Project Setting and Context

The Tocantins River originates in the Pireneus Mountains of Brazil, in the state of Goiás near the national capital city of Brasília, and discharges to the Atlantic Ocean near the mouth of the Amazon River. At over 2,600 km of length and an average discharge of over 13,000 m^3/s, the Tocantins is among the world's largest rivers. The Tocantins is navigable over much of its length during high water periods, but during low water, exposed rock outcrops impede navigation in several areas. One of these areas, a 35 kilometer outcrop of basalt and granite known as the Pedral do Lourenço (roughly "Lawrence's rocky place"), is a critical impediment because when impassable, it establishes the upstream limit of navigability on the Tocantins. The Pedral do Lourenço is in the state of Pará, approximately 150 km north of the city of Marabá between river kilometers 350 and 393 (Figure 1). The Pedral do Lourenço is located just upstream (south) of the upper reaches of the Tucuruí Reservoir, one of the world's largest with a volume of over 45 km^3. Therefore, the water surface at this site is not a function of river flow alone, but of river flow along with the downstream boundary condition of the stage in the reservoir.

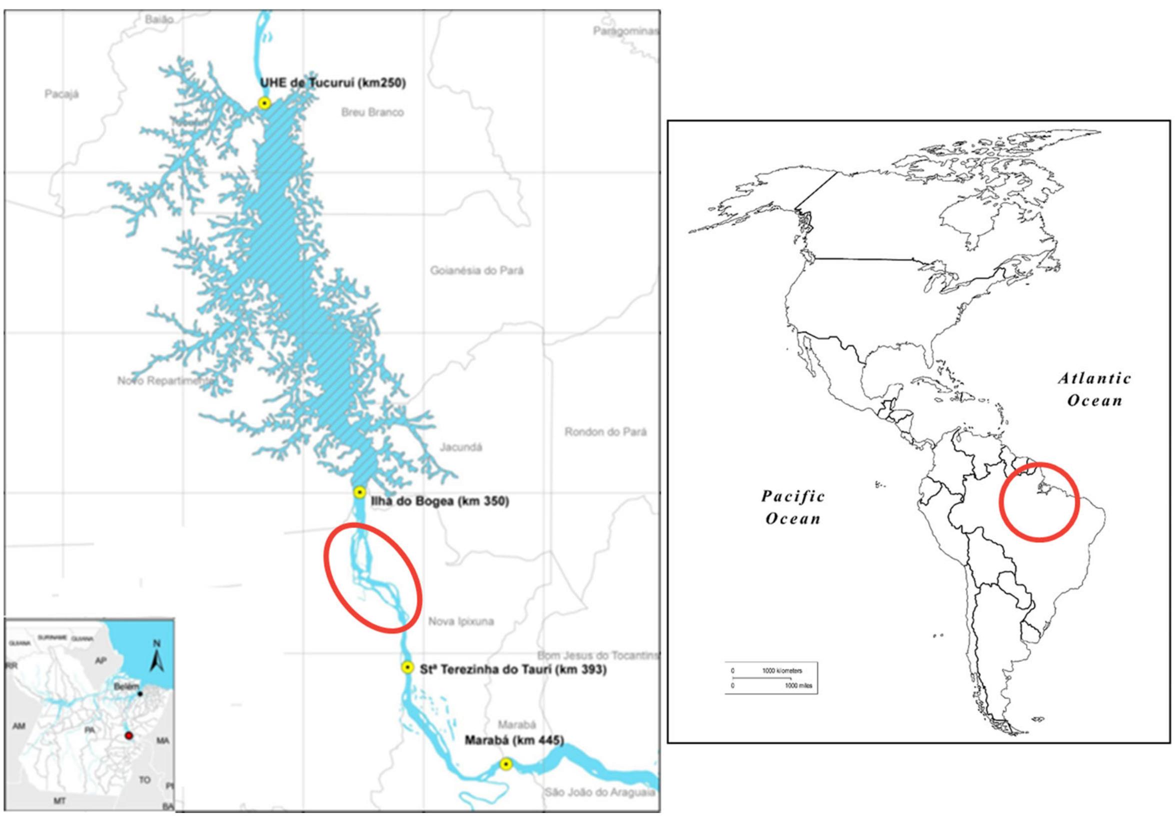

Figure 1. Project site location in State of Pará, Brazil.

