Environmental Modelling and Software 136 (2021) 104947

Contents lists available at ScienceDirect

Environmental Modelling and Software

journal homepage: http://www.elsevier.com/locate/envsoft

An open source reservoir and sediment simulation framework for identifying and evaluating siting, design, and operation alternatives

Thomas B. Wild[a,b,*], Abigail N. Birnbaum[c], Patrick M. Reed[d], Daniel P. Loucks[d]

[a] Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA
[b] Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD, 20740, USA
[c] Department of Civil and Environmental Engineering, Tufts University, Medford, MA, USA
[d] School of Civil and Environmental Engineering, Cornell University, Ithaca, NY, USA

ARTICLE INFO

Keywords:
Dams
Hydropower
Ecology
Mekong
Sediment management
Reservoir operation

ABSTRACT

This paper introduces PySedSim, an open-source, object-oriented, Python-based, daily time step river basin simulation screening model for flow, sediment, and hydropower in networks of reservoirs and river channels. The model enables users to explore representations of four key concerns relevant to the selection and evaluation of alternative reservoir configurations: 1) management approaches to improve the passage of sediment through and around reservoirs to avoid storage capacity loss and downstream ecological impacts; 2) search for flexible and adaptive reservoir operating policies designed to achieve multiple objectives; 3) alternative design features such as dam gates, which are necessary to enable ecologically-focused reservoir features; and 4) uncertainties associated with hydroclimatic drivers and sediment processes. PySedSim is intended to support deliberative decision-making and design processes. We highlight PySedSim's functionality by demonstrating its use in a real decision context focused on identifying siting, design, and operation alternatives for the proposed Sambor mega Dam in Cambodia.

Software availability

Name of Software: PySedSim
Description: PySedSim is an open-source, object-oriented, Python-based daily time step river basin simulation model for flow, sediment, and hydropower production in networks of reservoirs and river channels. It is intended to predict in relative terms the spatial and temporal accumulation and depletion of sediment in river reaches and in reservoirs under different reservoir operating and sediment management policies. The model can be run in both stochastic (Monte Carlo) and deterministic modes. It also offers integrated support for coupling with an external evolutionary optimization algorithm to identify tradeoffs among operating policies designed to perform well across a suite of user-defined objectives.
Developer: T.B. Wild (twild@umd.edu), A. Birnbaum, P. Reed, D.P. Loucks
Funding Sources: Cornell University's David R. Atkinson Center for a Sustainable Future (ACSF); National Science Foundation Grant No. 1855982
Source Language: Python
Dependencies: pandas, OpenPyXL, numpy, matplotlib, mpi4py, borg
Supported Systems: Linux, Windows
License: BSD-2 Clause
Availability: https://github.com/FeralFlows/PySedSim

1. Introduction

Plans exist for building over 3700 hydropower dams globally in the next 20 years (Zarfl et al., 2015). Intensive hydropower development is currently being planned in river basins that host over one third of the world's riverine biodiversity, including the Mekong, Amazon, and Congo, among others (Winemiller et al., 2016; Vörösmarty et al., 2010; Zarfl et al., 2019). Most of these rivers flowed freely several decades ago, but have recently experienced increased pressure from hydropower development. Currently, less than 25% of large rivers flow uninterrupted for their entire length (Grill et al., 2019). Given that hydropower dams are typically sited, designed, and operated to maximize power production rather than to preserve ecosystem health and productivity

* Corresponding author. Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA.
E-mail address: twild@umd.edu (T.B. Wild).

https://doi.org/10.1016/j.envsoft.2020.104947
Accepted 5 December 2020
Available online 9 December 2020

(IFC, 2015), they pose a direct and significant risk to several hundred million impoverished people who depend upon riverine ecosystem services to support their food security and economic welfare (McIntyre et al., 2016).

The world's most productive riverine ecosystems typically rely on highly dynamic and complex biophysical processes to drive productivity. For example, in the Mekong and Amazon River basins, a dynamic annual flood pulse drives productivity by annually transporting sediment, nutrients, and many fish species into floodplains. The floodplains then rapidly expand in areal extent, encouraging the exchange of energy between terrestrial and aquatic environments (Junk et al., 1989). Dams in such river basins, and elsewhere, have historically disrupted these natural processes, including altering natural flow regimes (Poff et al., 1997); trapping sediment (Vörösmarty et al., 2003) and nutrients (Maavara et al., 2015); preventing fish migration (Noonan et al., 2012; Bunt et al., 2012); and reducing ecosystem connectivity by fragmenting habitats, especially for migratory fish species (Andrén, 1994; Larinier, 2001; Fahrig, 2003; Noonan et al., 2012; Bunt et al., 2012). The externalities associated with dams have led some to argue that healthy freshwater fisheries and dams cannot coexist, especially in tropical river basins (Winemiller et al., 2016; Fearnside, 2016).

Regardless of these potential negative consequences, hydropower development is likely to proceed in many river basins globally (Moran et al., 2018). Given this reality, society could benefit from planning approaches that seek to support the discovery of more balanced outcomes with respect to ecological, energy, food, and other potential demands. To achieve this balance may require significant, integrated, and ecologically-focused modifications to the siting, design, and operation (SDO) features of planned dams (Wild et al., 2019a). Even in river basins where dams are no longer being planned but are instead being removed (e.g., in the United States), or retrofitted with ecologically-focused design features, it seems reasonable to explore significant reoperation of the modified network of dams to restore ecological integrity (Opperman et al., 2011). This will require a departure from the traditional hydropower development paradigm, which considers ecological concerns only after hydropower potential is optimized.

This study contributes PySedSim, an open-source, object-oriented, Python-based, daily time step river basin simulation model for flow, sediment, and hydropower in networks of reservoirs and river channels to facilitate exploring ecologically-oriented SDO alternatives. The model is designed for use in feasibility and pre-feasibility (IFC, 2015) screening assessments of alternative river basin infrastructure plans involving reservoirs. The model is flexible, both in its software design (e.g., object-oriented structure) and its core functionality and features (e.g., exploring tradeoffs across multiple conflicting objectives). PySedSim users can explore representations of four key concerns relevant to the selection and evaluation of alternative reservoir configurations: 1) management approaches to improve the passage of sediment through and around reservoirs to avoid storage capacity loss and downstream ecological impacts; 2) search for flexible and adaptive alternative reservoir operating policies designed to achieve multiple objectives; 3) alternative design features such as dam gates, reservoir bypasses, and other hydraulic infrastructure, which are necessary to enable ecologically focused reservoir operational practices (e.g., fish and sediment passage); and 4) uncertainties in hydroclimatic drivers and in the physical processes of sediment production, transport, reservoir trapping, and reservoir management. While some existing river basin modeling tools can address one or several of these concerns, we know of none that address them all in a single tool.

Modeling tools designed to support river basin infrastructure planning and management have tended to focus on water. Examples include IRAS (Matrosov et al., 2011; Loucks et al., 1995), WEAP (Yates, 2005), OASIS (Sheer, 2000), Riverware (Zagona et al., 2001) and Modsim (Labadie et al., 2000). Such water management-oriented models have not typically accounted for natural and managed sediment processes, such as alternative strategies for better managing sediment flows through and around reservoirs. Thus, they have not been effective for exploring options for managing basin-scale sediment balances via alternative dam network configurations and reservoir operation strategies. This lack of focus on sediment-related functionality in river basin planning models historically has occurred for at least two reasons. First, sediment transport and accumulation in reservoirs has not traditionally been viewed as a major objective of concern in river basin planning efforts (Annandale, 2013), despite the threat that reservoir sedimentation poses to water management and ecosystem health (Grant et al., 2003; Petts and Gurnell, 2005). Second, sediment production, transport, trapping, and management are complex to represent, particularly when it comes to the distribution and management of sediment within large networks of complex reservoir bodies.

The complexity posed by the movement of sediment through natural and man-made water bodies has led to the development of several models that consider sediment management at very fine spatiotemporal process resolution, and often for a small number of sediment management approaches such as reservoir flushing (Chang et al., 2003; Gallerano and Cannata, 2011; Khan and Tingsanchali, 2009; Shokri et al., 2013; U.S. Army Corps of Engineers, 2016; Danish Hydraulic Institute, 2017; Shin et al., 2019). Increased process resolution creates extra computational burden, and carries additional data collection requirements, such as river and reservoir bathymetry and sediment grain size distribution. This computational and data collection burden can make these higher-resolution tools difficult to deploy in the multi-objective, multi-reservoir, stochastic river basin planning contexts for which PySedSim was designed. There are some tools that take a coarser resolution approach to sediment simulation to enable basin-scale analyses. For example, Pal and Galelli (2019) and Tangi et al. (2019) have developed models capable of exploring options for controlling sediment flows and managing basin-scale sediment balances via alternative configurations of dam networks. These tools are very effective in basin-scale, sediment-focused infrastructure planning contexts, but they lack the detailed representations of reservoir and dam infrastructure required to explore the implications of alternative multi-objective reservoir operation strategies, including those seeking to improve water management, or increase the passage of sediment through or around reservoirs. Conversely, PySedSim simulates alternative reservoir sediment management strategies in reservoir networks with enough detail to capture the implications for sediment balances, hydropower, hydrology, ecology, and other considerations, but without so much detail that basin-scale Monte Carlo analyses are not possible. In particular, its representation of dam features (e.g., gates) and reservoir operations, and the ability to search for alternative operating policies designed to achieve multiple objectives, also make PySedSim suitable for use in a traditional stakeholder-driven river basin planning context, even when sediment is not a focus.

PySedSim has a software architecture that allows users to rapidly explore alternative SDO problem formulation hypotheses. This is integral to facilitating exploration and evaluation of candidate hydropower SDO modifications that may be necessary to reduce reservoirs' impacts on the ecological integrity of river basins. Indeed, the most effective modeling tools and scientific studies in influencing policy agendas have often been those that change the way key issues are defined and framed, and on the array of options for dealing with issues that are considered, rather than only the actions that are ultimately taken (Cash et al., 2003). PySedSim is intended to serve as a flexible iterative problem exploration framework (Fig. 1) that can be deployed to support deliberative decision-making processes.

Fig. 1 illustrates the deliberative decision support framework that PySedSim has been designed to support. It begins with initial problem formulation (Step 1), which includes defining objectives (deterministic or probabilistic), constraints, and uncertainties; the extent to which reservoir operating policies will be pre-specified or searched for; the network of reservoirs and river channel locations to be considered; reservoir design features such as dam gates; and reservoir sediment

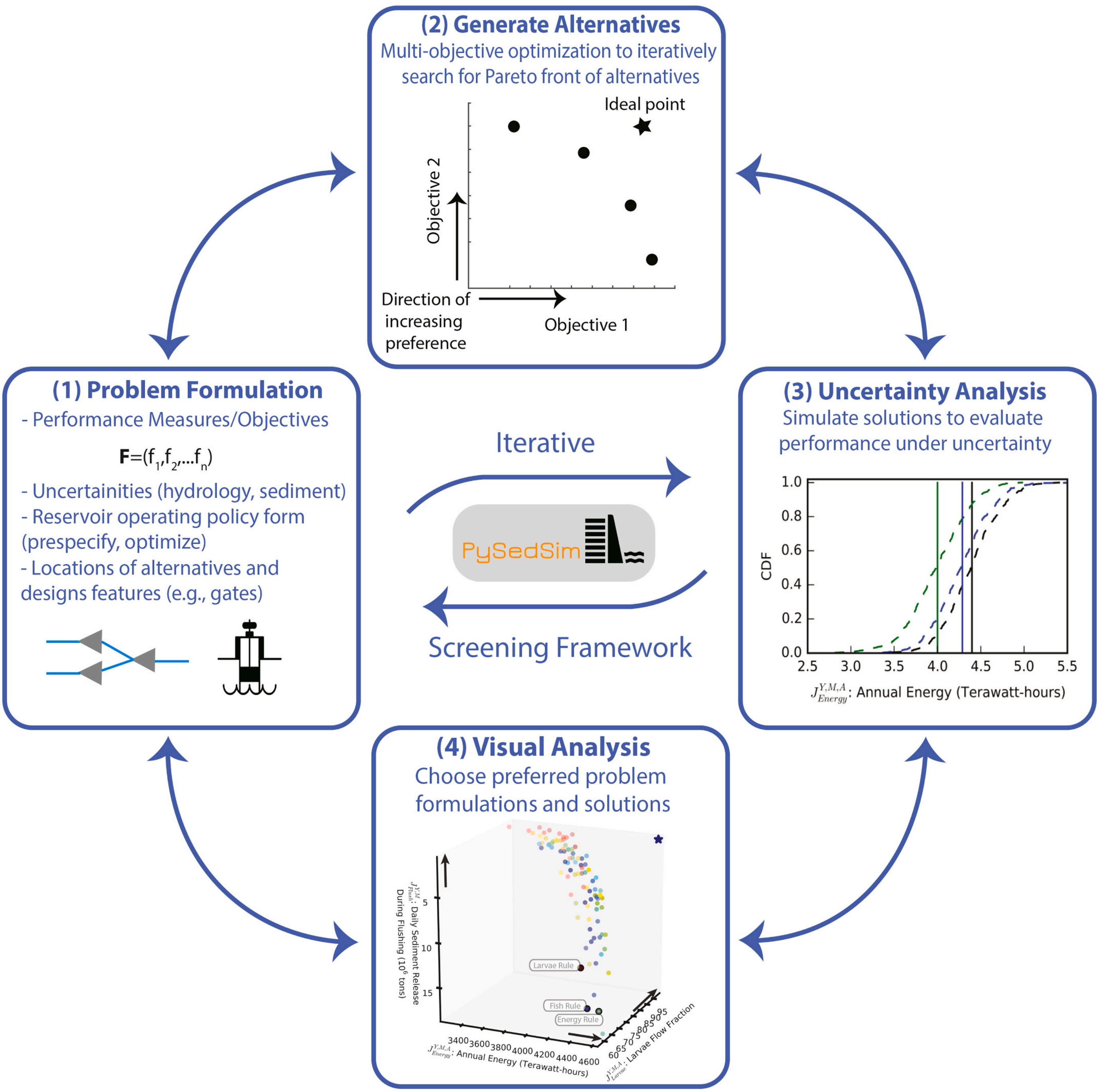

Fig. 1. PySedSim is best used as part of an iterative process that involves first formulating the problem (i.e., key uncertainties, style of reservoir operating policies, and performance metrics), specifying or generating alternative reservoir operating policies that satisfy the various performance metrics given the desired extent of uncertainty, and exploring the tradeoffs those many policies create. This iterative approach is illustrated in this paper through three alternative problem formulations that represent the real process undertaken by a team of experts during the pre-feasibility study of Sambor Dam in Cambodia.

management strategies to be applied. In Step 2, PySedSim leverages advances in multi-objective evolutionary optimization (Coello et al., 2007; Reed et al., 2013; Maier et al., 2014) to identify tradeoffs among objectives comprised of a suite of alternative reservoir SDO options. Some users may wish to initially skip this step, beginning instead with simulating pre-specified SDO options (e.g., reservoir rule curves in an existing reservoir design), returning later to optimization if warranted.

In Step 3, the performance of all (or a subset) of the identified or pre-specified alternatives can be simulated under a range of uncertainties in hydrologic and sediment processes defined in Step 1. In Step 4, users can connect to external visual analytic tools to navigate alternative solutions. This includes visually searching for policies that balance concerns across conflicting objectives and comparing the results across alternative formulations. Any given problem formulation may only involve a subset of these steps, and indeed any step along the way may offer some insight (e.g., into new objectives) that warrants returning to the problem formulation step to reframe the problem.

The remainder of this paper is organized as follows. The methodology section describes key PySedSim model features, functionality, and software design principles, and compares PySedSim to existing river basin models. The case study section introduces the design and operational context for the proposed Sambor Dam in Cambodia, for which we will demonstrate PySedSim's capabilities to analyze hydropower production, sediment management, and fish passage concerns. This section also introduces three alternative problem framings that are representative of the real decision context where PySedSim was used to iteratively (Fig. 1) identify and evaluate alternative SDO options for the Sambor Dam. Our results compare the insights gained from these alternative formulations, demonstrating how PySedSim facilitates iterative problem formulation and refinement to aid the discovery of decision-relevant insights in complex SDO contexts. Readers interested in detailed guidance on PySedSim features and use should also reference the model's user manual, which is available at the model's GitHub repository.

2. Methods

2.1. Classification of modeling functionality

Fig. 2 provides a graphical taxonomy for classifying PySedSim's functionality relative to existing tools that might be considered for use in a river basin reservoir planning context. The figure highlights common differences among existing models with respect to three categories (each shown in a different colored box): the processes they include (both physical processes and management processes), the mathematical representations of those processes, and the nature of the questions the model is designed to explore (e.g., simulation versus optimization). Within each of the three colored boxes there exist categories of choices, each of which is represented by a tree. In general, these trees are intended to describe some of the key features that models used in a river basin planning context may have. Options within a given tree are not necessarily mutually exclusive modeling choices. For example, models such as PySedSim can have both deterministic and stochastic simulation options, and may even represent different processes with different levels of detail. Boxes outlined in red are used to highlight where PySedSim's features reside within this hierarchy of potential modeling choices.

