Management of Global Reservoir Sedimentation: An Evaluation of RESCON 2 Beta

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Abstract

Several methods for managing reservoir sedimentation have been developed to help extend project life. In 2017, the World Bank sponsored RESservoir CONservation (RESCON) 2, a pre-feasibility, Excel-based program aimed to help users select sediment management practices to consider for more detailed studies. Perhaps RESCON's greatest contribution to its users is its comparative analysis of different sediment management strategies, wherein net present values are calculated for each alternative, whether or not it is sustainable, and the long-term storage capacity and lifetime of the reservoir.

While this is certainly useful, the objective of this paper is to gain insight into RESCON's efficacy for evaluating and suggesting sediment management options by comparing its results against the Sediment Management Options Diagram (SMOD) and the actual practice in use at the reservoir. Brief descriptions of the SMOD and RESCON 2 will be provided. RESCON-required inputs will be summarized, and some key entries will also be presented.

Twenty reservoirs from around the world were modeled in RESCON 2, with storage capacities ranging between 0.187 million cubic meters and 39.3 billion cubic meters. All sediment management alternatives whose net present values lied within 30% of the highest alternative were deemed practicable for the reservoir. Of the twenty models, ten did not practice sediment management (i.e., no action is being taken to manage sediments at the site). Analyzing only those reservoirs where sediment management is being employed, RESCON predicted the actual practice eight out of ten times.

Introduction

Several methods for managing reservoir sedimentation have been developed to help extend project life (Morris and Fan 1998). In 2017, the World Bank sponsored RESservoir CONservation (RESCON) 2, an Excel-based program currently in its beta development stages but expected to be finished over the next two years (Efthymiou 2019). This program can analyze up to nine alternatives and attempts to help users and analysts select practices to consider for more detailed studies. Users input required information and the program returns a pre-feasibility analysis comparing the nine alternatives side-by-side. The analysis identifies practicable solutions for the reservoir, whether or not each method is sustainable, its net present value, and the long-term reservoir storage capacity and reservoir lifetime. The objective of this paper is to gain insight into RESCON's efficacy for evaluating and suggesting sediment management options.

RESCON Background

Originally published in 2003, RESCON was created with the purpose of providing users with a rapid assessment and pre-feasibility analysis of sediment management alternatives (Palmieri et al. 2003). Similarly, Annandale et al. (2017) commented on what RESCON 2 was and was not designed to do:

> "It is noted that the objective of the RESCON 2 model, as was the objective of the RESCON model, is to assess the technical viability and economic optimality of reservoir sedimentation management alternatives at policy and pre-feasibility level. It is not intended for feasibility and design phases of projects. The intent of RESCON 2 is to identify sediment management strategies that may be considered and analyzed using more detailed analysis approaches during the feasibility and final design stages of projects."

Thus, the main idea behind RESCON 2 is rapidly assessing sediment management alternatives with data that are, generally speaking, readily available. With sound engineering judgment, alternatives may then be selected to study and inspect more closely.

Several improvements have been made to the program since it first launched. The original RESCON only included assessments of sediment removal techniques: flushing, hydrosuction-sediment removal systems (HSRS), dredging, and trucking. Since then, sediment routing and inflow reduction practices have been added (Table 1). In addition to new sediment management strategies, RESCON 2 improved on its economic analysis and added an additional feature assessing climate change effects on reservoir sustainability (Annandale et al. 2017). The economic analysis can consider various implementation schedules for sediment management strategies and optimizes timing or recurrence to produce the highest net present value (NPV). The climate change assessment is comprised of multiple steps which are documented in the RESCON 2 user manual. To summarize, RESCON analyzes possible future climate scenarios and selects a set that "spans the full range of climate futures," and evaluates the different sediment management strategies under these potential conditions (Efthymiou et al. 2017).