The Brazilian National Department of Transportation Infrastructure (*Departamento Nacional de Infraestrutura de Transportes*, or DNIT) has identified the Tocantins River as a priority waterway for navigational improvement. A DNIT feasibility study concluded that improvement of navigational reliability is technically feasible, and a conceptual design for a navigation channel through the Pedral do Lourenço site was completed in 2015 by the Federal University of

Paraná (UFPR). The US Army Corps of Engineers and DNIT entered into an agreement in 2016 to support DNIT objectives in the areas of river engineering and river navigation services. DNIT is responsible for planning, design, and construction of transportation infrastructure in Brazil, including waterways. USACE supports this mission by providing capacity building and knowledge transfer using subject matter experts embedded at DNIT headquarters in Brasília and support from USACE districts in the United States.

The stated goal of the Tocantins navigation project is to achieve 96% navigational reliability along the river, but the complex interactions between the reservoir and river at the Pedral do Lourenço mean that various combinations of conditions can cause this standard to go unmet in this location. A 2013 study by engineering firm CB&I (originally known as Chicago Bridge and Iron Works, now part of McDermott International) recommended using a design flow of 1,898 m^3/s (said to be the 4% annual non-exceedance low flow) with a reservoir stage of 58.0 m, the minimum stage for operation of the navigational lock at the downstream end of the reservoir. USACE and DNIT engineers sought to reassess these design assumptions in the context of navigational reliability and determine the required volume of rock removal necessary to achieve a reliable channel.

Conceptual Background

The total probability of a continuous outcome y (e.g. river stage) that results from two continuous underlying conditions q and h (e.g. river flow and downstream stage) is given by

$$F(y) = \int \int F(y|q,h) f(q,h)\, dq\, dh \tag{1}$$

The first term $F(y|q,h)$ describes the likelihood of observing a particular river stage given a particular combination of flow rate and downstream reservoir stage, while the second term $f(q,h)$ is the joint probability of that particular pair of conditions being exceeded (Need et al. 2008). If the exceedance probabilities of the two underlying conditions are independent of each other, then the probability of exceeding both at once is simply the product of the two marginal probabilities,

$$f(q,h) = f(q)f(h) \tag{2}$$

If the two events are not independent, then other formulations such as copulas may be used to address this dependence, though in many practical hydrological contexts the period of available data is too short to establish the nature of this dependence with confidence. The $F(y|q,h)$ term may be determined from a hydraulic model such as HEC-RAS (USACE Hydrologic Engineering Center's River Analysis System; Brunner, 2010). However, inserting an HEC-RAS model into equation (1) does make it rather harder to compute the total probability integral. Therefore, it is common to rely again on the law of total probability, constructing a series of conditional probability curves for the response as a function of one of the two underlying variables, each for a specific "index" value of the other variable. These conditional curves are then summed together into a total probability curve by multiplying the probability from each conditional curve by the probability of each index value, estimated by the proportion of time that index value is exceeded.

$$F(y) = \Sigma f(y|h) f(h) \tag{3}$$

Here, $f(y|h)$ is the probability of observing the stage y, as a function of the variable q, given a fixed index value of variable h. This is the method recommended by USACE Engineering Manual 1110-2-1415 (USACE, 1993) and implemented in HEC-SSP (HEC Statistical Software Package; Brunner and Fleming, 2010).

Alternative methods to the one described above exist. Need et al. (2008) recommended fitting a Gumbel copula to model the flood risk along a tidal river, when the downstream ocean boundary and the river discharge are somewhat, but not perfectly, correlated. Kilgore et al. (2013) explored several methods for computing coincident design flows for areas near the confluence of two streams, including bivariate probability distributions, copulas, the total probability approach, regression approaches, and synthetic storms. Finally, one could simply posit that the two underlying variables are perfectly correlated, so that the river stage with a given coincident probability is simply the result of the river flow and downstream boundary conditions that each have that marginal probability. While this is a conservative assumption, it is not as conservative as it might initially appear. Over most of the project domain the overall stage response is largely a function of only one of the two variables, so this conservatism significantly overestimates risk only in the transitional region where both variables are highly influential on the response (Need et al. 2008).