Beginning with Box I ("Processes Included"), river basin models often include representations of natural physical processes, which describe how water and sediment move through the natural landscape (e.g., rainfall and runoff); as well as management processes, which describe the various ways in which these natural processes may be modified by infrastructure (e.g., management of water and trapping of sediment in reservoirs). Striking a balance between computational demands and end use purpose, PySedSim is limited in its abstraction of detailed natural physical processes. In the water resources domain, natural physical processes frequently accounted for in models include rainfall, runoff, groundwater infiltration, and channel flow. Among these processes, PySedSim accounts only for routing of flows through networks of river channels, relying on user-selected external models (e.g., SWAT) for the other processes. With respect to sediment, models are often classified as either loading models, which account for production of sediment suspended in watershed runoff, or as receiving models, which route sediment through channels and reservoirs (Kalin and Hantush, 2003). PySedSim is a receiving model, designed to receive input from a loading model (e.g., SWAT). An important difference among receiving models is with respect to the degree to which sediment management processes are included. PySedSim includes numerous sediment management processes, such as the trapping of sediment in reservoirs, the distribution of that sediment within reservoirs' storage geometry, and the various ways in which sediment can be removed or passed through or around reservoirs.

In reviewing existing river basin simulation models (e.g., Matrosov et al., 2011; Loucks et al., 1995; Yates, 2005; Sheer, 2000; Zagona et al., 2001; Labadie et al., 2000), we found a dearth of models that include treatment of both sediment and water processes, especially reservoir sediment management. Sediment management-focused models typically do not include detailed representations of water management issues. Likewise, water management-focused models typically do not explicitly account for any of the natural or managed sediment processes from Box I. PySedSim includes water management features such as reservoir operations and river routing capabilities, though it does not include water demand and supply modeling, or groundwater, which water management-focused models typically do.

Box II ("Process Representations") in Fig. 2 shows that all of the natural and managed water and sediment processes from Box I can be represented with varying degrees of complexity, including the mathematical representations of relationships, the extent to which uncertainty is represented, and the resolution of the model in both space and time. PySedSim employs empirical process relationships with a specific intent to enable SDO analyses given the data-limited nature of most problem settings. It also offers the flexibility to explore, through Monte Carlo simulation, the uncertainty in the numerous parameters that define these empirical relationships, including parameters for sediment production, sediment transport, reservoir sediment trapping, and reservoir sediment management. With respect to spatiotemporal resolution, PySedSim is a lumped model in that users are permitted to define parameters for discrete model elements (e.g., river channel segments). The model is a one-dimensional fixed-bed model, in that it does not explicitly represent channel or reservoir cross-sections and their feedbacks with flow processes, as can be accounted for in more detailed models such as HEC-RAS (U.S. Army Corps of Engineers, 2016). A daily time step was selected to facilitate coupling with existing daily time step loading models such as SWAT.

With respect to process representation in reservoir sediment management, models focused on sediment management often represent only a limited number of alternative sediment management strategies, such as flushing (e.g., Chang et al., 2003; Gallerano and Cannata, 2011; Khan and Tingsanchali, 2009; Shokri et al., 2013), and do so at fine resolution. Such detailed process representations require more data, such as sediment grain size distribution and reservoir bathymetry. Detailed simulations also tend to be more computationally intensive and are difficult to embed within a broader multi-reservoir network simulation. For example, HEC-RAS (U.S. Army Corps of Engineers) and Mike21C (Danish Hydraulic Institute, 2017) offer physically-based simulations of management processes such as sluicing and flushing. Conversely, PySedSim enables less detailed assessments of multiple alternative sediment management strategies for large-scale multi-reservoir systems.

Box III ("Identification and Evaluation of Management Actions") within Fig. 2 highlights how existing models differ in the questions they are designed to answer. PySedSim is a simulation model in that it addresses "what-if" scenarios—what may happen if a particular scenario (e.g., hydroclimatic inputs or reservoir network configuration) is assumed or if a particular decision (e.g., reservoir operating policy) is made. Conversely, optimization models seek to identify the "best" decision or tradeoffs among alternative equally optimal decisions. While PySedSim is a simulation model at its core, it facilitates direct coupling with external optimization models. Finally, as with process representations, management actions can be identified and evaluated in both deterministic and stochastic (Monte Carlo) contexts in PySedSim. For example, the model's stochastic simulation-optimization functionality will search for robust operating policies that perform well under a range of future uncertainties. PySedSim is a "preliminary screening model" (Loucks and Van Beek, 2017; Loucks 2020) in that its best use is to explore a wide range of alternatives and the tradeoffs in performance across them. The coupled simulation-optimization functionality enables users to "screen out" a large number of less desirable alternatives, leaving a relatively smaller number of potentially desirable alternatives to be evaluated later with other, more detailed (e.g., finer spatiotemporal resolution) simulation models. For example, during the hydropower project development process (IFC 2015), this more detailed modeling is typically done during the detailed design phase, rather than during preliminary screening of alternatives. This detailed phase of analysis could also include higher-resolution assessment of specific sediment management alternatives (e.g., sluicing, flushing, dredging, etc.) at specific reservoir sites (e.g., using process-based models like

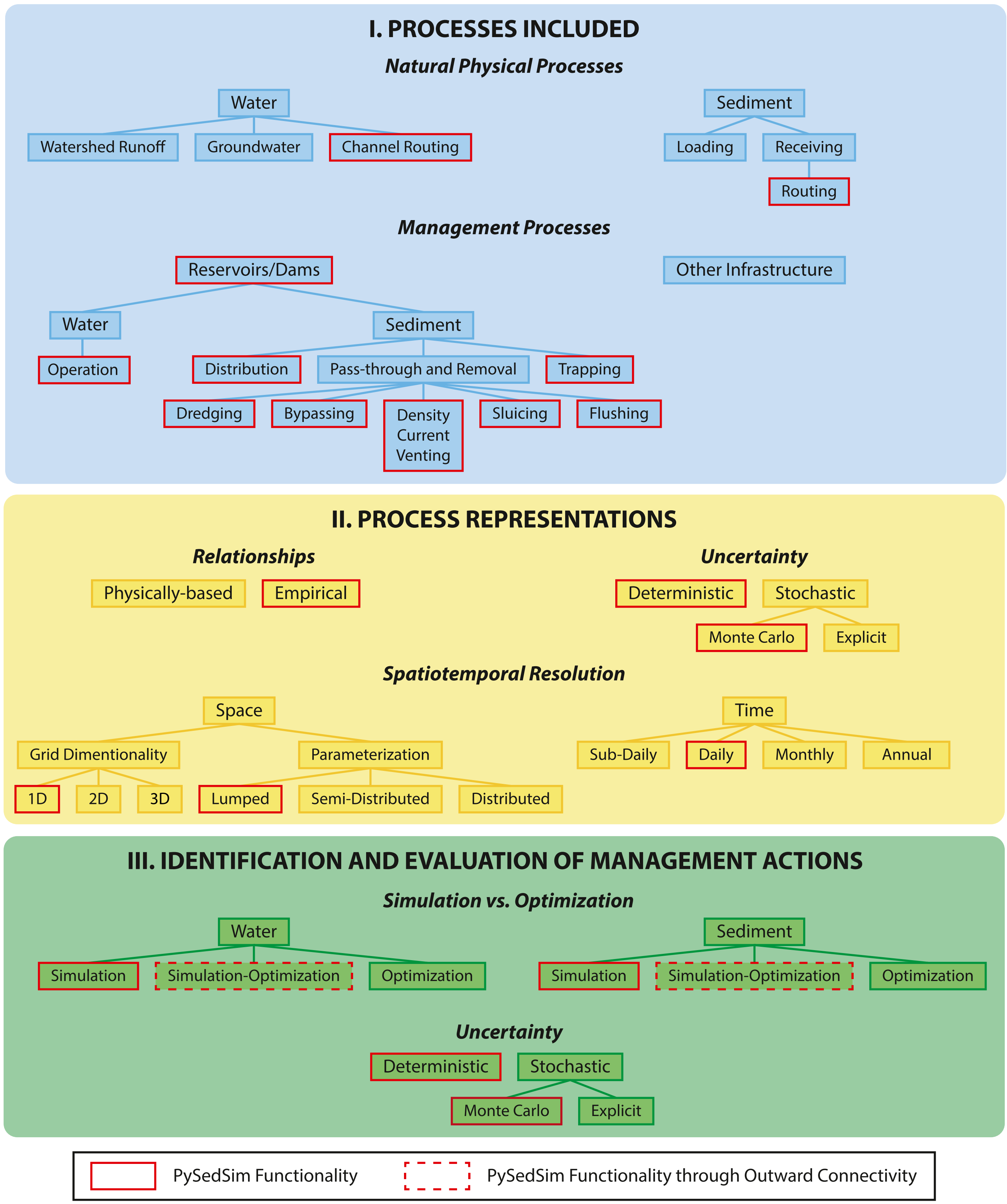

Fig. 2. Classification diagram of key differences in model functionality among the range of existing modeling tools that might be considered for use in the river basin infrastructure planning context for which PySedSim was designed.

HEC-RAS).

2.2. Detailed model functionality and assumptions

2.2.1. Overview

PySedSim includes a unique combination of four core model features: 1) representing alternative reservoir sediment management approaches, 2) representing detailed dam design features (e.g., gates), 3) supporting multi-objective optimization frameworks for discovering reservoir operating policies and their resulting tradeoffs, and 4) facilitating stochastic Monte Carlo simulation for characterizing uncertainty in hydrologic and sediment processes. Fig. 3 illustrates some of these model features in the context of an example PySedSim simulation network of river channel segments, reservoirs, and connecting junctions, through which water and sediment are routed and stored on a daily basis in a simulation. Any PySedSim simulation network is comprised of some combination of these three building blocks. The features illustrated in Fig. 3a are organized into two categories: sediment (left) and water (right).

2.2.2. Natural water and sediment processes

In keeping with its intended use as a screening model, PySedSim employs relatively simplistic (i.e., empirical) approaches to representing complex sediment processes, including sediment production, transport, reservoir trapping and distribution, and reservoir management (left-hand side of Fig. 2). At its core, PySedSim includes most of the sediment simulation functionality present in the SedSim simulation model (Wild et al., 2019b; Wild and Loucks, 2015a; https://github.com/FeralFlows/SedSim), but with new features that support stochastic simulation and multi-objective optimization. *SedSim* has been applied in other studies to evaluate the hydrologic, sediment, and hydropower implications of reservoirs (Wild and Loucks 2014, 2015b, 2016; Souter et al., 2020). While PySedSim's python-based, object-oriented software design (section 2.4) is much different from SedSim's Visual Basic for Applications (VBA)-based software design, both models allow users to exploit the same EXCEL-based interface if desired. This simple interface ensures backward compatibility with previous SedSim applications, and facilitates training of less advanced users (e.g., river basin stakeholders).

As shown in Fig. 3b, water and sediment can only enter the modeled system at junctions. Flows specified at junctions represent incremental daily water and sediment runoff from the local watershed (i.e., between successive incremental flow junctions). The model simulates a single median sediment grain size rather than a grain size distribution. Junction inputs must be externally gathered (e.g., from gage station data) or generated (e.g., simulated with a separate model such as SWAT (Neitsch et al., 2009)). Users can also specify parameters for a rating curve function that describe daily sediment load production as a function of daily hydrologic flow.

Water and sediment entering a junction in a given day immediately enter the next downstream channel segment or reservoir, and are thereafter routed through that downstream element along with any sediment and water entering from upstream. Fig. 3c depicts this routing process for an example river channel segment *i*. The model maintains flow routing options consistent with some of those available in the SWAT model (Neitsch et al., 2009), including Manning's equation routing. As shown in Fig. 3c, each channel segment is assumed to have a 'carrying capacity' (Bagnold, 1977) to produce suspended sediment in its outflow as a power function of water outflow rate. If the concentration of sediment suspended in the water column exceeds the channel's carrying capacity, some sediment settles to the channel bed (i.e., deposition dominates). Otherwise, sediment is scoured from the channel bed (i.e., resuspension dominates).

2.2.3. Managed water and sediment processes

2.2.3.1. Reservoir sediment trapping, distribution, and management. The model includes representations of reservoir sediment trapping, distribution, and management processes (as shown in Fig. 3d). The fraction of inflowing sediment mass trapped in a reservoir during each time period, or trapping efficiency, is determined as a function of sediment particle size and residence time of water in the reservoir (Brune, 1953). This results in declining trapping efficiency with declining storage capacity (Minear and Kondolf 2009; Morris and Fan, 1998). Within the reservoir's storage capacity, the volume occupied by settled sediment mass depends on its user-specified bulk density. Fig. 3d shows that the model differentially distributes deposited sediment within the reservoir's active and dead storage zones (Lara and Pemberton, 1963), which captures the impact of sedimentation on reservoir operations.

Despite the availability of techniques to improve sediment passage through and around reservoirs (Kondolf et al., 2014b; Annandale 2013), planning studies of large reservoir networks typically focus on predicting sediment trapping (e.g., Kummu et al., 2014; Kondolf et al., 2014), rather than on assessing the potential to reduce it (Wild et al., 2016, 2019a; Wild and Loucks, 2014; Schmitt et al., 2018). This capability is needed when simulating alternative dam development configurations in basins such as the Amazon, Congo, and Mekong, as these river basins transport among the world's highest annual sediment loads (Milliman and Meade, 1983). Fig. 3 does not depict PySedSim's representations of sediment management processes, which are relatively more complex and therefore appear in the model's user manual. In general, PySedSim employs empirical approaches to simulating the effectiveness of flushing (Atkinson, 1996), sluicing (Churchill, 1948), and density current venting (Morris and Fan, 1998) at removing or passing sediment through a reservoir. Before considering simulating particular reservoir sediment management techniques with PySedSim, an external model such as RESCON should first be used to assess the economic and technical feasibility of those techniques given the reservoir's site-specific characteristics (Palmieri et al., 2003, Efthymiou et al., 2017).

2.2.3.2. Reservoir operations and dam design features. Reservoirs are assumed to be regulated by a dam, the daily outflows from which are determined by an operating policy, subject to constraints related to the dam's outlet works and primary operational objectives. As listed on the right-hand side of Fig. 3, PySedSim offers flexibility in exploring reservoir operations. Numerous studies have noted the potential value of optimization in contributing to the ongoing multi-objective river basin development dialogue globally (Sabo et al., 2017; TNC, 2016; Ziv et al., 2012; Opperman et al., 2015; Grill et al., 2014, 2015; Roy et al., 2020; Cronin et al., 2016; Kondolf et al., 2018; Schmitt et al., 2018; Wild et al., 2019a; Schmitt et al., 2019; Intralawan et al., 2018; Song et al., 2020). PySedSim has been developed to support the flexible representation of candidate reservoir operations and simulation of their performance. The software offers specific support for the evolutionary multi-objective direct policy search (EMODPS) analytic framework (Giuliani et al., 2016; Guariso et al., 1986; Oliveira and Loucks, 1997; Koutsoyiannis and Economou, 2003) for quantifying operational tradeoffs. The EMODPS simulation-optimization framework is implemented by facilitating a full coupling of PySedSim with external multi-objective evolutionary optimization algorithm (MOEA) solvers (Coello et al., 2007; Reed et al., 2013; Zatarain Salazar et al., 2016). The closed-loop feedback structure of the identified operating policies can flexibly adapt to changing site conditions, where site conditions can be abstracted using any relevant reservoir state variables as inputs (e.g., water surface elevation, inflow, and time of year). Objectives are defined by the user as a function of any PySedSim model state variables (e.g., daily suspended sediment passage, flow rates, etc.) for any system element (i.e., junction, reservoir, or channel). The ability to identify adaptive operating policies is a distinct advantage in assessing the potential for SDO alternatives to

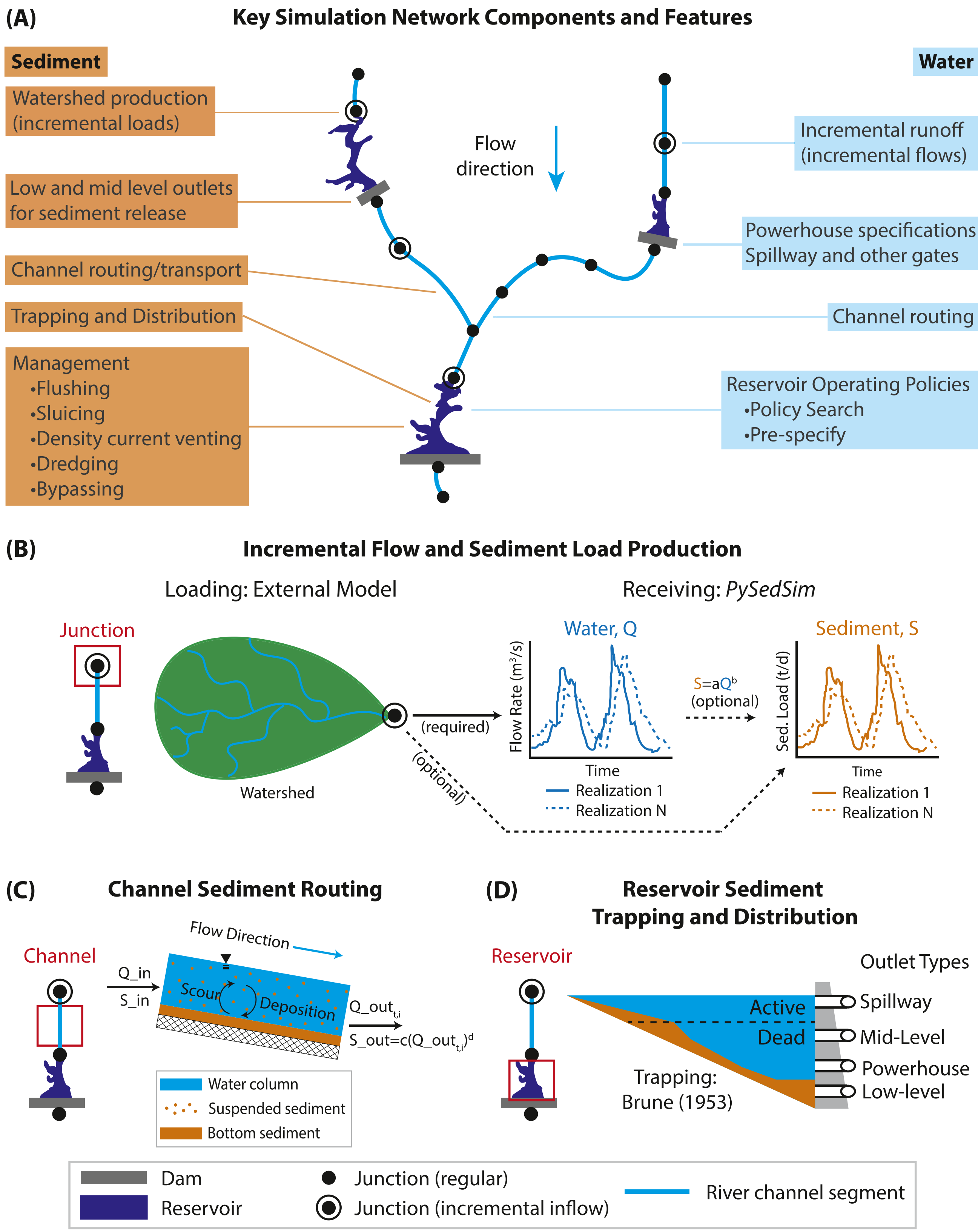

Fig. 3. (a) Schematic of a PySedSim simulation network composed of three building blocks: reservoirs, river channel segments, and the junctions that connect them. Core simulation processes and model features are highlighted with colored boxes, blue representing water and brown representing sediment. (b) deterministic or stochastic time series of incremental flow and sediment enters the modeled system at incremental junctions. (c) Channel processes include flow and sediment routing. (d) Sediment trapping is simulated using Brune (1953), then distributed within the active and dead storage zones per user specifications. Multiple dam outlet (i.e., gate) types can release water and sediment.

mitigate ecological impacts (Wild et al., 2019a). The theoretical details of PySedSim's EMODPS approach to identifying tradeoffs composed of alternative reservoir operating policies appears in Wild et al. (2019a), as well as in the model's user manual.