Table 1. RESCON 1 and RESCON 2 Sediment Management Alternatives

Included in RESCON 1	Included in RESCON 2
Flushing	Flushing
HSRS	HSRS
Dredging	Dredging
Trucking	Trucking
-	Sluicing
-	Bypass tunnel
-	Catchment management
-	Density-current venting
-	No action

Sediment Management Options Diagram

Aside from RESCON, another practical approach for analyzing sediment management alternatives is the Sediment Management Options Diagram (SMOD). In the past, the SMOD has been referred to as the Basson Diagram (Palmieri et al. 1998; Aras 2009); however, Dr. Basson stated he used work previously done by Chinese researchers to develop this graph, and agreed the name "Sediment Management Options Diagram" would be an appropriate title for the chart (Basson 2018; see also Basson 1996).

The SMOD relates water and sediment inflows to storage capacity, and considers only these physical characteristics of the reservoir when analyzing alternatives (see Figure 1). The x-axis represents the reservoir storage capacity divided by the mean annual inflow. This ratio is indicative of the hydraulic retention time (HRT), or the amount of time water remains in the reservoir before passing downstream. A low HRT value means water can fill the reservoir regularly, whereas a large HRT value suggests water is slower to enter and leave the reservoir, either because the volume of water entering the reservoir is relatively small or the reservoir capacity is large, or some combination of the two.

The y-axis is representative of the storage capacity divided by the mean annual sediment inflow, and can be interpreted as the reservoir's life expectancy (Auel et al. 2016). This latter ratio does not perfectly represent the lifetime of the reservoir, as reservoirs tend to fill more slowly over time as storage capacity is lost (Morris and Fan 1998). RESCON 2 attempts to account for the decrease in sedimentation rates through various trapping efficiency methods. The SMOD is a somewhat simplistic approach to consider sediment management strategies, but, like RESCON, it is meant to be used at the pre-feasibility stage and can provide practical feedback for selecting alternatives to review under more detailed analyses.