Methods

For the analysis of the Pedral do Lourenço, the team selected the total probability approach for the computation of the design water surface profile. However, the method described above presented two challenges. First, it had been developed for analysis of floods, not droughts, and to the team's knowledge had not been applied previously to a navigational design project. Indeed, HEC-SSP software was unable to perform a coincident probability analysis using a flow frequency non-exceedance curve (though it performs perfectly well for a frequency exceedance curve). Second, the implementation of the total probability approach using conditional exceedance curves requires that one of the two underlying variables be deemed the "more influential" variable and the other the "less influential" of the two. The more influential variable determines the probability of the response for the conditional curves, each of which is indexed to a fixed value of the less influential variable. For the Pedral do Lourenço, this creates an issue because the choice of which variable is more influential varies along the project reach. At the downstream end of the project near the Tucuruí reservoir delta, the reservoir stage is much more influential than the river flow, while at the upstream end the opposite is true (Figure 2).

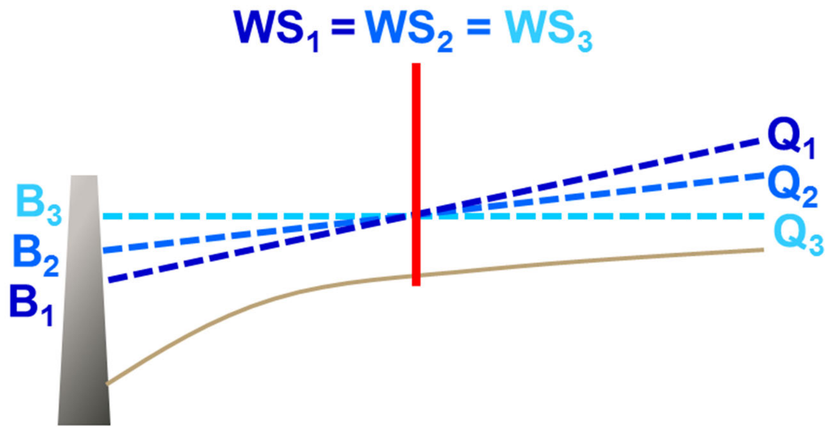

Figure 2. At the downstream end of the reach, the reservoir stage "B" is the more influential variable, while at the upstream end the river discharge "Q" is more influential. There is therefore no single correct choice of index variable to use in construction of the coincident frequency exceedance curves.

Before the coincident frequency analysis could begin, exploratory data analyses were performed to assess the stability of the stage-discharge rating curve and the assumption of independence between river flow and reservoir stage. Discharge data for the Itupiranga gage near river kilometer 393 were downloaded from the Hidroweb database operated by the Brazilian National Water Agency (*Agência Nacional de Águas*, or ANA) for the period of record, January 1977 through May 2016. Quality-assured data were available through 2006 and were prioritized over raw data when available, and obvious errors such as zeroes were deleted. A specific-gage analysis was used to assess the stability of the discharge rating at Itupiranga. While it would have been preferable to use the direct-step method for this analysis (assessing changes in the observed discharge measurements themselves), data availability was insufficient for that approach. Therefore, the observed data were used to generate a moving-window five year rating curve, allowing the stage associated with a given flow to be extracted from each curve and plotted as shown in Figure 3. While periods of missing data complicate the task of computing the statistical significance of any change in stage over time, visual inspection does not show an obvious trend. The rating was deemed to be sufficiently stable, and a single-value rating curve was used to generate a daily record of river flows.