While PySedSim directly supports a search for alternative reservoir operating policies, the software's architecture also theoretically enables searching alternative relevant decision spaces, such as the locations of reservoirs in networks, by including these decision variables among those that define reservoir operating policies. The code modifications required to do this are discussed in the user manual at the paper's online repository. Conducting such joint planning-management simulation-optimization, particularly for large scale systems (e.g., with numerous dams), creates the potential for steep computational expense. This is one of the reasons that such joint planning-management analysis has long posed a challenge in the water resources and environmental systems literature (Zeff et al., 2016; Loucks and van Beek, 2017; Wild et al., 2019; Bertoni et al., 2019; Herman et al., 2020; Trindade et al., 2020). The EMODPS approach PySedSim uses to explore tradeoffs across alternative portfolios of decision variables avoids the "curse of dimensionality" (Bellman, 1957) that limits the power of dynamic programming-based approaches in joint planning-management contexts (Giuliani et al., 2016).

In order to accurately evaluate sediment removal, sediment passage, and fish passage, PySedSim enables users to explore the performance of dams with alternative detailed design features. This includes not only reservoir storage capacity and geometry (i.e., elevation-volume-area curve) but the presence of low-level outlets, mid-level outlets (i.e., sluice gates), spillways, and hydraulic bypass channels, and their specifications (e.g., elevation-discharge capacity curves).

2.2.4. Uncertainty analysis

The effectiveness of the previously discussed design and operational features can be evaluated in either stochastic (Monte Carlo) or deterministic mode. This enables users to explore performance of alternative operating policy and design configurations under different hydrologic and sediment uncertainties, as well as to identify SDO features that perform robustly under these uncertainties. PySedSim's Monte Carlo functionality enables users to sample the multiple empirical model parameters employed in representing sediment processes, including sediment production from the watershed, transport in river channels, trapping in reservoirs, and various representations of reservoir sediment management processes. Parameter sampling is possible across a diverse array of probability distributions (e.g., normal, uniform, triangular, etc.). To explore uncertainty in hydroclimatic conditions, users may generate stochastic sequences of daily hydrologic and sediment inflows using external models or techniques (e.g., Stedinger and Taylor, 1982). PySedSim provides support for Monte Carlo simulation by sampling these externally-generated time series and organizing the stochastic simulation results.

In comparing PySedSim to other river basin simulation models, we found widespread exclusion of uncertainty analysis capabilities regardless of a model's core process focus (i.e., water or sediment). In the water management domain, existing models are often limited in their ability to handle even well-characterized (e.g., hydroclimatic) uncertainty. Uncertainty analysis is theoretically possible in any simulation model for which execution can be automated, but many models do not directly support Monte Carlo simulation with simple user specifications. With respect to sediment management, few models include stochastic representations of the sediment management processes (e.g., Shokri et al., 2013). Regardless, accounting for uncertainty in models with very detailed representations of sediment management would render these models even more unlikely to be applicable in a river basin planning setting. The capability to evaluate the impacts of key uncertainties is foundational to evaluating the risk-driven objectives of decision relevance in many river basins (Quinn et al., 2017).

2.3. Software design

As illustrated in Fig. 4, PySedSim's software architecture is designed to support flexibility, extensibility, transparency, provenance, and scalability. Flexibility is addressed by providing a breadth of river basin and infrastructure features that can be readily represented in SDO applications. Transparency refers to the extent to which model users and prospective developers can view and understand the software's design and structure. Provenance refers to the chronology of ownership and development of a model. Scalability refers to PySedSim's ability to be implemented across a range of computing resources, from laptops to high-performance parallel supercomputers. This helps users to effectively manage the computational demands in their analyses (e.g., simulations of larger systems, uncertainty assessments, simulation-optimization). Finally, extensibility refers to facilitating a broad range of analytical workflows that exploit current and emerging software tools. Each of these five software architecture design features is addressed separately below.

Flexibility is achieved in PySedSim through object-oriented and modular software design. The enlarged box on the upper right-hand side of Fig. 4 demonstrates a simplified Unified Modeling Language (UML) diagram of a representative sample of core PySedSim classes and their hierarchical relationships. This serves as just one example of the numerous classes used to organize the model's key processes and features. Core sub-classes are shown at the bottom of the UML diagram. Any given model application requires creating multiple of these core sub-classes and piecing them together into a unique network of reservoirs, channels, and junctions. PySedSim's object-oriented design facilitates integration of multiple energy and ecological concerns into a single model, because prospective co-developers can easily extend the model's functionality to include new or different ecological or other concerns.

PySedSim facilitates extensibility through outward connectivity to external Python-based packages and tools. The enlarged box on the lower right-hand side of Fig. 4 provides a sample of existing connections between PySedSim and external python packages, as well as examples of potential future external connections. Some packages are required for PySedSim to run basic simulations, whereas others are used to extend PySedSim's functionality only in select circumstances (e.g., optimization). For example, Fig. 4 shows that to facilitate identification of tradeoffs and optimization of operating policies, PySedSim connects to the Borg multi-objective evolutionary optimization algorithm (Hadka and Reed, 2013). While PySedSim directly supports the Borg MOEA, PySedSim can be coupled with any open-source MOEA that is Python-based or has a Python wrapper, such as the Project Platypus library (https://github.com/Project-Platypus/Platypus). To facilitate scalability, especially in Monte Carlo simulation or simulation-optimization experiments, PySedSim uses the Python-based Message Passing Interface for Python (i.e., mpi4py) package (Dalcin et al., 2005, 2008, 2011). To facilitate user interaction with the model software and efficient data import, PySedSim uses the Python-based OpenPyXL library to import Excel-based data (Gazoni and Clark, 2017). To facilitate data processing and export, PySedSim uses the Python-based pandas software for panel data manipulation and analysis (McKinney, 2012) to organize, process, and export simulation data. By enabling the use of an Excel-based user interface and efficient production of data outputs, these connections facilitate PySedSim's goal to serve as a decision support system (Loucks, 1995). To facilitate data visualization, PySedSim uses the matplotlib package (Hunter, 2007). To facilitate use of external hydrologic and sediment modeling tools, PySedSim is built to accept inflows and sediment loads in the same style as those produced by the SWAT model (Neitsch et al., 2009). Such external modeling exercises (e.g., SWAT) that enhance PySedSim analyses often require extensive expertise and data sets. Thus, PySedSim applications can benefit from leveraging the modeling outputs produced by other, more-detailed studies. While the model does not currently connect directly to an external Python-based stochastic hydrology

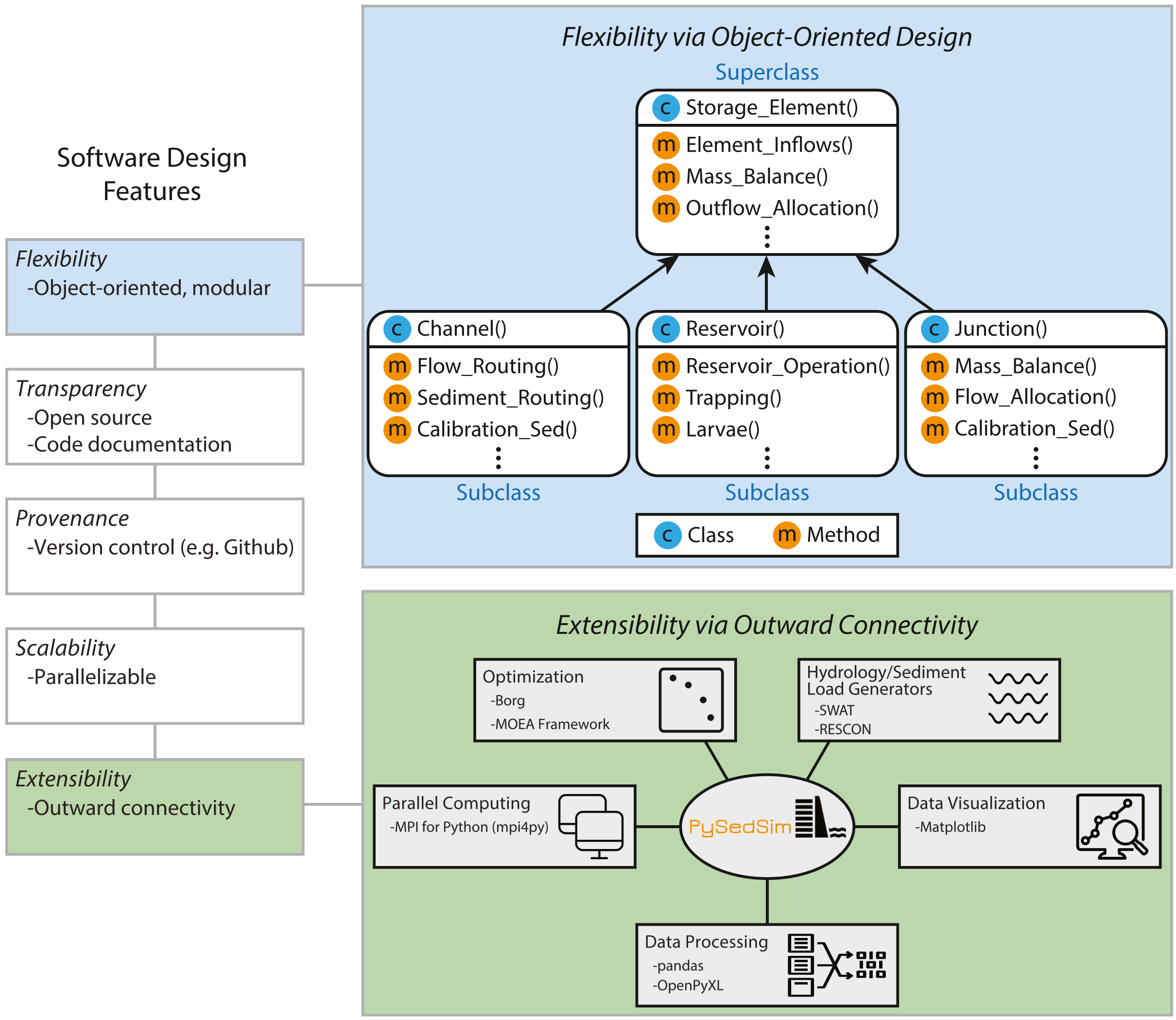

Fig. 4. PySedSim's five core software design features (left hand side): flexibility, transparency, provenance, scalability, and extensibility. Flexibility and extensibility are highlighted (right-hand side).

package for hydroclimatic uncertainty analysis, the model is structured to facilitate establishment of such a future connection, as well as to Sensitivity Analysis libraries (e.g., the sensitivity analysis library SALib developed by Herman and Usher, 2017).

In a river basin modeling context, transparency is likely the single most important factor in facilitating replicability and reproducibility (Ceola et al., 2012), which are often overlooked but fundamentally important requirements for designing and executing sound scientific experiments (Peng, 2011). Transparency also encourages extensibility by enabling users to more effectively understand and extend the model. PySedSim is transparent via its object-oriented and modular code design, and extensive in-code documentation, which clarify model structure; by providing fully replicable example model applications, which are explored in this paper; and in that the code is open-source. The model's open-source repository facilitates provenance by enabling co-developers to contribute code on the model's public repository. Finally, scalability is important in the context of evolutionary optimization methods, which can require many simulations to converge on reliable solutions. PySedSim is scalable in that it supports cluster-based parallelization of simulation-optimization and Monte Carlo simulation experiments. This functionality is available to users through several PySedSim functions that optionally call the mpi4py package. Details are provided in the model user documentation and in function docstrings.

3. Model application case study: Sambor Dam, Mekong River basin (Cambodia)

3.1. Background

The Mekong River in Southeast Asia is one of the world's most productive and dynamic rivers, hosting an open-access wild capture fishery of over 1200 fish species (Poulsen et al., 2004). The basin's 60 million inhabitants rely on the river for food and income security, harvesting 2.1 million metric tons of fish per year at a retail value of up to $7.8 billion US per year (Hortle, 2009). Less than 30 years ago, the river (Fig. 5a) flowed freely for 4350 km (MRC 2016). Today, over 40 large hydropower dams exist, with over 100 more dams proposed or under construction (MRC 2016). The proposed Sambor mega Dam has been a major focus for the Government of Cambodia (GoC) in its efforts to generate hydropower revenue and secure a reliable domestic energy supply.

Sambor's original design (China Southern Power Grid Company, 2008) was proposed to extend 18 km across the Mekong River, which would make it one of the world's longest dams (Lehner et al., 2011). As the basin's downstream-most proposed dam, it would be sited in proximity to Tonle Sap Lake, one of the world's most productive freshwater lakes (Lamberts, 2006) that provides up to 80% of Cambodia's protein in some areas (Hortle, 2007). Over 50 species of fish annually migrate

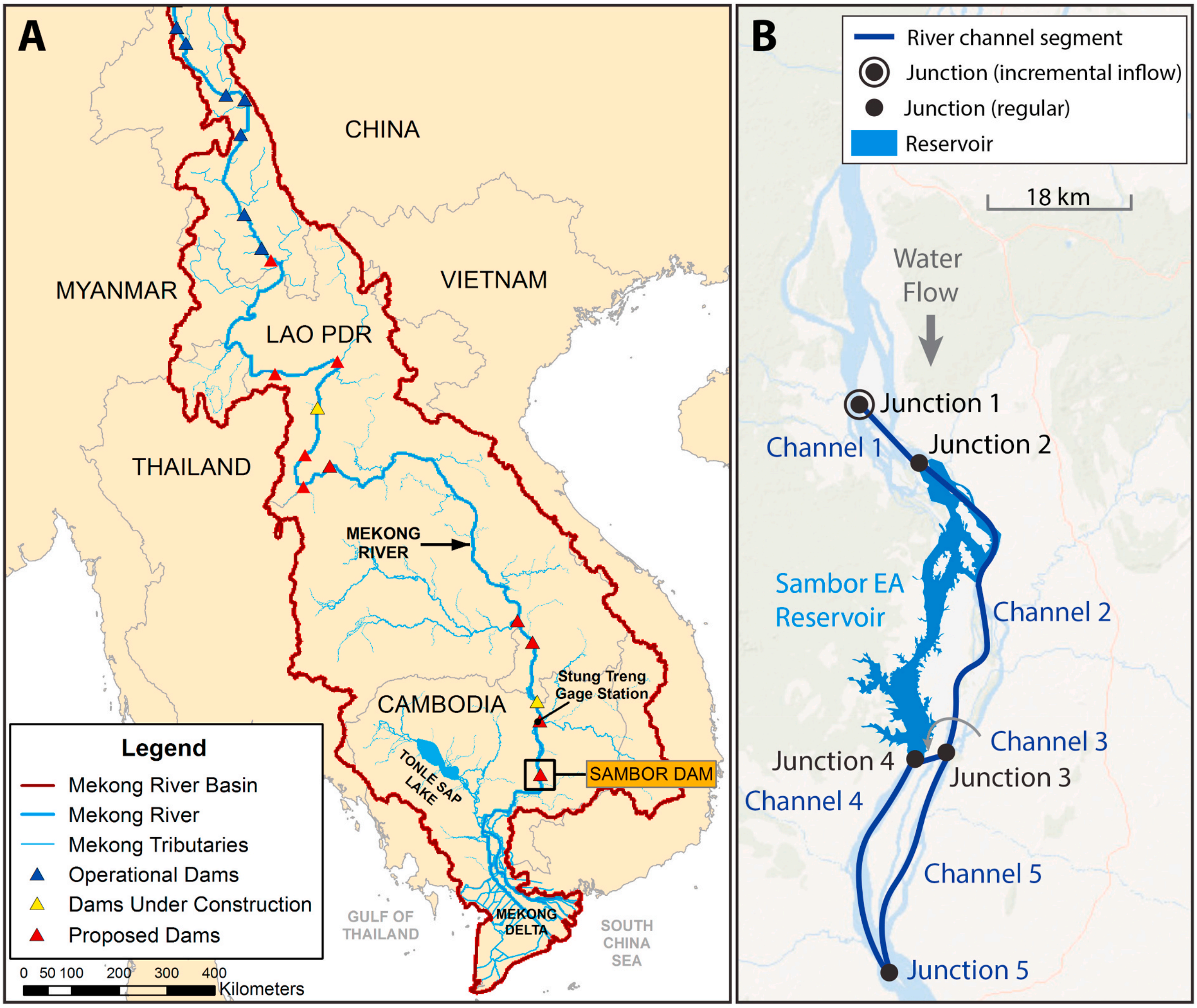

Fig. 5. (a) Sambor EA reservoir and dam location in the Mekong River basin. (b) Plan view of Sambor EA reservoir as a schematic showing the *PySedSim* simulation network of reservoirs, river channel segments, and junctions. In PySedSim's object-oriented structure, each of these core elements is defined by a class. Users define element names for Sambor EA that then become instances (i.e., objects) of these classes.

upstream past the planned dam site to main stem and tributary spawning grounds (Barlow et al., 2008; Halls and Kshatriya, 2009). After spawning, the fish swim downstream past the planned dam site, returning to the floodplains to feed. Eggs laid in tributaries become larvae that naturally passively drift back downstream to the floodplains while suspended in the river's flow. Nearly all of the Mekong's natural 160 Mt/y sediment load is transported annually past the dam site as well. Designed to maximize energy production, the Sambor design poses fundamental ecological concerns because it would provide inadequate means of passing the river's significant migratory fish biomass and would be too large and wide to effectively pass sediment, nutrients, and fish larvae downstream (Wild and Loucks, 2015b).