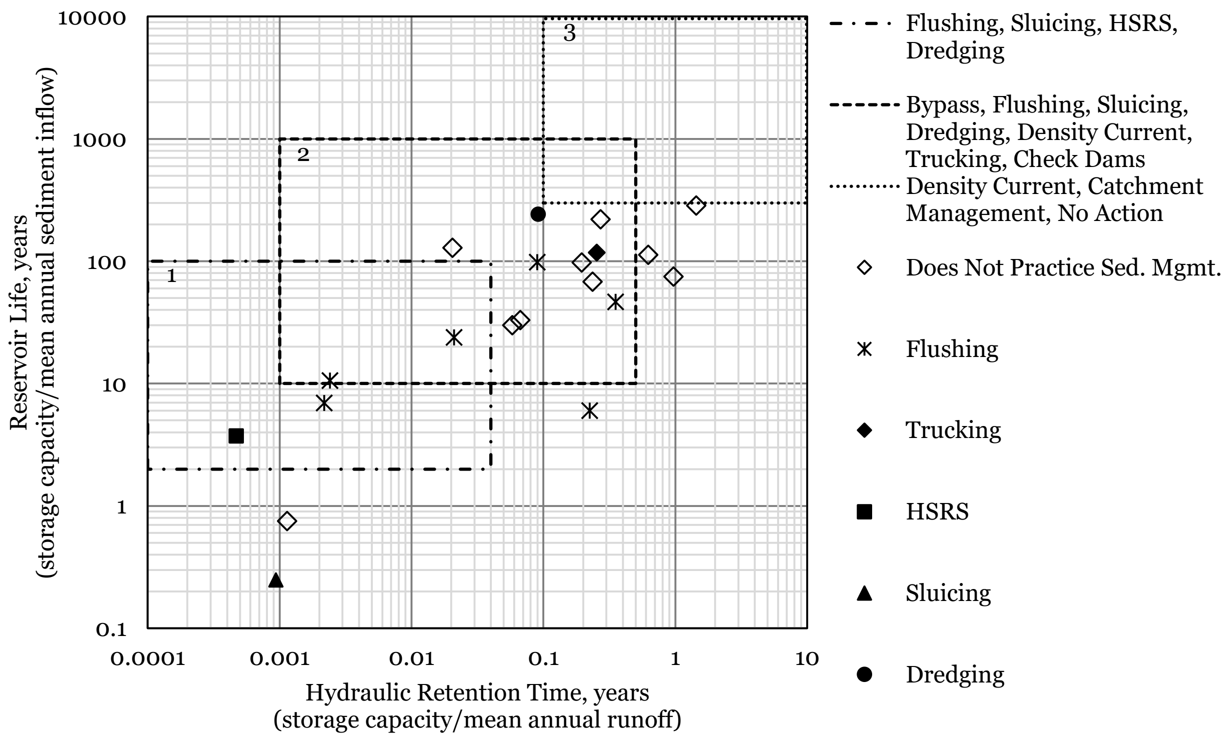

Figure 1. SMOD with RESCON-analyzed reservoirs (source, Annandale 2013; Basson 1996)

Figure 1 contains each RESCON-analyzed reservoir for this study, distinguishing between those reservoirs that do and do not practice sediment management. Reservoirs practicing sediment management are indicated by the various marker types. The three boxes contained within the diagram represent ranges where certain practices are considered more feasible than others (Annandale 2013). Reservoirs lying within or near box 1 were assumed to use either flushing, sluicing, HSRS, or dredging; box 2 to use sediment bypass tunnels, flushing, sluicing, dredging, density currents, trucking, or check dams; and box 3 to use density currents, catchment management or no action. Data for the SMOD can be found in Table 2.

Table 2. SMOD Data for Modeled Reservoirs

Reservoir	CAP (million m^3)	CAP/MAR (years)	CAP/MAS (years)	Source
Abdel Karim	11.3	0.24	68	Annandale, G.W. (2017)
Baira	2.4	0.0024	11	Annandale, G.W. (2019)
Banja	403	0.27	221	Adhikari, S. (2017)
Bin El Quidine	1,508	1.4	285	Annandale, G.W. (2017)
Çubuk	7.1	0.25	118	Aras, T. (2009)
El Canadá	0.187	0.00047	3.7	Zamora, J. (2018a)
Gavins Point	580	0.020	129	Boyd, P. (2019)
Gebidem	9	0.021	24	Annandale, G.W. (2019)
Ichari	11.6	0.0022	7	Annandale, G.W. (2019)
Iron Gate	100	0.067	33	Annandale, G.W. (2017)
Kali Gandaki	7.7	0.00094	0.25	Annandale, G.W. (2017)
Kulekhani	85.3	0.62	113	Shrestha, H.S. (2012)
Millsite	22.2	0.091	243	Hotchkiss, R.H. (2018)
Mohammed V	726	0.97	75	Annandale, G.W. (2017)
Sanmenxia	9,640	0.22	6	Annandale, G.W. (2019); Wu, B. (2018)
Sefid-Rud	1,760	0.35	47	Annandale, G.W. (2019)
Sidi Driss	7.2	0.058	30	Annandale et al. (2017)
Tarbela	14,350	0.19	98	Annandale, G.W. (2017)
Three Gorges	39,300	0.090	98	Annandale, G.W. (2019)
Upper Karnali	17.9	0.0011	0.8	Annandale, G.W. (2017)

Inputs Needed in RESCON

RESCON 2 attempts to progress pre-feasibility analyses from field observations to empirical approximations, and the number of input parameters dramatically increases. Table 3 illustrates the six input worksheets within RESCON 2, the number of inputs on each page, and some key entries found therein. In total, there are 233 input parameters in RESCON 2. However, note that the sediment management page does not require all 80 inputs to run, as not all sediment management options need to be analyzed. Also, some values can be empirically estimated using functions built into the program, such as the mean annual sediment inflow and the unit cost of dredging. Though the total number of inputs can be somewhat daunting at first glance, RESCON 2 is designed for rapid assessment, and many of the input parameters should be easily accessible to the user.