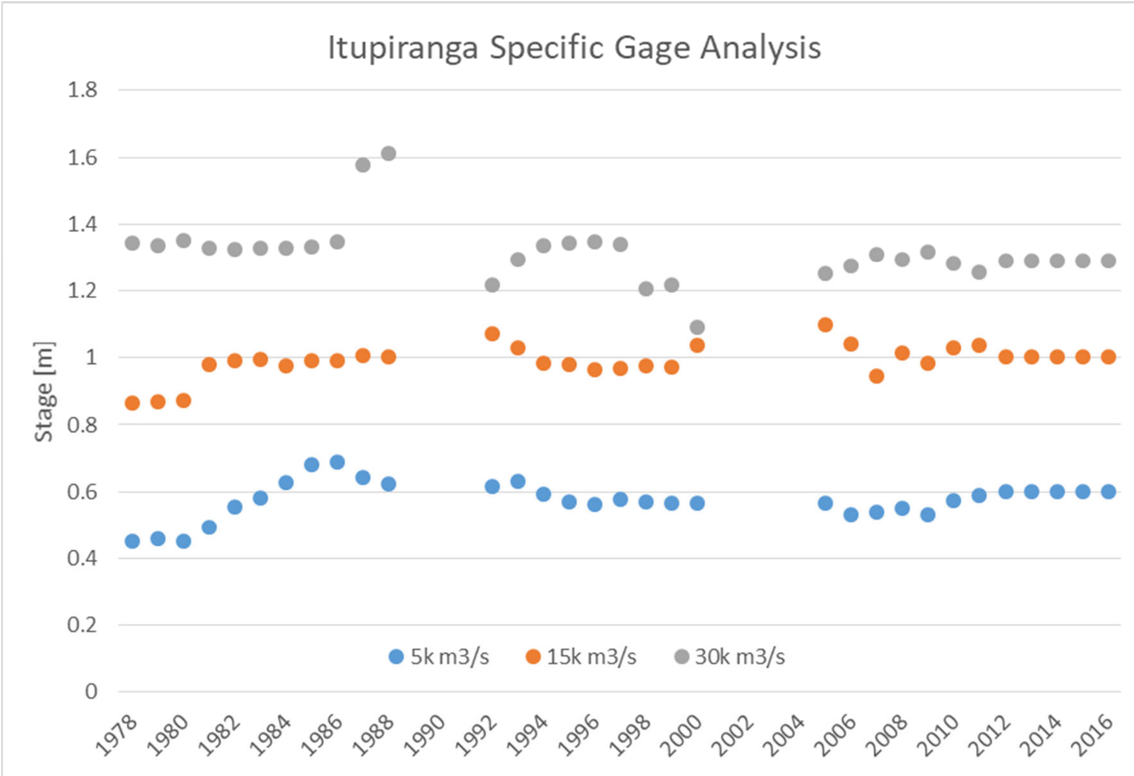

Figure 3. Specific gage analysis for Itupiranga gage. The stage-discharge rating was found to be sufficiently stable to use for generating the daily flow record.

As mentioned in the previous section, the coincident frequency approach is limited in most practical applications to situations where the two controlling variables can be assumed to be independent. The Tucuruí reservoir is so large that minimum stage in the reservoir tends to lag minimum flow in the river by several months, so a strong correlation between the two was not expected. To check this assumption, the annual minimum flows for the Tocantins at Marabá were plotted against the coincident stages in the reservoir as shown in Figure 4. With an r^2 of just 0.0034 and a p-value of 0.85 for the slope of the regression line, there was insufficient evidence to reject the null hypothesis of no significant correlation between the two variables, so the assumption of independence was adopted.

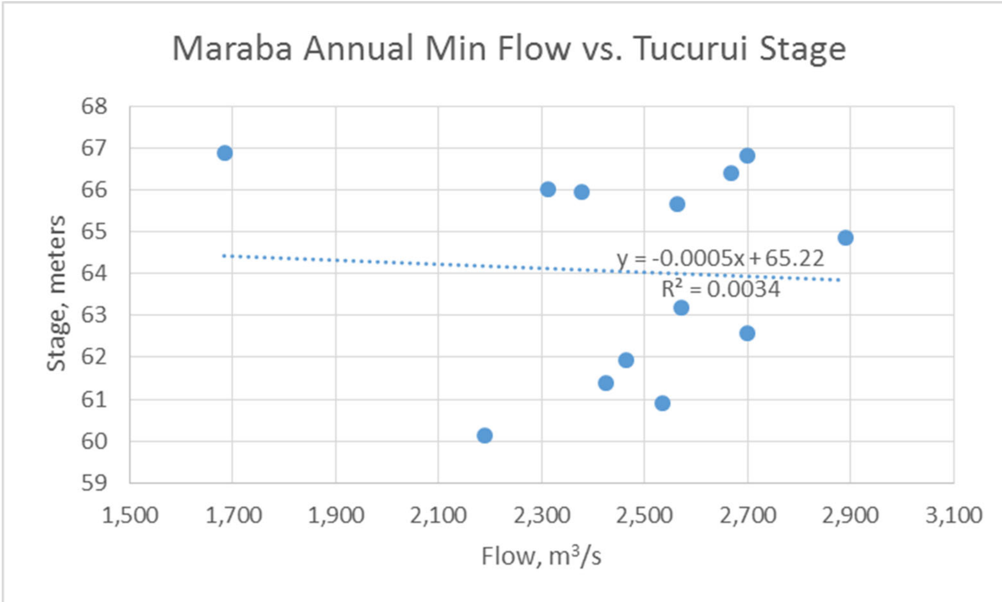

Figure 4. No significant correlation was found between annual minimum flow on the Tocantins River and the simultaneous stage in the Tucuruí reservoir, allowing the two variables to be considered independent.