In a multi-year partnership with the GoC (NHI, 2017), Wild et al. (2019a) used PySedSim to study the potential for alternative Sambor Dam SDO options to produce more balanced outcomes with respect to ecological and energy production goals. As shown in Fig. 5, an alternative dam concept, Sambor Ecological Alternative (i.e., Sambor EA), was identified that includes numerous siting and design features to encourage sediment and fish passage. The dam's salient design feature is a completely unregulated natural bypass channel to the east of the reservoir that exists to facilitate sediment passage and fish migration. Sambor EA's geographic location is shown in Fig. 4a. Fig. 4b shows a plan view of the dam and reservoir, overlaid by a PySedSim model schematic of the river channel segments, junctions and reservoir that make up the PySedSim implementation of Sambor EA used for demonstrative purposes in this paper. Ultimately, the iterative process of exploring Sambor alternatives (described in Section 3.2) contributed to the success of NHI (2017) in directly influencing the GoC to postpone all mainstem Mekong dam construction (Ratcliffe, 2020).

3.2. Iterative problem formulation overview

PySedSim supported the stakeholder engagement and pre-feasibility planning process surrounding Sambor and Sambor EA (NHI, 2017) through an extended, iterative problem formulation and exploration process with basin stakeholders (Fig. 1). In this paper we demonstrate PySedSim's use across three formulations that compare searching for (rather than pre-specifying) operating policies, conducting stochastic versus deterministic analysis, and exploring combinations of multiple performance metrics that reflect diverse stakeholder preferences. Each candidate formulation builds upon prior formulations to arrive at final recommendations to decision makers (NHI, 2017).

To evaluate performance across formulations, we evaluated Sambor EA reservoir operation alternatives using daily simulation output from the six PySedSim state variables below, which we selected to reflect diverse stakeholder preferences.

1. **Daily energy production (GW·h), E.** Hydropower production at the Sambor EA powerhouse.
2. **Daily bypass attraction flow rate (m^3/s), F.** The bypass channel in Fig. 5b will be the primary route for fish to circumnavigate the dam. This variable represents the attraction of fish into the bypass channel during upstream migration (Bunt et al., 2012; Noonan et al., 2012).
3. **Daily larvae flow fraction (unitless, 0–1), L.** Larvae can die due to predation and starvation if they are trapped in a reservoir while drifting downstream (Agostinho et al., 2007; Pelicice and Agostinho, 2008; Pompeu et al., 2011; Suzuki et al., 2011; Pelicice et al., 2015). This variable uses the fraction of main stem flow each day that either enters the bypass (i.e., safe passage), or enters the reservoir when velocities are suitable for passage (Fig. S1), to estimate the daily fraction of larvae safely passing the site. Wild et al. (2019a) describe the modeling approach to evaluate suitability of reservoir hydraulic conditions for larvae passage.
4. **Daily trapped sediment load (kg), S_T.** This variable represents the suspended sediment load trapped in the reservoir's storage capacity. The river's suspended sediment load sustains the river's geomorphic structure (Rubin et al., 2015) and habitats (Halls et al., 2013), transports nutrients (Liljeström et al., 2012; Arias et al., 2014), and slows the subsidence of the Mekong delta landform, which poses an existential threat to its nearly 20 million inhabitants (Kondolf et al., 2018; Schmitt et al., 2017).
5. **Daily reservoir total storage capacity loss (%), S_C.** This variable represents the loss in total reservoir storage capacity (m^3). Total storage capacity is the sum of "active" storage capacity, which is accessed during normal operations, and "dead" storage capacity. Sedimentation reduces reservoir storage capacity and hence energy production and reliability, as well as other benefits dams provide (Mahmood, 1987; White, 2001). Globally, storage capacity is being lost in reservoirs at a rate of 0.5%–1% per year (Mahmood, 1987; White, 2001).

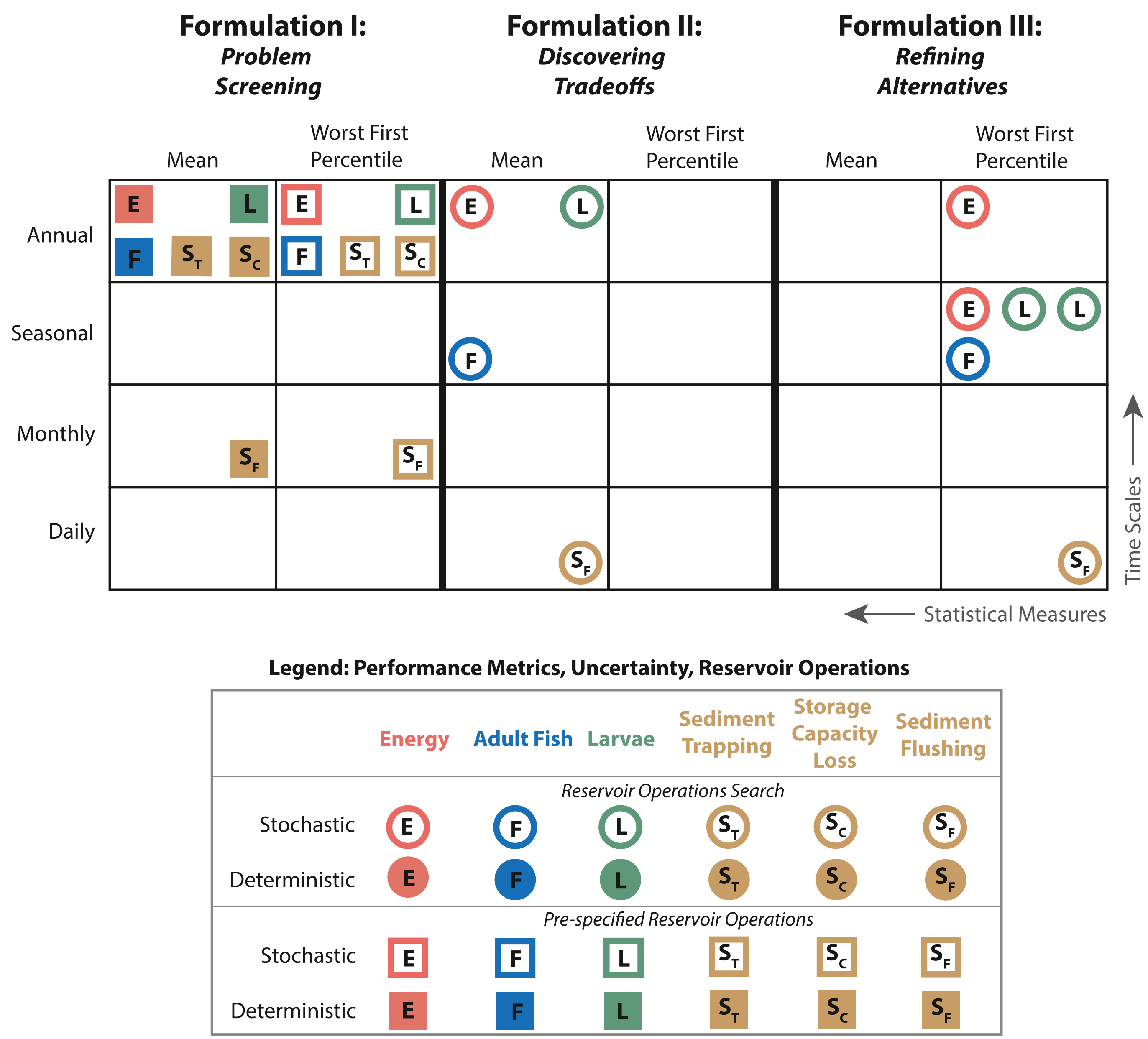

Fig. 6. Comparison of three alternative problem formulations seeking to identify balanced reservoir operation strategies for the Sambor EA Dam (shown in Fig. 5b) with respect to the use of optimization, inclusion of uncertainty, and the number and nature of performance metrics used to evaluate policies.

6. **Daily sediment load released from the dam during flushing events (kg)**, S_F. To enable passage of sediment through the site, our simulations implemented annual sediment sluicing (i.e., pass-through) and flushing (i.e., removal). The less frequently flushing takes place, the larger the short-term sediment pulses released downstream become relative to natural conditions, thereby posing risks to ecosystems downstream (Wild et al., 2016).

We summarized each daily time series variable temporally (e.g., annually, monthly, or daily) and statistically (e.g., mean and quantile) to create decision-relevant performance metrics, such as mean annual energy production. Detailed mathematical definitions of these performance metrics are provided in Section II of the paper's Supplement. In particular, Table S3 shows each formulation's performance metrics and corresponding equations. Fig. 6 summarizes the key differences across the three formulations with respect to performance metrics. Each formulation has a potential space of 2 columns and 4 rows in which performance metrics can reside. Columns represent the nature of statistical metrics of performance, focused on either risk neutral mean performance or a more risk-averse worst first percentile of the empirical cumulative distribution function, depending on the formulation. Rows represent the time scales of interest for each of the performance metrics, ranging from daily to annual. Within each formulation, each individual shape (i.e., square or circle) in the figure corresponds to a different metric. Squares reflect pre-specification of reservoir operating policies, whereas circles reflect a search for operating policies via optimization. The color of a shape represents the category of its corresponding performance metric, including sediment, fish, larvae, and energy. The sediment (i.e., brown-colored) category includes all three of the sediment-related time series variables discussed previously. Filled and hollow shapes correspond to deterministic and stochastic simulation of metrics, respectively.

Deterministic evaluations consisted of a historical simulation using the full 100-year long flow record available at the Stung Treng gage station near the Sambor EA dam site. Alternatively, the Monte Carlo simulations consisted of a stochastic ensemble of five 100-year simulations, each driven by a randomly drawn sequence of synthetically generated (Nowak et al., 2010; Kirsch et al., 2013) inflow hydrology and corresponding daily sediment loads. See Section III (e.g., Fig. S2) of the paper's Supplement for further details on our approach to synthetic flow generation. As shown in Fig. 6, formulations implementing optimization (Formulations II and III) seek to maximize or minimize performance with respect to the mean or 1st percentile of the empirical cumulative distribution function (CDF) for the 500 values (i.e., 5 realizations of 100 years). Performance was maximized in all objectives except for the sediment-related objectives, which were minimized.

In the following subsections we briefly introduce a short synopsis of each of the three formulations and discuss their results. Detailed mathematical definitions for each of the formulations and performance metrics appears in Section IV of the Supplement. Section V of the Supplement details the paper's computational experiments, including model configurations and computing requirements. To run each formulation, follow the model installation instructions on the model's GitHub repository, then run the desired formulation's Python script (e.g., formulation_I_serial.py for the serialized version of the Screening formulation).

3.3. Formulation I: problem screening

3.3.1. Formulation I overview

The Problem Screening formulation ("Screening") represents a typical starting point in a dam pre-feasibility study (IFC 2015), wherein a particular dam concept (i.e., location and basic design specifications) has been identified, but in order to evaluate its suitability for investment the dam's performance potential must be evaluated (e.g., with respect to energy production and adverse ecological impacts). Sambor EA has the capacity to store less than 0.5% of mean annual inflow. The tendency in pre-feasibility studies of similarly hydrologically small (i.e., low capacity:inflow ratio) reservoirs is to specify energy-maximizing run-of-river operations, much like specifying a static design feature. To reflect this standard planning approach, the Screening formulation includes an energy-maximizing rule curve (i.e., Energy rule curve), as shown in Fig. 7. Rule curves for Sambor EA were strongly shaped by the reservoir's complex hydraulic configuration, which is detailed in the Appendix (Fig. S1). In brief, the reservoir's unregulated upstream end means that lower water levels increase reservoir inflows and reduce spillage into the unregulated bypass channel. Thus, energy production is not maximized by maximizing water level, because high water levels imply significant spillage. To reflect diverse stakeholder preferences, and to attempt to capture the potential for tradeoffs across objectives, we also include two ecologically-focused rule curves: one focused on larvae passage (i.e., the Larvae rule curve) and one focused on adult fish passage (i.e., Adult Fish rule curve). The Larvae rule curve was designed to enable year-round downstream passage of fish larvae. The Adult Fish rule curve was designed to benefit adult fish passage around the dam by maximizing the rate of flow spilled into the bypass channel. Disciplinary experts identified these rule curves during the pre-feasibility study of Sambor Dam (NHI, 2017). Across all formulations, operating policies implement identical approaches to improving sediment passage through and around the Sambor EA reservoir, including annually passing inflowing sediment through the reservoir (i.e., sluicing through mid-level outlets) and infrequently removing deposited sediment from the reservoir (i.e., flushing through low-level outlets).

To highlight the difficulty in pre-specifying rule curves that perform well under uncertainty across multiple metrics, the three rule curves were simulated both deterministically, using the 107-year historical hydrologic record, and stochastically, using synthetically generated hydrologic sequences to modestly sample well-characterized hydrologic uncertainty. Performance was then evaluated both deterministically and stochastically with a wide range of metrics reflecting different temporal and statistical filtering of the six time series variables introduced in section 3.2.1. Formulation I is referred to as the Problem Screening Formulation because we initially explore a large set of metrics, then sift through those metrics to inform a more targeted subset of metrics for future problem formulations. Fig. 6 shows that all metrics in the Screening formulation were evaluated annually, except for sediment flushing, which was evaluated on a monthly basis to capture the potential for ecologically harmful short-term spikes in sediment load. In

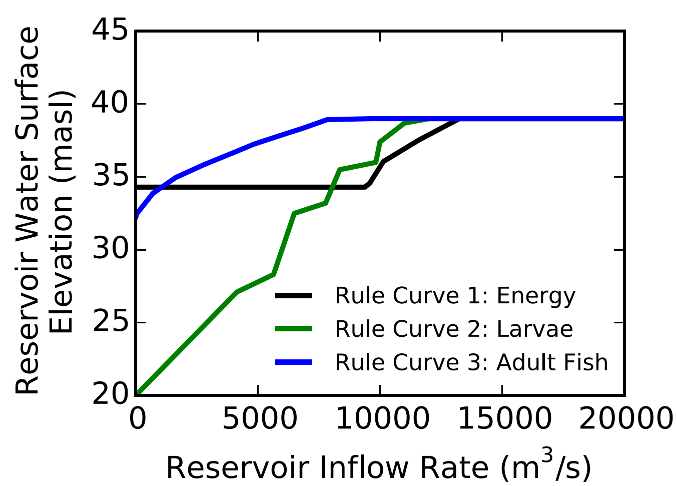

Fig. 7. Three operating policies (i.e., rule curves) were identified by experts from different fields during the pre-feasibility study of Sambor Dam (NHI, 2017) to capture diverse stakeholder preferences. The Energy rule curve reflects the preference to maximize energy production, while the Adult Fish and Larvae rule curves focus on maximizing different aspects of ecological performance.

total, the Screening formulation consists of 12 simulations: one deterministic and one stochastic simulation for each of the three rule curves, with and without reservoir sediment management taking place. In this sense, the Screening formulation is a departure from the traditional dam pre-feasibility analysis because it emphasizes evaluating policy performance under a wide range of performance metrics and uncertainties to better understand performance potential and tradeoffs.

3.3.2. Formulation I results

The nine plots in Fig. 8 report the performance of the three expert-elicited operational rule curves. The top row of plots (Fig. 8a–c) report the rules' attained performance for energy production, larvae passage, and fish passage. Fig. 8d–i summarize the rule curves' performance for sediment, including the quantity trapped, the effect of the trapped load on storage capacity, and the magnitude of sediment released downstream of the dam during the month of June (when the majority of flushing events take place). For these metrics, Fig. 8d–f reflect simulations in which no sediment management takes place, whereas Fig. 8g–i account for sediment management effects. Within each figure, the three rule curves are designated by different colors. Across the metrics of performance, the deterministic performance results are plotted as single mean values (i.e., vertical lines) representing the three candidate rule curves' mean annual performance for a single historical time series of hydrologic and sediment inflows. In contrast, stochastic performance (dashed lines) for a given rule curve is plotted as an empirical cumulative distribution function (CDF). Each CDF represents the distribution of performance across all years in the Monte Carlo simulation. As the slope of the CDFs become flatter, the variance in attained performance metrics is increasing. Each stochastic CDF represents a simulation with five inflow sequences of 100 years, or 500 annual values. This sampling level was confirmed to provide stable convergence for the more extreme quantiles in the empiric CDFs.