Table 3. RESCON Required Inputs

Page Name	Number of Inputs	Key Entries
Project Definition	9	Required reliability of water supply
Environmental Safeguard	97	Allowable environmental and social damage
Reservoir Geometry	12	Storage capacity (live and dead), pool and bed elevations
Hydrology and Sediment	26	Mean annual runoff and sediment inflows
Economic Parameters	9	Unit cost of construction, discount rate, unit value of reservoir yield, maximum duration of financial analysis
Sediment Management	80*	Allowable loss, year of implementation, frequency of events
Total:	233	

* - Optional, does not need all 80 inputs to run

Results

RESCON 2 provides a comparison of sediment management alternatives and summarizes results with three recommendations:

1) A sustainable solution yielding the highest net present value (NPV);
2) A non-sustainable solution yielding the highest NPV that will eventually require decommissioning; and
3) A non-sustainable solution yielding the highest NPV that will eventually become a run-of-river dam.

Additionally, each sediment management technique considered is evaluated and given a sustainable or non-sustainable estimated net present value, long-term storage capacity, and life expectancy under such a regime. This is depicted below in Table 4, an example of RESCON's comparison taken from the Tarbela Reservoir. All alternatives within 30% of the highest NPV were considered practical for the reservoir and are labeled as "RESCON Predicted" solutions in Table 5.

Table 4. RESCON 2 Comparison of Results for Tarbela Reservoir

Sediment Management Strategy			Aggregate Net Present Value	Long Term Reservoir Gross Storage Capacity	Reservoir Lifetime
Technique	Sustainability	Action in case of storage elimination	[US$]	[m^3]	[Years]
No Action	Sustainable		N/A	0	224
	Non Sustainable	Decommissioning	187,243,555,417		
		Run-Of-River	187,332,960,214		
Catchment Management	Sustainable		N/A	0	236
	Non Sustainable	Decommissioning	191,248,494,906		
		Run-Of-River	191,317,423,516		
Sluicing	Sustainable		N/A	192,307,615	> 217
	Non Sustainable	Decommissioning	N/A		
		Run-Of-River	249,393,287,482		
By-Pass	Sustainable		N/A	0	284
	Non Sustainable	Decommissioning	176,227,609,498		
		Run-Of-River	176,239,951,715		
Density Current Venting	Sustainable		N/A	0	196
	Non Sustainable	Decommissioning	75,395,440,831		
		Run-Of-River	75,400,274,878		
Flushing	Sustainable		267,331,032,335	1,471,780,945	> 300
	Non Sustainable	Decommissioning	N/A		
		Run-Of-River	N/A		
HSRS	Sustainable		N/A	N/A	N/A
	Non Sustainable	Decommissioning	N/A		
		Run-Of-River	N/A		
Dredging	Sustainable		297,621,522,010	9,855,539,822	> 300
	Non Sustainable	Decommissioning	N/A		
		Run-Of-River	N/A		
Trucking	Sustainable		247,866,217,286	7,409,392,165	> 300
	Non Sustainable	Decommissioning	N/A		
		Run-Of-River	N/A		

Figure 2, Figure 3, and Table 5 display the comparative results between RESCON 2, the SMOD, and the currently employed practice at the reservoir. Figure 2 and Table 5 display the results from all twenty models used in this study. Figure 3 displays only the results from reservoirs practicing some form of sediment management (i.e., anything but "no action"). In Figure 2 and

Figure 3, the term “agree” refers to the sediment management practice in use at the reservoir. Looking at all twenty cases, RESCON and the actual practice agreed thirteen times, while the SMOD agreed with the actual practice twelve times. In four instances were neither model able to correctly predict the currently employed alternative. Considering only those reservoirs that practice sediment management, ten of the twenty models were applicable, and RESCON and the actual practice agreed eight out of ten times, while the SMOD and actual practice agreed in all ten cases.