To address the issue of the dominant variable switching from one to the other over the project domain, the team decided to develop two low-water profiles, the first using downstream stage as the more influential variable and the second considering river flow to be more influential. The two profiles would then be compared, with the final profile being governed by whichever of the two is lowest at any given point along the reach. This "envelope" approach is implied (for estimating flood elevations) though not specifically recommended by both EM 1110-2-1415 and Kilgore et al. (2013).

Results

Low-Water Profiles and Design Condition Envelope

Two low-water profiles were computed in Microsoft Excel software via the total probability approach, by generating sets of conditional probability curves and summing them together in a weighted sum according to the likelihood of each index value of the less influential variable. The response surface defining the river stage for various combinations of river flow and reservoir stage was extracted from a one-dimensional HEC-RAS model developed jointly by USACE and DNIT. The total probability approach allows an exceedance curve to be computed for any probability of exceedance and for any confidence interval around the curve. The team decided that the best match to the project intent of 96% navigational reliability would be achieved by first generating an annual series of 4% stage duration values, then computing the 2-year recurrence interval (i.e. best estimate) of this series for each location of interest using a Gumbel distribution. Other recurrence intervals were also computed, though ultimately not used for this design. The coincident frequency analysis was repeated for nine locations along the reach, with locations between these points interpolated using a water surface profile from the hydraulic model. The two resulting profiles are shown in Figure 5, with the design profile being governed at every point by whichever of the two profiles is lowest.

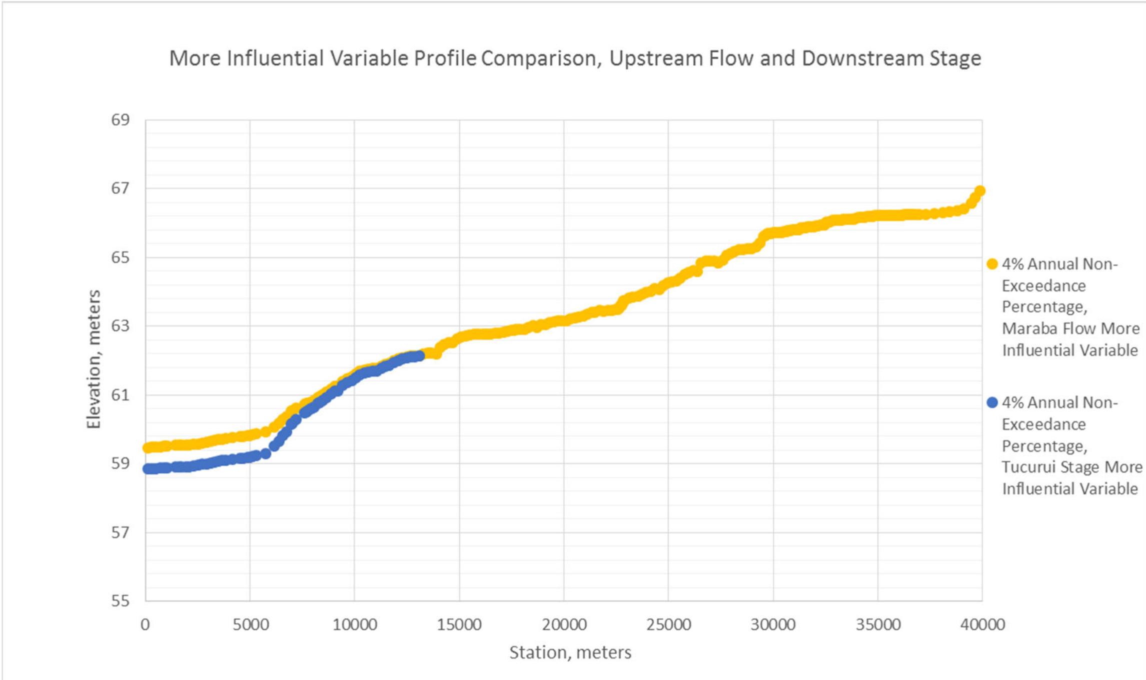

Figure 5. The two profiles resulting from two applications of the total probability approach. At every point along the profile, the design is governed by whichever profile is lowest.

Having computed the design profile, the team then computed the corresponding required volume of rock removal and the actual resulting navigational reliability based on historical data. Transit of the Pedral do Lourenço in a towboat requires approximately one day, so the profile was compared to observed data from 2003-2015 to determine how many days of that time the channel would have been safely navigable if the specific volume of rock had been removed. If any part of the channel did not meet the Brazilian minimum criteria for safe draft, channel width, turning radius, or length between curves, the entire channel was deemed to be impassable for that day. Results are shown in Table 1, with the without project alternative and two other design approaches shown for comparison.