Fig. 8 reveals three key points for guiding the evolution of future Sambor EA problem formulations. First, there is significant variance in performance across numerous performance metrics under a modest sampling of well-characterized uncertainty. As an example of important variance at Sambor EA, Fig. 8a shows that annual energy production varies from the mean by as much as 50% in best and worst case years for

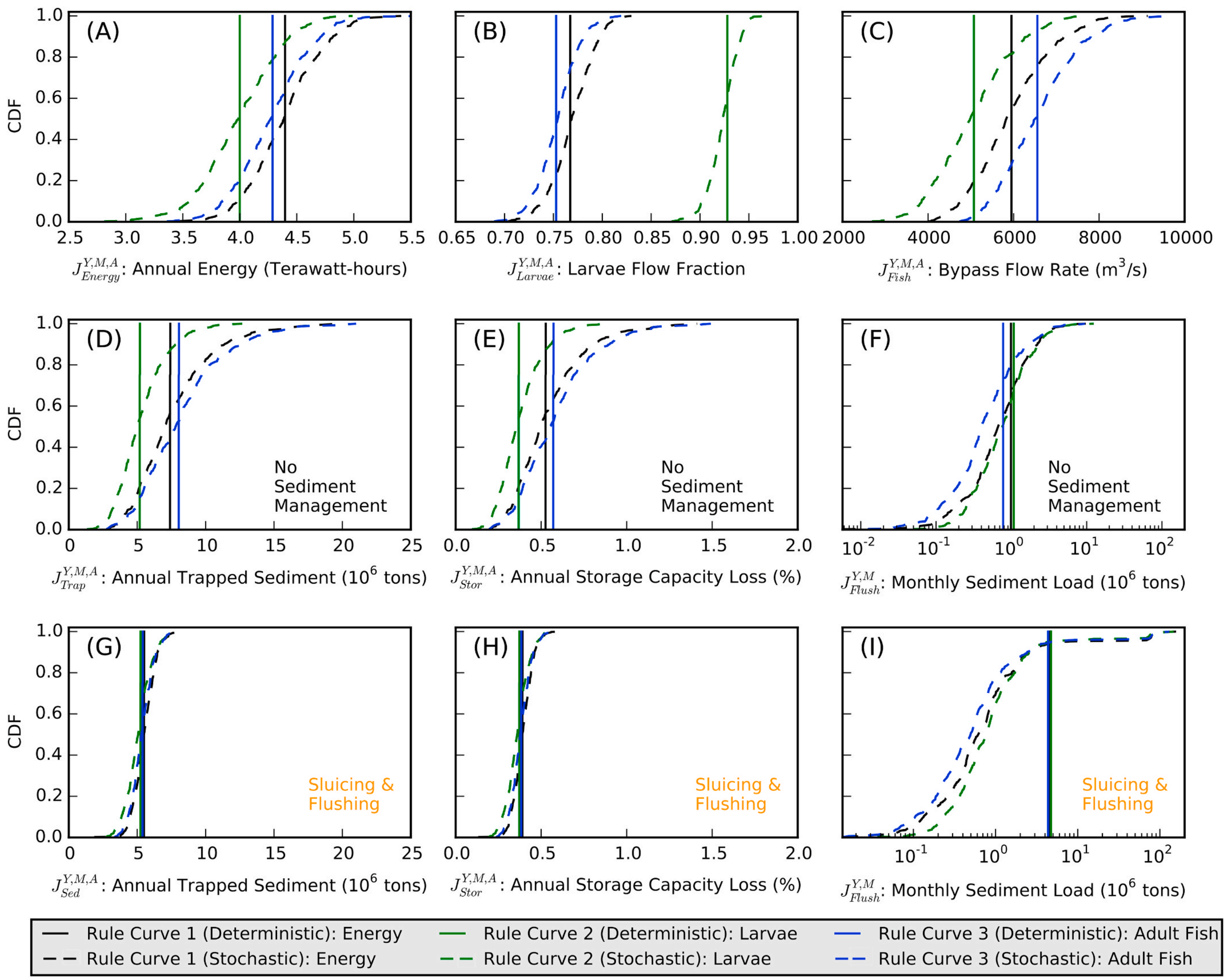

Fig. 8. Deterministic and stochastic multi-objective performance for the three Screening formulation rule curves identified by experts from different fields in the pre-feasibility study of Sambor EA dam. Deterministic performance is plotted as a single mean value (i.e. vertical line) for each rule curve, whereas stochastic performance under synthetically generated sequences of hydrologic and sediment inflows is captured with empirical cumulative distribution functions (CDFs). The first row of figures shows the performance of the three rule curves for energy production, larvae passage, and anabranch channel adult fish attraction flow. The middle row of figures shows sediment-related performance for the three rule curves if no reservoir sediment management is conducted, whereas the bottom row shows performance for these same policies and metrics with sediment management (i.e., flushing and sluicing) implemented.

each of the three policies. This has important financial implications, as the dam's financier must maintain adequate cash flows to service the debt incurred in constructing the dam, not just on average but also during periods of lower hydrologic inflows. This strongly suggests future problem formulations should account for uncertainty in identifying and evaluating candidate operating policies. It has long been known that optimizing policies to achieve mean-focused performance metrics often tacitly exposes policies to broader variability in performance (Beyer and Sendhoff, 2007). The variability in performance across the probability distribution for each metric underscores the importance of sampling multiple stochastic hydrologic futures to more reliably approximate the distribution tails (i.e., extreme events).

Second, the results from the Screening formulation show that evaluating a small handful of pre-specified policies designed to achieve performance in a single objective has two important consequences. To begin, this approach suffers from the potential for strong decision maker regrets as performance could likely be substantially improved in all metrics (i.e., a dominated set of candidate actions), despite the best efforts of disciplinary experts. Additionally, even if the policies are theoretically optimal in each single metric, evaluating a small handful of policies can only reveal that performance conflicts exist, rather than explicitly quantifying their complex tradeoffs. For example, the Larvae rule curve was unsurprisingly the best performing with respect to the larvae passage objective (Fig. 8b), yet it performed the worst of the three policies with respect to energy production (Fig. 8a) and bypass flow for adult fish passage (Fig. 8c). Together, these results suggest future problem formulations should include an optimal search for reservoir operating policies and the tradeoffs they create, rather than pre-specifying rule curves, which is at present standard practice in most simulation frameworks (Loucks et al., 1995; Sheer, 2000; Labadie et al., 2000; Zagona et al., 2001; Matrosov et al., 2011; Yates, 2005).

Third, the middle and bottom panels of Fig. 8 demonstrate the value of PySedSim's ability to evaluate reservoir sediment management metrics. Fig. 8d shows that despite its ecologically-focused redesign, Sambor EA could trap 5–8 million metric tons of ecologically important suspended sediment on average annually. Fig. 8d shows that this could result in an annual loss of 0.25–0.6% of total reservoir storage capacity per year. This implies the reservoir could lose up to nearly 25% of its storage capacity by the time of transfer of ownership of the dam. This result has important implications for the GoC, who would only assume ownership of the devalued reservoir after a concession period of up to 40 years (NHI, 2017).

Options are available to mitigate storage capacity loss. Fig. 8g and h show that implementation of annual sediment pass-through (i.e., sluicing) and irregular removal (i.e., flushing) every 15 years for drawdown periods of about one week significantly limit deposition and storage capacity reduction by regularly preventing and removing deposited sediment. These increased sediment flows show that significant basin-wide sediment trapping (e.g., as predicted by Kondolf et al., 2014), both in the Mekong and elsewhere, is not a foregone conclusion. Much of the scientific literature focused on reservoir sedimentation, particularly in the Mekong (e.g., Kondolf et al., 2014; Kummu et al., 2010), is geared toward impact prediction and vulnerability assessment, rather than practical management approaches to mitigating impacts (Wild and Loucks, 2014, 2015b, 2016; Wild et al., 2019a). However, implementing these approaches requires dams be sited and designed (e.g., with low-level outlets) to enable these approaches to be applied (Kondolf et al., 2015; Annandale, 2013; Kondolf et al., 2014; MRC, 2009). PySedSim captures design details, such as low- and mid-level gates, that facilitate this evaluation.

While the potential for sediment management options exist, a comparison of Fig. 8f–i shows that techniques such as flushing can have negative impacts if not managed carefully. Specifically, irregularly flushing sediment from the reservoir can significantly distort the river's natural probabilistic sedigraph (i.e., sediment duration curve) downstream of the dam site during the month of June, when flushing occurs most frequently. Sediment discharge increases not only on average, but also in the more extreme quantiles of the probability distribution, creating the potential for significant ecological impacts downstream (Wild and Loucks, 2016). One potential solution is to increase the frequency of flushing, though this creates a tradeoff with the objective to maximize annual energy production.

3.4. Formulation II: Discovering Tradeoffs

3.4.1. Formulation II overview

While the three Screening formulation rule curves potentially represent reasonable efforts at maximizing performance among three objectives, there is no guarantee these policies perform well compared to other possible operational rules or that they perform well under uncertainty. Moreover, it is difficult to assess how the expert-defined operational rules are striking compromises across the complex tradeoffs that likely exist across ecological concerns and power production. Ending the analysis at the Screening formulation could misrepresent Sambor EA's potential to achieve balanced ecology-energy outcomes. This motivated the need for the Discovering Tradeoffs (i.e., "Tradeoffs") formulation, in which we conduct an optimal search for policies designed to perform well across multiple objectives under uncertainty.

The Tradeoffs formulation seeks to identify, rather than pre-specify, alternative reservoir operating policy alternatives that perform well on average under hydrologic uncertainty. As shown in Fig. 6, this formulation seeks to identify policies that perform well with respect to a subset of four of the performance metrics that demonstrated strong tradeoffs and decision relevance in the Screening formulation. Namely, reservoir sediment trapping and storage capacity loss metrics are dropped compared to the Screening formulation, and finer temporal scale is adopted for the adult fish passage and sediment flushing metrics.

Rather than seeking to identify a single "optimal" operating policy, PySedSim's multi-objective simulation-optimization approach identifies the suite of candidate operating policies whose performance in at least one objective cannot be improved without degrading performance in one or more of the remaining objectives (i.e., Pareto approximate solutions). A fully coupled multi-objective evolutionary algorithm (MOEA), the Borg MOEA (Hadka and Reed, 2013), parameterizes and iteratively refines operating policies, optimizing them in response to their simulated performance with respect to four metrics. Reservoir operating policies take the form of parameterized non-linear gaussian radial basis functions (RBFs). These RBF parameters serve as the decision variables the MOEA uses to control policy performance. Additionally, the Tradeoffs formulation includes three sediment management variables in its optimal search related to sediment flushing: (1) the frequency of sediment flushing operations, constrained from 1 to 15 years; (2) the day of the year on which to begin considering flushing the reservoir, constrained from days 120–225 to avoid dry season and monsoon conditions (Wild et al., 2016); and (3) the reservoir inflow rate (m^3/s) triggering flushing drawdown to occur, constrained from 6000–10,000 m^3/s. Section V of the Supplement contains a summary of key MOEA-related assumptions across formulations, and the performance of the MOEA in relevant formulations.

3.4.2. Formulation II results

The four-objective ecology-energy tradeoffs (in Fig. 9) resulting from the Tradeoffs formulation provide a broader context for understanding key performance conflicts and for exploring diverse stakeholder preferences. Fig. 9 represents the best approximation for Sambor EA's control policy tradeoffs accumulated across 25 trials of MOEA-based search. For visual clarity, Fig. 9 only displays a representative subset of 100 policies from the approximately 500 in the original set. PySedSim *processing_reference_set* module optionally automates this thinning using the concept of ϵ-dominance (Laumanns et al., 2002). In Fig. 9, each of three axes corresponds to a different objective, while color represents a fourth objective to maximize dry season flow rate spilled into the bypass

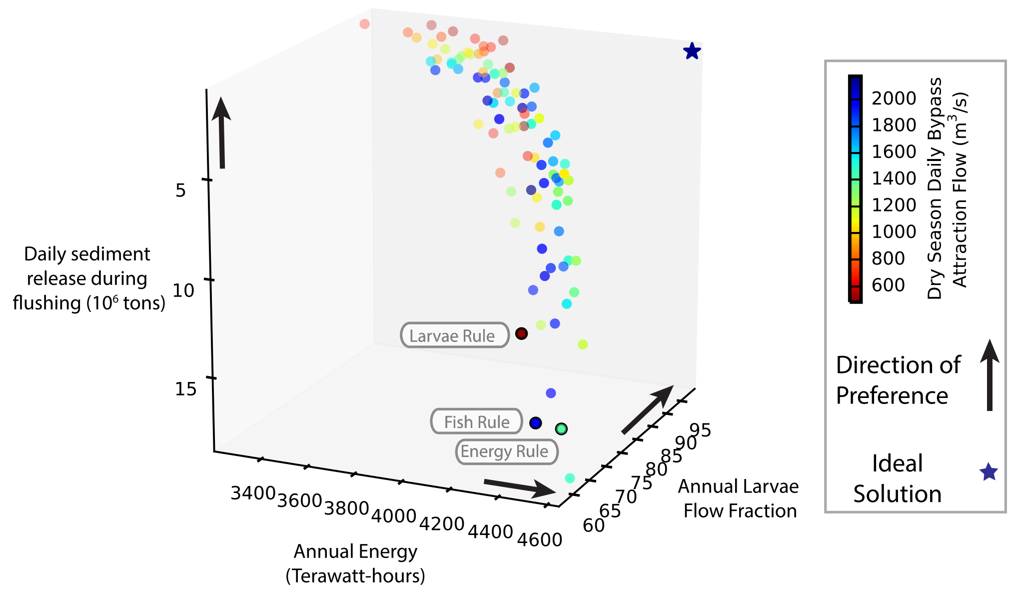

Fig. 9. Visualization of tradeoffs in performance across four objectives (energy, larvae, adult fish and sediment) in the Tradeoffs formulation for Sambor EA dam. Each plotted point represents a different candidate operating policy. The three expertly-derived rule curve policies from the Screening formulation are also highlighted.

channel to attract migrating fish. The direction of better performance in Fig. 9 is toward the upper right of the figure, as marked by black arrows. The theoretical ideal policy in Fig. 9 is represented by a blue star at the upper right of the plot.

The Screening formulation policies are included among the reference set of the Tradeoffs formulation policies in Fig. 9 to facilitate comparison. Each of the three pre-specified rule curves was dominated (i.e., outperformed in all four objectives) by at least one member of the Tradeoffs formulation reference set of control policies identified through optimization, when re-evaluated with random sequences of inflow hydrology and sediment loads (via the *processing_reference_set* module). While the Screening formulation policies were outperformed, they were still close to optimality. However, the Screening formulation policies all reside in one extreme region of the broader tradeoff frontier discovered in the Tradeoffs formulation. Thus, while pre-specified rule curves may perform reasonably well without any optimization, it is nevertheless very difficult to capture the complex, nonlinear nature of the tradeoff frontier by designing a small set of pre-specified policies. This result clearly demonstrates the value of identifying rather than specifying operating policies in a river basin infrastructure planning context.

The Tradeoffs formulation results show that reducing the magnitude of sediment load released during flushing requires a tradeoff with energy production. Importantly, the Tradeoffs formulation was designed with no long-term sediment passage objective because the Screening formulation results (Fig. 9) showed that the combination of sluicing and flushing, and small storage capacity relative to annual inflow, would likely enable highly effective sediment passage at Sambor EA. However, the quantity of sediment load released during flushing events is of ecological importance. Fig. 9 reveals that some policies produced an average sediment load release during flushing events of up to 18 Mt/d. In contrast, the natural daily sediment load during the monsoon season is 1 Mt/d (Koehnken, 2014). Policies with ecologically problematic sediment releases (toward the front and bottom of Fig. 9a) also produced the most hydropower, and vice versa. The presence of this important tradeoff underscores the value of PySedim's flexibility to include flushing-related parameters in the optimal search process. This tradeoff occurs because emptying a reservoir to conduct flushing reduces energy production, so policies prioritizing energy production flushed as infrequently as possible, thus releasing much larger sediment loads during flushing events.

Finally, the presence of blue- and green-colored policies (i.e., with the highest bypass spillage rates) throughout much of the tradeoff space in Fig. 9 demonstrates that this objective is not in strong conflict with other objectives as anticipated. The lower limit of the color bar (5200 m^3/s) shows that even the poorest performing policies with respect to fish bypass flow were still on average spilling in excess of 50% of the main stem's 13,200 m^3/s mean annual flow rate into the bypass channels. Given that all policies in the Tradeoffs formulation performed well with respect to mean annual bypass flow rate, the Alternatives formulation was designed to include a dry season bypass flow objective to evaluate fish passage potential in both seasons. A dry season energy production metric was also created in the Alternatives formulation to enable better understanding of the energy sacrifice required to pass dry season larvae and adult fish.