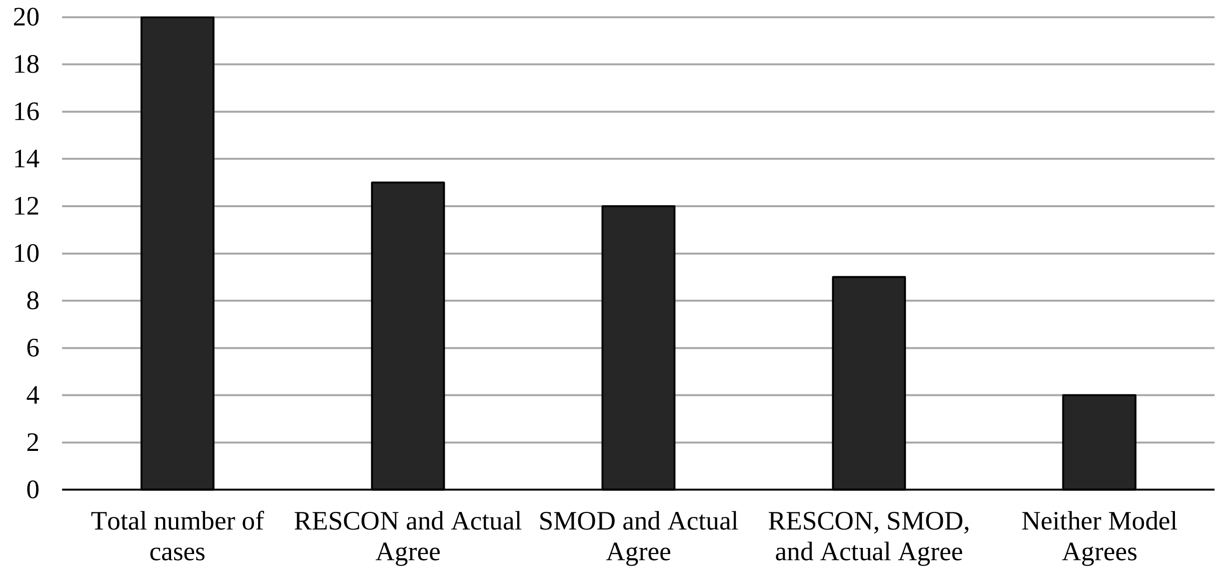

Figure 2. Comparison of predicted alternatives, all cases

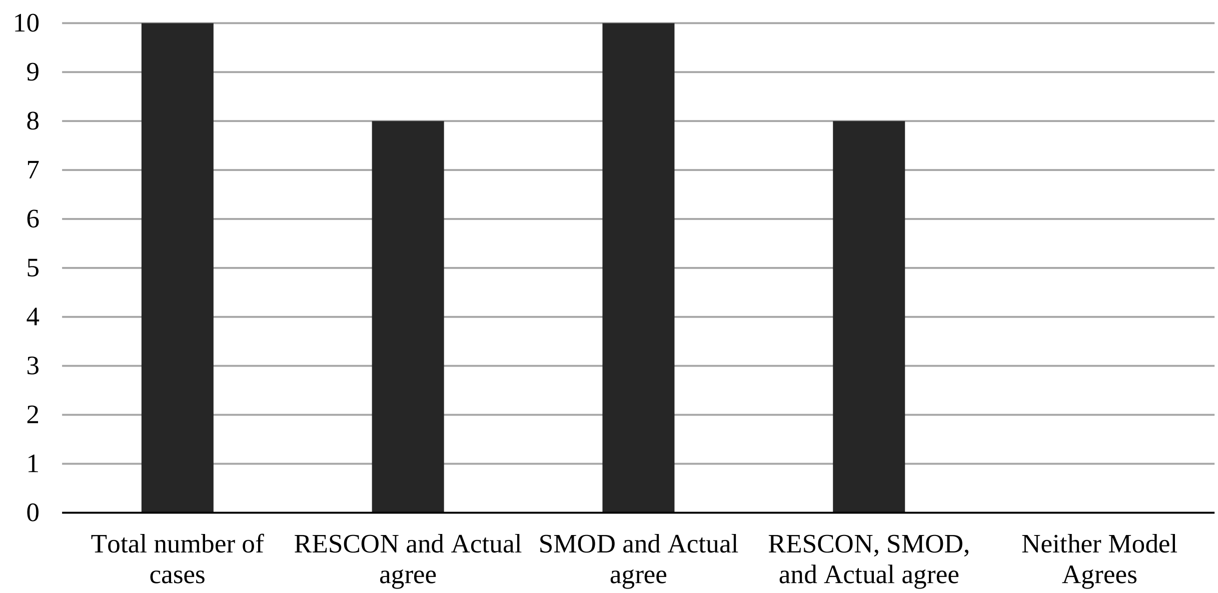

Figure 3. Comparison of predicted alternatives, only reservoirs practicing sediment management considered

Table 5. Comparison of RESCON's Predicted Sediment Management Alternative

Reservoir	RESCON Predicted	SMOD Predicted	Actual Practice
Abdel Karim	No Action, Catchment Management, Sluicing, Flushing, Dredging	Bypass Tunnel, Flushing, Sluicing, Dredging, Density Current, Trucking, Check Dams	No Action
Baira	No Action, Flushing, HSRS	Flushing, Sluicing, HSRS, Dredging, SBT, Density Current, Trucking, Check Dams	Flushing
Banja	Dredging	Bypass Tunnel, Flushing, Sluicing, Dredging, Density Current, Trucking, Check Dams, Catchment Management, No Action	No Action
Bin El Quidine	No Action, Catchment Management, Sluicing, Bypass Tunnel, Density Current, Dredging	Density Current, Catchment Management, No Action	No Action
Çubuk	No Action, Flushing, HSRS, Dredging, Trucking	Bypass Tunnel, Flushing, Sluicing, Dredging, Density Current, Trucking, Check Dams	Trucking
El Canadá	Dredging, No Action	Flushing, Sluicing, HSRS, Dredging	HSRS
Gavins Point	No Action, Flushing, HSRS, Dredging, Trucking	Bypass Tunnel, Flushing, Sluicing, Dredging, Density Current, Trucking, Check Dams	No Action
Gebidem	No Action, Flushing, HSRS	Flushing, Sluicing, HSRS, Dredging, SBT, Density Current, Trucking, Check Dams	Flushing