Table 1. Required rock volume excavation and navigational reliability for the coincident frequency design as compared to two alternative designs and the without project alternative

Condition	Approximate Rock Volume Removed, million m^3	Estimated Historic (2003-2015) Reliability
No navigation channel project	0	15-20%
Coincident Frequency [a]	1.78	76%
Duration Exceedance [b]	1.95	90%
Established boundary conditions [c]	4.23	98.9%

[a] 50% confidence estimate of 96% annual chance of exceedance

[b] 96% duration exceedance

[c] Q=1,898 m^3/s Tucuruí=58.0 m

Discussion

As shown in Table 1, a coincident probability based navigational channel design, using a 50% annual total probability of non-exceeding a 96% duration stage, results in a channel that is navigable on approximately 76% of days based on historic data from 2003-2015. This apparently paradoxical finding is explained by three observations. First, the coincident frequency-based 96% reliability stage applies to each specific location along the profile where it is calculated. In other words, a 96% duration stage at a given location corresponds to a water surface elevation that is not exceeded approximately 15 days per year. However, at a different location along the profile, where either the reservoir stage or flow becomes more influential, the calendar days where water surface elevations are below this threshold may be non-simultaneous. This results in a profile for which more than 15 days of navigation may be impacted, meaning the 96% duration profile corresponds to an actual level of reliability closer to 76% along the entire 35 km reach (or 88 days of impacted navigation). Second, because the entire channel is considered impassable if any part of it is impassable, there may be days when the river flow or the downstream reservoir stage are too low to allow for navigation, even if the overall conditions, considered together, are less extreme than those represented by the profile. And finally, uncertainty (irreducible error) exists around the profile, which is unaddressed when the profile is considered at the 50% confidence interval.

Three other approaches for profile design are also shown in Table 1 for comparison. The first is the without-project condition. It should be noted that there is no commercial navigation at present in the proposed channel through the Pedral do Lourenço; rock pinnacles are visible above the water surface even during high water conditions. An alternate route around these pinnacles exists that is potentially navigable during high water conditions, and this is route referred to in Table 1. The "duration exceedance" design refers to a profile such that each point along the route is exceeded by 96% of the data, evaluated using the HEC-RAS hydraulic model and historical data. Again this design does not yield 96% navigational availability because the entire channel is considered impassable if any part of it does have sufficient draft. Finally, the last design is the one based on the boundary conditions from the CB&I (2013) study. It delivers very high reliability but requires an extremely large amount of rock excavation. The optimal design is still to be determined. Due to the strong seasonality of river conditions in the Amazon Basin, year-round availability may be less essential than navigability during the agricultural harvest and shipping season. This is an area for further study.

The envelope approach used here may be considered most accurate as the profile approaches the two extremes of the project reach. In these areas, the choice of which variable is most influential is clear, and the lower of the two profiles is the more accurate estimate of the true 50% annual coincident non-exceedance curve. In the transition region between the two, the choice is less clear, and the design profile here may be considered less certain. There is no precise definition for where this transition zone begins and ends, so engineering judgment may be used to determine whether areas of concern exist based on the incidence of rock pinnacles in parts of the channel where the two coincident frequency profiles are near to each other. In accordance with risk-based design, this part of the reach may be an appropriate area to use a greater degree of confidence (beyond 50%) or, equivalently, a less frequent non-exceedance event (than 2-year recurrence) to define the design profile in recognition of this increased uncertainty.

Conclusion

A total probability approach was used to develop a low-water profile for a navigational channel through a rocky outcrop on the Tocantins River in northern Brazil. Coincident frequency analysis was required because the river stage in this area is a function of both river flow and the stage in the downstream reservoir. Which of these two variables is most influential on river stage changes over the course of the project area, so two coincident frequency analyses were performed, with the lower of the two governing the design at all points. This design results in a profile corresponding to conditions that can be expected to have a 50% annual chance of being non-exceeded during 4% of the year. Historical data indicate that the proposed channel with approximately 1.8 million cubic meters of rock removed would have been completely passable without the need for light loading on about 76% of days from 2003-2015. This level of reliability is not as high as the stated project goal of 96%, but it also requires a dramatically smaller volume of rock removal than the boundary conditions approach defined in a previous study. To the authors' knowledge, this is the first application of a coincident frequency envelope design to a navigation channel (i.e. low-water) project.

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