While Fig. 9 is a crude representation of tradeoffs across complex ecological objectives, it nevertheless facilitates a detailed discussion among decision makers and technical experts regarding how to define acceptable ecological performance targets, in order to navigate tradeoffs in search of a subset of candidate alternatives. Literature regarding ecological performance metrics and thresholds is sparse in the Mekong, in large part due to the paucity of data describing the life cycle processes of over 1200 species of fish. The Mekong River Commission (MRC) defines effective fish passage as "providing safe passage for 95% of the target species under all flow conditions" (Mekong River Commission, 2009). While it is not straightforward to directly apply this criterion to fish pass flow rates, it can readily be applied to larvae passage flow rates. Referring to Fig. 9, policies that only meet or exceed this 95% criterion would require substantial (and likely economically nonviable) energy production losses. This result initiated some key questions and extensive debate regarding the temporal and statistical definition of the 95% criterion. For example, given fish life cycle processes in the wet season contribute relatively more to the fishery's productivity, could sustainable fishery outcomes still result from a compromise in which the criterion is met more frequently in the wet season as opposed to the dry season? Also, is the criterion defined only for average conditions, or does it need to be met even in worst case conditions? Given the potential impact of Sambor EA on the appreciable socioeconomic value of the Mekong fishery, we pursued the Alternatives Formulation, in which ecological objectives are optimized with respect to an approximation of worst-case conditions (i.e., 1st percentile of performance metric CDFs) (Quinn et al., 2017). Maximizing performance in worst-case conditions is likely to produce policies robust to future hydrologic uncertainty that perform well even in the worst (e.g., drought) years. Recent geopolitical tension resulting from drought conditions (Stone, 2010) underscores the value of such policies.

3.5. Formulation III: Refining Alternatives

3.5.1. Formulation III overview

The Screening formulation sought to identify a subset of decision-relevant metrics from among a large set, while the Tradeoffs formulation took that subset of metrics and sought to identify a wide array of alternative operating policies that perform well across that subset of measures. However, the presence of sharp tradeoffs among energy and ecological objectives in a critical and sensitive ecosystem such as the Mekong naturally raises questions about how best to carefully define ecological performance metrics and thresholds. In response, the Refining Alternatives formulation ("Alternatives") reflects a shift in focus to more carefully defining ecological performance metrics, and navigating the resulting refined tradeoffs in search of candidate alternatives. Specifically, Fig. 6 shows that larvae passage is converted into a seasonal variable to discover strategies more capable of facilitating ecologically critical wet season larvae passage. Dry season larvae passage is also evaluated, which is why two larvae metrics appear under Formulation III in Fig. 6. Additionally, the sediment flushing metric is converted into a daily metric to reflect the ecological impacts of large sediment releases over very short periods of time. Given the potential for problematic ecological performance in this critical ecosystem, the Alternatives formulation also shifts all performance metrics to definition in the worst first percentile rather than the mean. This ensures that policies will be robust, in that they will be designed to perform well in an approximation of worst-case conditions (Quinn et al., 2017). A worst first percentile (i.e., the 1st or 99th) was used as an estimator to approximate worst case behavior because quantiles are more stable and convergent than the maximum or minimum values resulting from a given stochastic simulation, as is commonly done in robust optimization (Taguchi, 1986; Quinn et al., 2017; Stedinger et al., 1993; Castelletti et al., 2012; Beyer and Sendhoff, 2007).

3.5.2. Formulation III results

The Alternatives formulation differs from previous formulations primarily in its conservative approach to defining worst-case (i.e., 1st percentile) metrics. The parallel axis plot in Fig. 10, which is reproduced from Wild et al. (2019a) for purposes of comparing formulations, summarizes the tradeoffs across the six objectives that define the Alternatives formulation. Each vertical axis represents performance for one of the six objectives. The axes are oriented such that performance improves moving vertically upward on each axis. Each line represents a different operating policy. Each policy's performance is designated by where it intersects each vertical axis. The steepness of the diagonal lines between two adjacent axes displays the degree of tradeoff for solutions between the two objectives. The theoretical ideal policy would be a single blue horizontal line crossing at the top of all the axes. Rather than representing objectives defined in the mean, the performance of policies in Fig. 10 represents an approximation of worst-case conditions by evaluating performance in the 1st percentile of the CDF of corresponding performance metrics.

Fig. 10 reveals the potential for 1st percentile performance to be significantly worse than mean performance. For example, dry and wet season larvae passage performance can be as poor as 18% and 40%, respectively, compared to 56% in mean annual conditions. Also, sediment loads can be over twice as large in worst-case conditions. Additionally, the Tradeoffs formulation (Fig. 9) did not reveal a particularly strong tradeoff between mean annual fish bypass attraction flows and other objectives. Conversely, Fig. 10 shows worst-case dry season flows can be below 500 m^3/s. Depending on the timing of these discharge values, this could potentially represent less than 10% of dry season main stem discharge, which would supply less than the generic 10% fish pass criterion employed in many studies (Thorncraft and Harris, 2000).

Numerous policies in Fig. 10 reflect this problematic dry season flow condition. Referring to Fig. 10 (third axis), a cluster of red-colored policies creates very low worst-case bypass attraction flows for fish migration during the dry season. However, many of these same policies create hydraulic conditions in the reservoir capable of achieving high levels of dry season larvae passage (fourth axis). These policies also significantly reduce high-value dry season energy (fifth axis), because

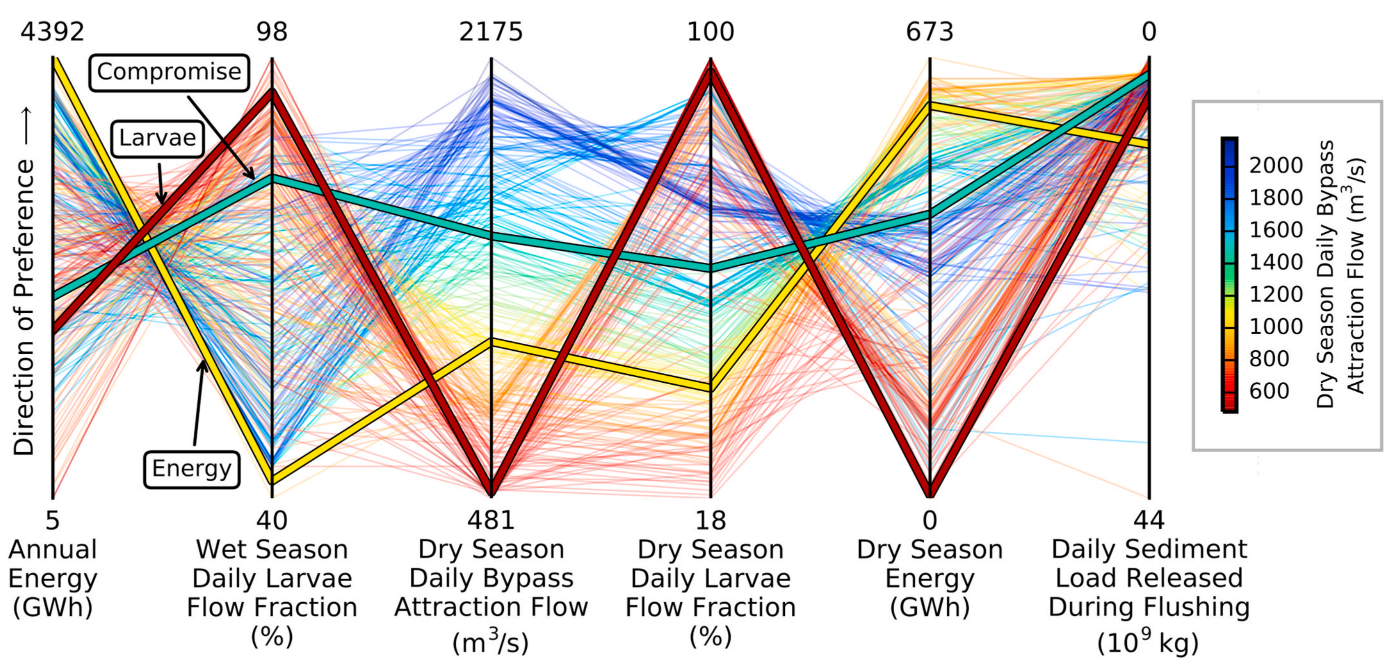

Fig. 10. Parallel coordinate plot demonstrating multi-objective tradeoffs for the Alternatives formulation, as shown in Wild et al. (2019a).

the site's hydraulics (Fig. S1 in the Supplement) require extensive drawdown to increase inflow and thus velocities. This requires directing more water down the main stem instead of spilling it into the bypass. This existence of a potential tradeoff among ecological objectives themselves (i.e., larvae and adult fish passage), as opposed to between energy and ecological objectives, was entirely unforeseen, and was not clearly identified in Formulations I and II. The appearance of problematic performance and unforeseen tradeoffs underscores the benefit of an iterative formulation approach (Fig. 1) in a complex, multi-stakeholder river basin decision context.

Having identified rich tradeoffs across multiple probabilistic seasonal fish life cycle and energy production metrics, it is next possible to navigate Fig. 10 in search of potential solutions worth exploring in more detail. Three policies highlighted in Fig. 10 ("Energy", "Compromise", and "Larvae") illustrate examples of different candidate decision preferences. The "Larvae" policy achieves acceptable fish-related performance in 95% of days in both seasons with hydraulic conditions conducive to larvae passage. The "Larvae" policy performs poorly in the dry season larvae passage objective, making this policy less attractive across stakeholder interests. Just as with the "Larvae" policy, the "Energy" policy in Fig. 10 performs poorly with respect to the larvae flow fraction objective. In response to the potentially problematic multi-objective performance of the "Larvae" and "Energy" policies, we highlight a potential "Compromise" policy. The "Compromise" policy shows that compromising on larvae passage in both seasons could significantly improve energy production compared to the "Larvae" policy, while also significantly improving rates of dry season bypass spillage for fish migration and reducing the magnitude of flushed sediment loads. This policy prioritizes wet season larvae passage because of its relative importance to the fishery, achieving 90% larvae performance in the wet season, but only 60% in the dry season. Rarely will a single formulation of a particular problem result in the refined insight and compromise solutions that result from Fig. 10. The iterative approach to problem formulation and refinement (of complexity in representing uncertainties, objectives, and reservoir operations) described in Fig. 1 ultimately enabled more distinct tradeoffs to take shape and potential compromises to be identified.

3.6. Reservoir operations

To better understand the new knowledge that is gained in each successive problem formulation, it is helpful to view the operating policies of which the tradeoffs are comprised. Fig. 11 plots a representative subset of reservoir operating policies from each formulation. Each column of figures represents a different formulation. The top figure in each column represents simulated mean monthly Sambor EA water surface elevation, while the lower figure represents the reservoir release rate resulting from the operating policy. Each colored line represents a different operating policy. (The dashed gray line in the lower row of figures represents the mean monthly main stem flow rate at the reservoir site. Main stem flow rate is included, as opposed to reservoir inflow, because it remains the same across the formulations and policies. Reservoir inflows differ across policies as a result of the site's hydraulic configuration, which induces different inflow rates depending on the reservoir's water levels, as shown in Fig. S1). The Screening formulation policies represent the three expert-specified rule curves introduced in

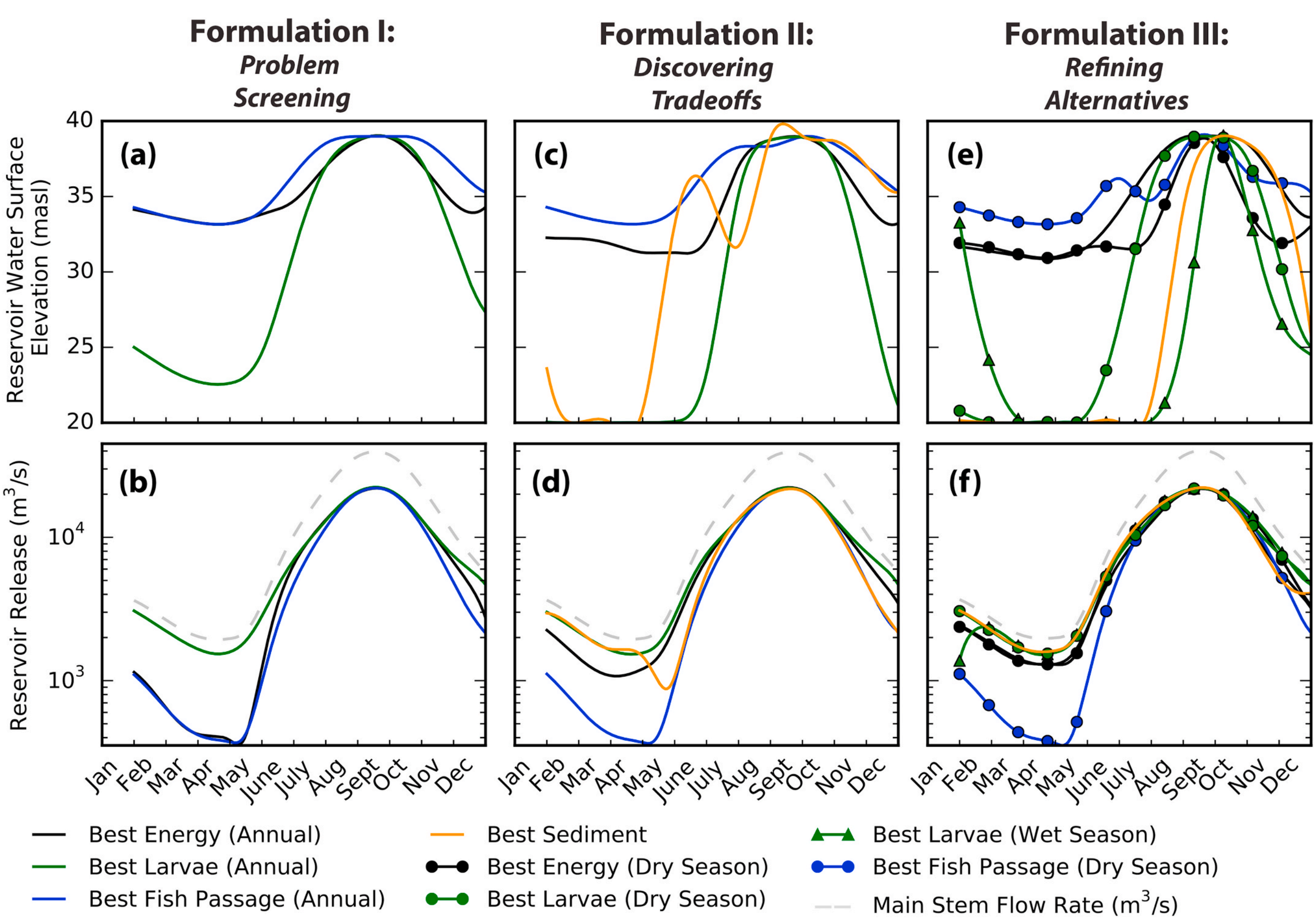

Fig. 11. Visualization of selected policies from across the three formulations. The three expert-specified rule curves are evaluated in the Screening formulation, whereas the best performing policies across objectives are evaluated in the Tradeoffs and Alternatives formulations.

Fig. 7. The Tradeoffs formulation and Alternatives formulation policies, selected from the reference sets of their respective formulations, represent the very best performing policies for each objective. Hence, the number of policies grows as the formulations evolve to reflect the increasing number of objectives in those formulations. Colors are used to reflect four objective themes: energy, larvae, adult fish, and sediment. Solid lines are used to distinguish policies corresponding to objectives defined in the mean, whereas dotted lines correspond to objectives defined in the 1st percentile. Each policy was reevaluated using randomly generated sequences of inflow hydrology and sediment loads that were not used during the identification (i.e., pre-specification or optimization) of the policies.

Beginning with the Screening formulation, Fig. 11a and b show that the energy policy and fish policy maintain similar water levels and similar reservoir releases. This important finding, which suggests (at this dam site) that energy-focused operations naturally produce conditions favorable for adult fish passage, is a direct result of the reservoir's unique ecologically-oriented hydraulic design, which naturally induces significant spillage into the reservoir's anabranch channel at the reservoir water levels required for significant energy production. Second, the operational strategy required for managing larvae (i.e., Larvae rule curve) requires maintaining low reservoir water levels (Fig. 11a) while main stem flow rates (Fig. 11b) are low. Water levels are increased only when flow rate (and corresponding velocity) increases to create conditions with sufficient sustained velocity to pass larvae through the reservoir. These strong seasonal differences in policies underscore the importance of PySedSim's flexibility to define objectives seasonally. In comparison to the Screening formulation, the Tradeoffs formulation policies (Fig. 11c and d) reflect the methodological differences in the approaches used to define the policies (i.e., optimization versus pre-specification). For example, the optimization-based Tradeoffs formulation produces a more refined larvae-focused policy that maintains lower water levels for longer into the dry season than the corresponding policy from the Screening formulation. Key differences in policies from the Alternatives formulation in comparison to policies from the Tradeoffs formulation are a direct result of the use of objectives defined (1) seasonally rather than only annually, and (2) in the 1st percentile versus the mean. For example, the policies performing the best with respect to wet and dry season larvae passage carefully time their reservoir emptying and refill processes very differently, keeping water levels lower during their respective seasons of focus. These policies are especially conservative, seeking to avoid poor performance even in the worst years. For this reason, water levels are kept lower, and for longer durations, than would otherwise be necessary.

The most important general result from Fig. 11, which is most evident in Fig. 11e and f, is the vast space of reservoir operation possibilities, and resulting differing multi-objective performance, that exist at such a hydrologically small reservoir. Hydrologically small reservoirs are widely regarded as relatively benign alternatives not requiring careful intra-annual operation. Fig. 7 demonstrates that this generalization is unlikely to apply to dams such as Sambor EA that have a diverse array of design features oriented toward improving sediment and fish passage. This demonstrates the importance of tools with PySedSim's flexibility in river basin infrastructure planning applications wherein ecologically-focused changes to the SDO features of planned dams are of interest. The importance of reservoir operations in this case study highlights the potential drawbacks of focusing solely on spatial optimization of dam locations in identifying alternative hydropower portfolios (Ziv et al., 2012; Schmitt et al., 2018; Opperman et al., 2015; Jager et al., 2015). Failing to search for reservoir operation options could constrain the potential to identify more balanced alternatives to proposed dams.