Ichari	Flushing	Flushing, Sluicing, HSRS, Dredging	Flushing
Iron Gate	No Action, HSRS, Trucking	Bypass Tunnel, Flushing, Sluicing, Dredging, Density Current, Trucking, Check Dams	No Action
Kali Gandaki	Sluicing	Flushing, Sluicing, HSRS, Dredging	Sluicing
Kulekhani*	HSRS	Bypass Tunnel, Flushing, Sluicing, Dredging, Density Current, Trucking, Check Dams	No Action
Millsite	No Action, Bypass Tunnel, HSRS	Bypass Tunnel, Flushing, Sluicing, Dredging, Density Current, Trucking, Check Dams, Catchment Management, No Action	Dredging
Mohammed V	No Action, Catchment Management, Sluicing	Bypass Tunnel, Flushing, Sluicing, Dredging, Density Current, Trucking, Check Dams	No Action
Sanmenxia	Flushing	Flushing, Sluicing, HSRS, Dredging, SBT, Density Current, Trucking, Check Dams	Flushing
Sefid-Rud	Flushing, Dredging	Bypass Tunnel, Flushing, Sluicing, Dredging, Density Current, Trucking, Check Dams	Flushing
Sidi Driss*	Sluicing	Bypass Tunnel, Flushing, Sluicing, Dredging, Density Current, Trucking, Check Dams	No Action
Tarbela	Sluicing, Flushing, Dredging, Trucking	Bypass Tunnel, Flushing, Sluicing, Dredging, Density Current, Trucking, Check Dams	No Action
Three Gorges	No Action, Flushing, HSRS, Dredging	Bypass Tunnel, Flushing, Sluicing, Dredging, Density Current, Trucking, Check Dams	Flushing
Upper Karnali	Bypass Tunnel, Flushing	Flushing, Sluicing, HSRS, Dredging	No Action

* Models not had in possession but results were obtained via sources outlined in Table 2. Thus, other results may be considered practical under "RESCON Predicted."

Discussion

RESCON 2 Beta did not predict the correct alternative for the Millsite and El Canadá Reservoirs. Zamora (2018a) provided some commentary on why RESCON 2 may not apply to El Canadá.

1. It is a small regulation pond (0.187 million m^3), and the reservoir volume is small in comparison with the inflow.
2. It is an off-stream reservoir.
3. There is polyethylene lining in the reservoir.
4. The HSRS analysis included in RESCON seems to have a different approach than the one used at El Canadá.

For Millsite Reservoir, the NPV of the actually used practice (dredging) was approximately 36% lower than the highest NPV alternative (no action). As indicated in Table 2, Millsite has an unmanaged life expectancy of about 243 years, a reasonably long life for a reservoir, which may be why RESCON suggests no action as the ideal alternative. However, looking at life expectancy alone can be misleading, as a dam's functionality and purpose can be compromised well before the life of the reservoir has been fully exhausted (Morris and Fan 1998; Reclamation 2018). This would likely be shown in a detailed study, but the disparity between RESCON's results and the actual practice suggest something is amiss.

RESCON predicted the optimal alternatives for the Gebidem Reservoir would be no action, flushing, and HSRS. At Gebidem, flushing is used quite successfully, and a sediment balance has nearly been achieved—that is, outgoing sediments are equal to incoming sediments (Chamoun et al. 2016; Meile et al. 2014; Emamgholizadeh et al. 2006). Thus, the reservoir life is perpetuated almost indefinitely. However, RESCON suggests the lifetime of Gebidem under a flushing regime would last about 90 years.

Even though RESCON may not yield information revealed in detailed analyses, the rapid assessment and feedback provided by the program is valuable and informative at the conceptual stage of projects. All of the major sediment management techniques thus far developed can be evaluated from both an economic and sustainable development perspective. The SMOD-predicted strategies contained the actually used practice in all ten cases but, unlike RESCON, it provides no economic analysis, is not able to adjust for climate change, does not consider the presence or absence of low-level outlets, nor does it attempt to organize the various alternatives. RESCON 2 can help bridge the gap between potential alternatives and knowing with which practices to begin investigating.

Recommendations

As RESCON 2 progresses from a beta to fully developed program, a few concerns, if addressed, will increase the efficacy of the program and clarity of parameters.

HSRS Operation and Maintenance: Under the "Sediment Management" worksheet, there is no input for HSRS operation and maintenance (O&M) costs. RESCON assumes negligible costs are associated with HSRS O&M (Efthymious 2019), and while they are typically lower than conventional dredging, they aren't necessarily insignificant. In one case, Zamora (2018b) outlined and compared O&M costs for HSRS against conventional dredging at the El Canadá hydropower plant, and found HSRS to cost 75% more over a nine-year period. Thus, it is recommended that an HSRS O&M parameter be added to the program. However, if no such improvement is made, there are at least two possibilities to account for HSRS O&M costs.