4. Conclusions

Intensive and pervasive hydropower dam development is expected over the next several decades, including in some of the world's most ecologically diverse river basins (e.g., the Mekong, Congo, and Amazon) (Winemiller et al., 2016; Vörösmarty et al., 2010; Zarfl et al., 2015; Moran et al., 2018). This infrastructure development, as planned, is expected to result in severe consequences for ecosystems, as well as for the hundreds of millions of impoverished people who depend on riverine ecosystems to support their food security and economic welfare (McIntyre et al., 2016). These ecological impacts are anticipated because hydropower dams are typically sited, designed, and operated to maximize power production rather than to preserve ecosystem health and productivity (IFC, 2015). To strike more balanced performance across ecological, energy, food, and other potential objectives in these contexts will require re-thinking the traditional approach to hydropower planning in at least two respects. First, rather than focusing on planning one dam at a time, long-term hydropower planning should more strategically consider the cumulative interactions and impacts of all existing and planned dams (Sabo et al., 2017; TNC, 2016; Ziv et al., 2012; Opperman et al., 2015; Grill et al., 2014; Cronin et al., 2016; Kondolf et al., 2018; Schmitt et al., 2018; Wild et al., 2019a; Schmitt et al., 2019; Intralawan et al., 2018; Song et al., 2020; Grill et al., 2015; Roy et al., 2020). This could produce positive outcomes, such as building first those dams that marginally produce the most power relative to their negative (e.g., ecological) impacts. Second, significant modifications will be required to the siting, design, and operation (SDO) features of planned dams (Wild et al., 2019a), particularly those expected to be most impactful in the context of sensitive ecosystems. To facilitate this transition toward identifying hydropower alternatives with more balanced performance, this paper and its Supplement introduce and describe the features of the PySedSim modeling framework and its successful application in a real hydropower planning context.

PySedSim is an open-source, object-oriented, Python-based, daily time step river basin simulation model for flow, sediment, and hydropower in networks of reservoirs and river channels capable of exploring ecologically-oriented SDO alternatives. PySedSim is designed for use in feasibility and pre-feasibility (IFC, 2015) screening assessments of alternative river basin infrastructure plans involving reservoirs. The model is flexible, both in its software design and its core functionality and features. PySedSim users can explore representations of four key concerns relevant to the selection and evaluation of alternative reservoir configurations, particularly in the ecologically sensitive contexts described earlier: 1) management approaches to improve the passage of sediment through and around reservoirs to avoid storage capacity loss and downstream ecological impacts; 2) search for flexible and adaptive alternative reservoir operating policies designed to achieve multiple objectives; 3) alternative design features such as dam gates, reservoir bypasses, and other hydraulic infrastructure, which are necessary to enable ecologically focused reservoir operational practices (e.g., fish and sediment passage); and 4) uncertainties in hydroclimatic drivers and in the physical processes of sediment production, transport, reservoir trapping, and reservoir management. While some existing river basin modeling tools can address one or several of these concerns, we know of none that address them all in a single tool. PySedSim has a software architecture that allows users to exploit these four core features in a manner that facilitates rapid testing of alternative SDO problem formulation hypotheses. This is integral to facilitating exploration and evaluation of candidate hydropower SDO modifications that may be necessary to reduce reservoirs' impacts on the ecological integrity of river basins. Indeed, the most effective modeling tools and scientific studies in influencing policy agendas have often been those that change the way key issues are defined and framed, and on the array of options for dealing with issues that are considered, rather than only the actions that are ultimately taken (Cash et al., 2003).

PySedSim was used in a multi-year, multidisciplinary study conducted in partnership with the Government of Cambodia (GoC) seeking to identify and evaluate alternative dam sites, designs, and operation (SDO) options as candidates to replace the proposed Sambor Mega Dam on the Mekong River (Wild et al., 2019a; NHI, 2017). As proposed, Sambor Dam would be one of the world's longest and most environmentally impactful hydropower dams, spanning 18 km across the lower Mekong River's floodplains, with the potential to trap significant quantities of sediment critical for downstream ecosystems (e.g., the Vietnam Delta), and block the migration routes for over 50 species of fish. Using PySedSim, we focused on one particular alternative dam location and design (Sambor Ecological Alternative, or Sambor EA), and iteratively explored tradeoffs across multiple conflicting ecological and hydropower objectives of decision relevance, seeking to produce the information needed to allow the GoC to identify what they considered the most balanced plan. This iterative problem formulation process exposed us to the complexity of this system we were analyzing and the need to address a succession of new questions and issues as we proceeded. In this paper, we describe three alternative problem formulations that capture the evolution of this iterative decision support process. Each formulation builds upon prior formulations to arrive at the final recommendations to decision makers (NHI, 2017). Through these system representations, which naturally grow in complexity, we show that as operating policies were searched for rather than pre-specified, as more conflicting objectives were identified and included, and as more uncertainty was acknowledged, new objectives of interest, and tradeoffs among them, emerged. This increasing insight changed the way the problem was framed and also revealed new options for satisfying multiple objectives that were not previously considered. The flexibility of the modeling tools, both in software design and functionality, to iteratively explore and discover increasingly realistic formulations that reflect diverse stakeholder preferences greatly enhanced the discussions with the GoC surrounding river basin development that have been taking place. PySedSim could similarly be used to enhance the discussion surrounding river basin development that is currently taking place in other river basins globally. PySedSim's capacity to contribute solutions to challenging problems in these contexts can be enhanced by exploring new linkages with frameworks in the following areas: many-objective robust decision making (Hadjimichael et al., 2020; Hadka et al., 2015; Kasprzyk et al., 2013), power systems (Chowdhury et al., 2020a,b), energy-water-land nexus planning and management (Khan et al., 2020), and sensitivity analysis (Herman and Usher, 2017).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by Cornell University's David R. Atkinson Center for a Sustainable Future, Postdoctoral Fellowship in Sustainability, Grant No. 2015. Additionally, this material is based upon work supported by the U.S. National Science Foundation under Grant No. 1855982.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2020.104947.

References

Agostinho, A.A., Marques, E.E., Agostinho, C.S., Almeida, D.A.d., Oliveira, R.J.d., Melo, J.R. B.d., 2007. Fish ladder of Lajeado Dam: migrations on one-way routes? Neotrop. Ichthyol. 5 (2), 121–130.
Andrén, Henrik, Andren, Henrik, 1994. Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. Oikos 71 (3), 355. https://doi.org/10.2307/3545823.
Annandale, G.W., 2013. Quenching the Thirst: Sustainable Water Supply and Climate Change. CreateSpace, North Charleston, S. C.
Arias, M.E., Cochrane, T., Kummu, M., Lauri, H., Holtgrieve, G., Koponen, J., Piman, T., 2014. Impacts of hydropower and climate change on drivers of ecological productivity of Southeast Asia's most important wetland. Ecol. Model. 272, 252–263. https://doi.org/10.1016/j.ecolmodel.2013.10.015.
Atkinson, E., 1996. The feasibility of flushing sediment from reservoirs. TDR Project R5839, Rep. OD 137.
Bagnold, R.A., 1977. Bedload transport in natural rivers. Water Resour. Res. 13, 303–312.
Barlow, C., Baran, E., Halls, A.S., Kshatriya, M., 2008. How much of the Mekong fish catch is at risk from mainstream dam development. Catch Cult 14 (3), 16–21.
Bellman, R., 1957. Dynamic Programming. Princeton University Press, Princeton, NJ.
Bertoni, F., Castelletti, A., Giuliani, M., Reed, P.M., 2019. Discovering dependencies, trade-offs, and robustness in joint dam design and operation: an ex-post assessment of the kariba dam. Earth's Future 7 (12), 1367–1390. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019EF001235.
Beyer, H.G., Sendhoff, B., 2007. Robust optimization–a comprehensive survey. Comput. Methods Appl. Mech. Eng. 196 (33–34), 3190–3218.
Brune, G.M., 1953. Trap efficiency of reservoirs. Trans. AGU 34, 407–418.
Bunt, C.M., Castro-Santos, T., Haro, A., 2012. Performance of fish passage structures at upstream barriers to migration. River Res. Appl. 28 (4), 457–478. https://doi.org/10.1002/rra.1565.
Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., 2003. Knowledge systems for sustainable development. Proc. Natl. Acad. Sci. Unit. States Am. 100 (14), 8086–8091.
Castelletti, A., Pianosi, F., Soncini-Sessa, R., 2012. Stochastic and robust control of water resource systems: concepts, methods and applications. In: System Identification, Environmental Modelling, and Control System Design. Springer, London, pp. 383–401.
Ceola, S., Arheimer, B., Baratti, E., Blöschl, G., Capell, R., Castellarin, A., Freer, J., Han, D., Hrachowitz, M., Hundecha, Y., Hutton, C., 2015. Virtual laboratories: new opportunities for collaborative water science. Hydrol. Earth Syst. Sci. 19 (4), 2101–2117.
Chang, F.J., Lai, J.S., Kao, L.S., 2003. Optimization of operation rule curves and flushing schedule in a reservoir. Hydrol. Process. 17 (8), 1623–1640.
China Southern Power Grid Company, 2008. The Kingdom of Cambodia Feasibility Study Report of Sambor Hydropower Station. China Southern Power Grid Company, Nanning, China.
Chowdhury, A.K., Dang, T.D., Bagchi, A., Galelli, S., 2020a. Expected benefits of Laos' hydropower development curbed by hydroclimatic variability and limited transmission capacity: opportunities to reform. J. Water Resour. Plann. Manag. 146 (10), 05020019.
Chowdhury, A.K., Kern, J., Tang, T.D., Galelli, S., 2020b. PowNet: a network-constrained unit commitment/economic dispatch model for large-Scale power systems analysis. J. Open Res. Software 8 (1), 5. https://doi.org/10.5281/zenodo.3462879.
Churchill, M.A., 1948. Discussion of paper by L.C. Gottschalk, "Analysis of use of reservoir sedimentation data". Proceedings of the Federal Inter-Agency Sedimentation Conference 139–140.
Coello Coello, C., Lamont, G.B., Van Veldhuizen, D.A., 2007. Evolutionary Algorithms for Solving Multi-Objective Problems, 2 ed. Springer, New York, NY.
Cronin, Richard, Eyler, Brian, Weatherby, Courtney, 2016. Letters from the Mekong: A Call for Strategic, Basin-Wide Energy Planning in Laos. Stimson Center.
Dalcin, L., Kler, P., Paz, R., Cosimo, A., 2011. Parallel distributed computing using Python. Adv. Water Resour. 34 (9), 1124–1139. https://doi.org/10.1016/j.advwatres.2011.04.013.
Dalcin, L., Paz, R., Storti, M., D'Elia, J., 2008. MPI for Python: performance improvements and MPI-2 extensions. J. Parallel Distr. Comput. 68 (5), 655–662. https://doi.org/10.1016/j.jpdc.2007.09.005.
Dalcin, L., Paz, R., Storti, M., 2005. MPI for Python. J. Parallel Distr. Comput. 65 (9), 1108–1115. https://doi.org/10.1016/j.jpdc.2005.03.010.
Danish Hydraulic Institute (DHI), 2017. MIKE 21C: Curvilinear Model Scientific Documentation. Horsholm, Denmark.
Efthymiou, N.P., Palt, S., Annandale, G.W., Karki, P., 2017. Reservoir Conservation Model: RESCON 2 Beta, Economic and Engineering Evaluation of Alternative Sediment Management Strategies. World Bank, Washington DC.
Fahrig, Lenore, 2003. Effects of habitat fragmentation on biodiversity. Annu. Rev. Ecol. Evol. Syst. 34 (1), 487–515. https://doi.org/10.1146/annurev.ecolsys.34.011802.132419.
Fearnside, Philip M., 2016. Tropical dams: to build or not to build? Science 351 (6272), 456–457.
Gallerano, F., Cannata, G., 2011. Compatibility of reservoir sediment flushing and river protection. J. Hydraul. Eng. 137 (10), 1111–1125.
Gazoni, E., Clark, C., 2017. Openpyxl-A Python Library to Read/write Excel 2010 Xlsx/xlsm Files.
Giuliani, M., Castelletti, A., Pianosi, F., Mason, E., Reed, P.M., 2016. Curses, tradeoffs, and scalable management: advancing evolutionary multiobjective direct policy search to improve water reservoir operations. J. Water Resour. Plann. Manag. 142 (2), 04015050.
Grant, G.E., Schmidt, J.C., Lewis, S.L., 2003. A geological framework for interpreting downstream effects of dams on rivers. In: O'Connor, J.E., Grant, G.E. (Eds.), A Peculiar River, Water Sci. Appl., vol. 7. AGU, Washington, D. C, pp. 203–219.
Grill, Günther, Lehner, Bernhard, Lumsdon, Alexander E., MacDonald, Graham K., Zarfl, Christiane, Liermann, Catherine Reidy, 2015. An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global

dams at multiple scales. Environ. Res. Lett. 10 (1), 015001 https://doi.org/10.1088/1748-9326/10/1/015001.

Grill, Günther, Ouellet Dallaire, Camille, Chouinard, Etienne Fluet, Sindorf, Nikolai, Lehner, Bernhard, 2014. Development of new indicators to evaluate river fragmentation and flow regulation at large scales: a case study for the Mekong River basin. Ecol. Indicat. 45 (October), 148–159. https://doi.org/10.1016/j.ecolind.2014.03.026.

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Macedo, H.E., 2019. Mapping the world's free-flowing rivers. Nature 569 (7755), 215–221.

Guariso, G., Rinaldi, S., Soncini-Sessa, R., 1986. The management of Lake Como: a multiobjective analysis. Water Resour. Res. 22 (2), 109–120.

Hadjimichael, A., Gold, D., Hadka, D., Reed, P.M., 2020. Rhodium: Python library for many-objective robust decision making and exploratory modeling. J. Open Res. Software 8 (1). https://doi.org/10.5334/jors.293.

Hadka, D., Herman, J., Reed, P., Keller, K., 2015. An open source framework for many-objective robust decision making. Environ. Model. Software 74, 114–129. https://doi.org/10.1016/j.envsoft.2015.07.014.

Hadka, D., Reed, P., 2013. Borg: an auto-adaptive many-objective evolutionary computing framework. Evol. Comput. 21 (2), 231–259. https://doi.org/10.1162/EVCO_a_00075.

Halls, A., Kshatriya, M., 2009. "Modeling the Cumulative Barrier and Passage Effects of Main- Stream Hydropower Dams on Migratory Fish Populations in the Lower Mekong Basin." Report no., Mekong River Commission, Vientiane, Lao PDR.

Halls, A., Conlan, I., Wisesjindawat, W., Phouthavongs, K., Viravong, S., Chan, S., Vu, V., 2013. "Atlas of Deep Pools in the Lower Mekong River and Some of its Tributaries, Technical Paper No. 31." Report no., Mekong River Commission, Phnom Penh, Cambodia.

Herman, J., Usher, W., 2017. SALib: an open-source Python library for sensitivity analysis. The Journal of Open Source Software 2 (9).

Herman, J.D., Quinn, J.D., Steinschneider, S., Giuliani, M., Fletcher, S., 2020. Climate adaptation as a control problem: review and perspectives on dynamic water resources planning under uncertainty. Water Resour. Res. 56 (2), e24389.

Hortle, K.G., 2009. "Fishes of the Mekong—how many species are there? Catch Cult 15 (2), 4–12.

Hunter, J.D., 2007. Matplotlib: a 2D graphics environment. Comput. Sci. Eng. 9 (3), 90–95.

IFC, 2015. Hydroelectric Power: A Guide for Developers and Investors. World Bank Group, International Finance Corporation.

Intralawan, A., Wood, D., Frankel, R., Costanza, R., Kubiszewski, I., 2018. Tradeoff analysis between electricity generation and ecosystem services in the Lower Mekong Basin. Ecosystem services 30, 27–35.

Jager, H., Efroymson, R., Opperman, J., Kelly, M., 2015. Spatial design principles for sustainable hydropower development in river basins. Renew. Sustain. Energy Rev. 808–816. https://doi.org/10.1016/j.rser.2015.01.067.

Junk, Wolfgang J., Bayley, Peter B., Sparks, Richard E., 1989. The flood pulse concept in river-floodplain systems. Can. Spec. Publ. Fish. Aquat. Sci. 106 (1), 110–127.

Kalin, L., Hantush, M., 2003. Evaluation of Sediment Transport Models and Comparative Application of Two Watershed Models, EPA/600/R-03/139. National Risk Management Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio, 45268, September, 73pp.

Kasprzyk, Joseph R., Shanthi Nataraj, Patrick M. Reed, Lempert, Robert J., 2013. Many objective robust decision making for complex environmental systems undergoing change. Environ. Model. Software 42 (April), 55–71. https://doi.org/10.1016/j.envsoft.2012.12.007.

Khan, N.M., Tingsanchali, T., 2009. Optimization and simulation of reservoir operation with sediment evacuation: a case study of the Tarbela Dam, Pakistan. Hydrol. Process. 23 (5), 730–747.

Khan, Z., Wild, T.B., Vernon, C., Miller, A., Clarke, L., Miralles-Wilhelm, F., Munoz-Castillo, R., Moreda, F., Bereslawski, J.L., Suriano, M., Casado, J., 2020. Metis – a tool to harmonize and analyze multi-sectoral data and linkages at variable spatial scales. J. Open Res. Software 8 (1), 10. https://doi.org/10.5334/jors.292.

Kirsch, B.R., Characklis, G.W., Zeff, H.B., 2013. Evaluating the impact of alternative hydro-climate scenarios on transfer agreements: practical improvement for generating synthetic streamflows. J. Water Resour. Plann. Manag. 139 (4), 396–406. http://ascelibrary.org/doi/10.1061/%28ASCE%29WR.1943-5452.0000287.

Koehnken, L., 2014. "Discharge Sediment Monitoring Project (DSMP) 2009-2013 Summary and Analysis of Results." Report no., Mekong River Commission. Phnom Penh, Cambodia.

Kondolf, G. Mathias, Gao, Yongxuan, Annandale, George W., Morris, Gregory L., Jiang, Enhui, Zhang, Junhua, Cao, Yongtao, et al., 2014. Sustainable sediment management in reservoirs and regulated rivers: experiences from five continents. Earth's Future 2 (5), 256–280. https://doi.org/10.1002/2013EF000184.

Kondolf, G.M., Schmitt, R.J., Carling, P., Darby, S., Arias, M., Bizzi, S., Castelletti, A., Cochrane, T.A., Gibson, S., Kummu, M., Oeurng, C., 2018. Changing sediment budget of the Mekong: cumulative threats and management strategies for a large river basin. Sci. Total Environ. 625, 114–134.

Koutsoyiannis, D., Economou, A., 2003. Evaluation of the parameterization-simulation-optimization approach for the control of reservoir systems. Water Resour. Res. 39 (6).

Kummu, M., Lu, X., Wang, J., Varis, O., 2010. Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong. Geomorphology 119 (3–4), 181–197.

Labadie, J.W., Baldo, M.L., Larson, R., 2000. MODSIM: Decision Support System for River Basin Management: Documentation and User Manual. Dept. of Civil Eng., Colo. State Univ., Ft. Collins, CO.

Lamberts, Dirk, 2006. The Tonle Sap Lake as a productive ecosystem. Int. J. Water Resour. Dev. 22 (3), 481–495. https://doi.org/10.1080/07900620500482592.

Lara, J.M., Pemberton, E.L., 1963. Initial unit weight of deposited sediments. In: Proceedings of Federal Interagency Sedimentation Conference. USDA-ARS Misc. Publ., pp. 818–845, 970.

Larinier, M., 2001. Dams, Fish and Fisheries: Opportunities, Challenges and Conflict Resolution. FAO, Rome, pp. 45–90. FAO Fisheries Technical Paper No. 419.

Laumanns, M., Thiele, L., Deb, K., Zitzler, E., 2002. Combining convergence and diversity in evolutionary multiobjective optimization. Evol. Comput. 10 (3), 263–282.

Liljeström, I., Kummu, M., Varis, O., 2012. Nutrient balance assessment in the Mekong Basin: nitrogen and phosphorus dynamics in a catchment scale. Int. J. Water Resour. Dev. 28 (2), 373–391. https://doi.org/10.1080/07900627.2012.668649.

Loucks, D.P., Taylor, M.R., French, P.N., 1995. IRAS - Interactive River-Aquifer Simulation Model, Program Description and Operating Manual. Cornell University, Ithaca, NY.

Loucks, D.P., 1995. Developing and implementing decision support systems: a critique and a challenge. JAWRA Journal of the American Water Resources Association 31 (4), 571–582.

Loucks, D.P., Van Beek, E., 2017. Water Resource Systems Planning and Management: an Introduction to Methods, Models, and Applications. Springer.

Loucks, D.P., 2020. From analyses to implementation and innovation. Water 12 (4), 974.

Maavara, Taylor, Parsons, Christopher T., Ridenour, Christine, Severin Stojanovic, Dürr, Hans H., Powley, Helen R., Van Cappellen, Philippe, 2015. Global phosphorus retention by river damming. In: Proceedings of the National Academy of Sciences, December, 201511797. https://doi.org/10.1073/pnas.1511797112.

Mahmood, K., 1987. Reservoir Sedimentation: Impact, Extent, and Mitigation, vol. 71. World Bank Tech. Rep., Washington, D. C.

Maier, H.R., et al., 2014. Evolutionary algorithms and other metaheuristics in water resources: current status, research challenges and future directions. Environ. Model. Software 62, 271–299.

Milliman, J.D., Meade, R.H., 1983. World-wide delivery of river sediment to the oceans. Geology 91, 1–21.

Minear, T., Kondolf, G.M., 2009. Estimating reservoir sedimentation rates at large spatial- and temporal-scales: a case study of California. Water Resour. Res. 45, W12502. https://doi.org/10.1029/2007WR006703.

Matrosov, E.S., Harou, J.J., Loucks, D.P., 2011. A computationally efficient open-source water resource system simulator–Application to London and the Thames Basin. Environ. Model. Software 26 (12), 1599–1610.

McIntyre, Peter B., Reidy Liermann, Catherine A., Revenga, Carmen, 2016. Linking freshwater fishery management to global food security and biodiversity conservation. Proc. Natl. Acad. Sci. Unit. States Am. 113 (45), 12880–12885. https://doi.org/10.1073/pnas.1521540113.

McKinney, W., 2012. Python for Data Analysis: Data Wrangling with Pandas, NumPy, and IPython. O'Reilly Media, Inc. Accessible at. https://pandas.pydata.org/.

Moran, E.F., Lopez, M.C., Moore, N., Müller, N., Hyndman, D.W., 2018. Sustainable hydropower in the 21st century. Proc. Natl. Acad. Sci. Unit. States Am. 115 (47), 11891–11898.

Mekong River Commission (MRC), 2009. Preliminary Design Guidance for Proposed Mainstream Dams in the Lower Mekong Basin. Vientiane, Lao PDR, Mekong River Commission.

Morris, G.L., Fan, J., 1998. Reservoir Sedimentation Handbook. McGraw Hill, New York, USA.

MRC (Mekong River Commission), 2016. Hydropower Project Database. Basin Development Plan Programme, Vientiane, Lao PDR.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2009. Soil and Water Assessment Tool Theoretical Documentation. In: Texas Water Resources Institute Technical Report No. 406. Texas A&M University System, College Station, Texas.

NHI (Natural Heritage Institute), 2017. "Sambor hydropower dam alternatives assessment: final Re- port, submitted to the royal government of Cambodia." report no., san francisco, California. http://n-h-i.org/publications/.

Noonan, M.J., Grant, J.W.A., Jackson, C.D., 2012. A quantitative assessment of fish passage efficiency: effectiveness of fish passage facilities. Fish 13 (4), 450–464. https://doi.org/10.1111/j.1467-2979.2011.00445.x.

Nowak, K., Prairie, J., Rajagopalan, B., Lall, U., 2010. A nonparametric stochastic approach for multisite disaggregation of annual to daily streamflow: nonparametric daily disaggregation. Water Resour. Res. 46 (8) https://doi.org/10.1029/2009WR008530.

Oliveira, R., Loucks, D.P., 1997. Operating rules for multireservoir systems. Water Resour. Res. 33 (4), 839–852.

Opperman, Jeff, Grill, G., Hartmann, J., 2015. The Power of Rivers: Finding Balance between Energy and Conservation in Hydropower Development. The Nature Conservancy, " Washington, DC.

Opperman, Jeffrey J., Royte, Joshua, Banks, John, Day, Laura Rose, Apse, Colin, 2011. The penobscot river, Maine, USA: a basin-scale Approach to balancing power generation and ecosystem restoration. Ecol. Soc. 16 (3) https://doi.org/10.5751/ES-04117-160307.

Pal, D., Galelli, S., 2019. A numerical framework for the multi-objective optimal design of check dam systems in erosion-prone areas. Environ. Model. Software 119, 21–31.

Palmieri, A., Shah, F., Annandale, G.W., Dinar, A., 2003. Reservoir Conservation Volume I: the RESCON Approach, Economic and Engineering Evaluation of Alternative Strategies for Managing Sedimentation in Storage Reservoirs, A Contribution to Promote Conservation of Water Storage Assets Worldwide. Int. Bank for Reconstruction and Dev./The World Bank, Washington, D. C., p. 101

Pelicice, F.M., Agostinho, A.A., 2008. Fish-passage facilities as ecological traps in large neotropical rivers: fish passages as ecological traps. Conserv. Biol. 22 (1), 180–188.

Pelicice, F.M., Pompeu, P.S., Agostinho, A.A., 2015. Large reservoirs as ecological barriers to downstream movements of Neotropical migratory fish. Fish Fish. 16 (4), 697–715.

Petts, G.E., Gurnell, A.M., 2005. Dams and geomorphology: research progress and future directions. Geomorphology 71, 27–47.

Poff, N. LeRoy, David Allan, J., Bain, Mark B., Karr, James R., Prestegaard, Karen L., Richter, Brian D., Sparks, Richard E., Stromberg, Julie C., 1997. The natural flow regime. Bioscience 47 (11), 769–784. https://doi.org/10.2307/1313099.

Pompeu, P.S., Nogueira, L.B., Godinho, H.P., Martinez, C.B., 2011. Downstream pas- sage of fish larvae and eggs through a small-sized reservoir, Mucuri river, Brazil. Zoologia (Curitiba) 28 (6), 739–746.

Poulsen, A., Hortle, K., Valbo-Jorgensen, J., Chan, S., Chhuon, C., Viravong, S., Bouakhamvongsa, K., Suntornratana, N., Yoorong, T., Nguyen, T., Tran, B., 2004. "Dis- Tribution and Ecology of Some Important Riverine Fish Species of the Mekong River Basin." Report no., Mekong River Commission, Vientiane, Lao PDR.

Quinn, J.D., Reed, P.M., Giuliani, M., Castelletti, A., 2017. Rival framings: a framework for discovering how problem formulation uncertainties shape risk management trade-offs in water resources systems. Water Resour. Res. 53 (8), 7208–7233.

Ratcliffe, R., 2020. The guardian. Cambodia scraps plans for Mekong hydropower dams. https://www.theguardian.com/world/2020/mar/20/cambodia-scraps-plans-for-mekong_hydropower-dams.

Reed, P., Hadka, D., Herman, J., Kasprzyk, J., Kollat, J., 2013. Evolutionary multiobjective optimization in water resources: the past, present, and future. Adv. Water Resour. 51, 438–456.

Roy, S.G., Daigneault, A., Zydlewski, J., Truhlar, A., Smith, S., Jain, S., Hart, D., 2020. Coordinated river infrastructure decisions improve net social-ecological benefits. Environ. Res. Lett. 15 (10) https://doi.org/10.1088/1748-9326/abad58.

Rubin, Z.K., Kondolf, G.M., Carling, P.A., 2015. Anticipated geomorphic impacts from Mekong basin dam construction. Int. J. River Basin Manag. 13 (1), 105–121.

Sabo, J., Ruhi, A., Holtgrieve, G., Elliott, V., Arias, M., Ngor, P., Rasanen, T., Nam, S., 2017. Designing river flows to improve food security futures in the lower Mekong Basin. Science 358 (1270), 1–11. https://doi.org/10.1126/science.aao1053.

Schmitt, R.J., Kittner, N., Kondolf, G.M., Kammen, D.M., 2019. Deploy Diverse Renewables to Save Tropical Rivers.

Schmitt, R.J., Bizzi, S., Castelletti, A., Kondolf, G.M., 2018. Improved trade-offs of hydropower and sand connectivity by strategic dam planning in the Mekong. Nature Sustainability 1 (2), 96–104.

Sheer, D.P., 2000. OASIS OCL. Hydrologics, Inc., Columbia MD.

Shin, S., Her, Y., Song, J.H., Kang, M.S., 2019. Integrated sediment transport process modeling by coupling soil and water assessment tool and environmental fluid dynamics code. Environ. Model. Software 116, 26–39.

Shokri, A., Haddad, O.B., Mariño, M.A., 2013. Reservoir operation for simultaneously meeting water demand and sediment flushing: stochastic dynamic programming approach with two uncertainties. J. Water Resour. Plann. Manag. 139 (3), 277–289.

Song, C., O'Malley, A., Zydlewski, J., Mo, W., 2020. Balancing fish-energy-cost tradeoffs through strategic basin-wide dam management. Resour. Conserv. Recycl. 161, 104990.

Souter, N.J., Shaad, K., Vollmer, D., Regan, H.M., Farrell, T.A., Arnaiz, M., Meynell, P.J., Cochrane, T.A., Arias, M.E., Piman, T., Andelman, S.J., 2020. Using the freshwater health index to assess hydropower development scenarios in the sesan, srepok and sekong river basin. Water 12 (3), 788.

Stedinger, J.R., Taylor, M.R., 1982. Synthetic streamflow generation: 1. Model verification and validation. Water Resour. Res. 18 (4), 909–918.

Stedinger, J.R., Vogel, R.M., Foufoula-Georgiou, E., 1993. Frequency analysis of extreme events. In: Maidment, D.R. (Ed.), Handbook of Hydrology. McGraw-Hill, New York chap. 18.

Suzuki, F.M., Pires, L.V., Pompeu, P.S., 2011. Passage of fish larvae and eggs through the funil, itutinga and camargos reservoirs on the upper rio grande (minas gerais, Brazil). Neotrop. Ichthyol. 9 (3), 617–622.

Taguchi, G., 1986. Introduction to Quality Engineering: Designing Quality into Products and Processes. Asian Productivity Organiztion, Tokyo.

Tangi, M., Schmitt, R., Bizzi, S., Castelletti, A., 2019. The CASCADE toolbox for analyzing river sediment connectivity and management. Environ. Model. Software 119, 400–406.

Thorncraft, G., Harris, J., 2000. Fish Passage and Fishways in New South Wales: a Status report." Report No. 1/2000. Cooperative Research Centre for Freshwater Ecology, Australia.

TNC (The Nature Conservancy), 2016. Improving hydropower outcomes through system-scale planning: an example from Myanmar. https://thought-leadership-production.s3.amazonaws.com/2016/05/09/13/53/29/e26cf10b-9a56-463d-97fc-0309b1fde0d6/System-Scale%20Planning_Myanmar_Report.pdf.

Trindade, B., Gold, D., Reed, P., Zeff, H., Characklis, G., 2020. Water pathways: an open source stochastic simulation system for integrated water supply portfolio management and infrastructure investment planning. Environ. Model. Software 132, 104772.

U.S. Army Corps of Engineers, 2016. HEC-RAS River Analysis System. Hydraulic Reference Manual, Version 5.0, February 2016.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., et al., 2010. Global threats to human water security and river biodiversity. Nature 467 (7315), 555–561. https://doi.org/10.1038/nature09440.

Vörösmarty, Charles J., Meybeck, Michel, Fekete, Balázs, Sharma, Keshav, Green, Pamela, Syvitski, James PM., 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. Global Planet. Change 39 (1), 169–190.

Wild, T.B., Loucks, D.P., 2014. Managing flow, sediment, and hydropower regimes in the sre pok, Se san, and Se kong rivers of the Mekong basin. Water Resour. Res. 50 (6), 5141–5157.

Wild, T.B., Loucks, D.P., 2015a. An approach to simulating sediment management in the Mekong River Basin. In: Sediment Matters. Springer, pp. 187–199.

Wild, T.B., Loucks, D.P., 2015b. Mitigating dam conflicts in the Mekong River basin. In: Conflict Resolution in Water Resources and Environmental Management. Springer, pp. 25–48.

Wild, Thomas B., Loucks, Daniel P., Annandale, George W., Prakash, Kaini, 2016. Maintaining sediment flows through hydropower dams in the Mekong River basin. J. Water Resour. Plann. Manag. 142 (1), 05015004.

Wild, T.B., Reed, P.M., Loucks, D.P., Mallen-Cooper, M., Jensen, E.D., 2019a. Balancing hydropower development and ecological impacts in the Mekong: tradeoffs for sambor mega dam. J. Water Resour. Plann. Manag. 145 (2), 05018019.

Wild, T.B., Loucks, D.P., Annandale, G.W., 2019b. SedSim: a River basin simulation screening model for reservoir management of sediment, water, and hydropower. J. Open Res. Software 7 (1). https://doi.org/10.5334/jors.261.

White, W.R., 2001. Evacuation of Sediments from Reservoirs. Thomas Telford, London.

Winemiller, K.O., McIntyre, P.B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., Baird, I.G., et al., 2016. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. Science 351 (6269), 128–129.

Yates, D., Sieber, J., Purkey, D., Huber-Lee, A., 2005. WEAP21-A demand-, priority-, and preference-driven water planning model. Part 1: model characteristics. International Water Resources Association 30 (4), 487–500.

Zagona, E., Fulp, T., Shane, R., Magee, T., Goranflo, H., 2001. RiverWare: a generalized tool for complex reservoir systems modeling. Journal of the American Water Resources Association, AWRA 37 (4), 913–929.

Zarfl, C., Lumsdon, A.E., Berlekamp, J., Tydecks, L., Tockner, K., 2015. A global boom in hydropower dam construction. Aquat. Sci. 77 (1), 161–170.

Zarfl, C., Berlekamp, J., He, F., Jähnig, S.C., Darwall, W., Tockner, K., 2019. Future large hydropower dams impact global freshwater megafauna. Sci. Rep. 9 (1), 1–10.

Zatarain-Salazar, J., Reed, P.M., Herman, J.D., Giuliani, M., Castelletti, A., 2016. A diagnostic assessment of evolutionary algorithms for multi-objective surface water reservoir control. Adv. Water Resour. 92, 172–185.

Zeff, H., Herman, J., Reed, P., Characklis, G., 2016. Cooperative drought adaptation: integrating infrastructure development, conservation, and water transfers into adaptive policy pathways. Water Resour. Res. 52 (9), 7327–7346. https://doi.org/10.1002/2016WR018771.

Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I., Levin, S.A., 2012. Trading-off fish biodiversity, food security, and hydropower in the Mekong River basin. Proc. Natl. Acad. Sci. Unit. States Am. 109 (15), 5609–5614.