First, users could determine the lifetime of the reservoir using HSRS, estimate the annual O&M costs, multiply annual O&M costs by the expected lifetime, and add this number to the initial investment required to install HSRS. The second option is to add HSRS O&M costs to the total O&M costs of the reservoir under the "Input (Economic Parameters)" worksheet of the program. This latter alternative is discouraged because adjusting total reservoir O&M costs would affect all sediment management alternatives, not just HSRS. Thus, at least two separate runs would be needed: one to analyze every other sediment management option, and a second for HSRS.

Unit Benefit of Reservoir Yield: The parameter in RESCON 2 called "unit benefit of reservoir yield" attempts to account for all revenues associated with multiple reservoir purposes, including drinking water and irrigation supply, flood control, and hydropower generation (Efthymiou et al. 2017). This single value plays a significant role in calculating NPVs for all sediment management alternatives. As a pre-feasibility analysis, users are not required to perform a detailed study to gain accurate measurements of each of the revenue sources to depict this parameter. Instead, the RESCON 2 user manual provides references for estimating this value, yet none of these references are currently listed or found in the manual. Additionally, the manual refers to this parameter as "unit benefit of water yield." Using the same term in both the program and manual would likely decrease confusion about this variable, as the program currently only gives this help text: "Where possible use specific data for the project. If no data is available refer to User Manual for guidance."

It may also be beneficial to expand this parameter into multiple variables for which this parameter is meant to consider. For instance, Table 6 gives specific revenue sources that may more clearly indicate which factors apply and potential units for each respective field.

Table 6. Potential Expansion of Unit Benefit of Reservoir Yield

Current Parameter	Recommended Parameters	Unit
Unit benefit of reservoir yield	Hydroelectric generation	$/kWh
	Agricultural use	$/m³
	Municipality use	$/m³
	Industrial use	$/m³
	Flood control	$/year
	Recreational benefits	$/year

Flushing Operation and Maintenance and Annual Sedimentation Capacity: Sensitivity tests indicated that the flushing O&M parameter is not factored into the NPV calculation. For instance, the Tarbela reservoir was run with two very different O&M costs: $0 and $1,000,000,000. The aggregate NPV remained the same for both cases. This phenomenon was confirmed in other models as well. Additionally, there seems to be a cap on how much sediment RESCON 2 can handle. For example, the Sanmenxia Reservoir, which is known for having extremely high sedimentation rates (Wang et al. 2005), could not be simulated without reducing the mean annual sediment inflow by nearly 40%. It was confirmed and assurance was given that these were, in fact, bugs in the program and would be treated in later versions of RESCON 2 (Efthymiou 2019). In lieu of this, it may be helpful to include a list of all RESCON 2 versions with build numbers and bug treatments. This would help users know if they have the most up-to-date version of the program and if their problem has been resolved with new builds. Similarly, having a system for users to report bugs or suggest recommendations could be helpful to further enhance RESCON's efficacy.

Conclusions

RESCON 2 has been developed as a pre-feasibility tool to guide users and analysts in the early project development stages to select practices to consider under detailed studies. The information provided by RESCON 2 is resourceful and valuable, and findings in this report suggest RESCON very often predicts the optimal solution. Furthermore, RESCON allows users and analysts to compare all modern sediment management techniques from both an economic and sustainable perspective. Using additional pre-feasibility models, such as the SMOD, may serve as a check on what accumulated experiences elsewhere have shown.

As a beta program, RESCON 2 can improve by:

1. Including an HSRS O&M parameter;
2. Using identical terms for the unit benefit of reservoir yield parameter in both the model and user manual, and expand this parameter to more explicitly state what this value is meant to consider;
3. Including the sources for estimating unit the benefit of reservoir yield in the user manual's reference list;
4. Incorporating flushing O&M costs to factor into the NPV calculation;
5. Increasing the annual sediment inflow capacity to allow for higher sedimentation rates; and
6. Provide a list of RESCON model builds/versions to clearly indicate which bugs have been treated.

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