CLASSIFICATION OF US HYDROPOWER DAMS BY THEIR MODES OF OPERATION

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ABSTRACT

A key challenge to understanding ecohydrologic responses to dam regulation is the absence of a universally transferable classification framework for how dams operate. In the present paper, we develop a classification system to organize the modes of operation (MOPs) for US hydropower dams and powerplants. To determine the full diversity of MOPs, we mined federal documents, open-access data repositories, and internet sources. We then used CART classification trees to predict MOPs based on physical characteristics, regulation, and project generation. Finally, we evaluated how much variation MOPs explained in sub-daily discharge patterns for stream gages downstream of hydropower dams. After reviewing information for 721 dams and 597 power plants, we developed a two-tier hierarchical classification based on (i) the storage and control of flows to powerplants, and (ii) the presence of a diversion around the natural stream bed. This resulted in nine tier-1 MOPs representing a continuum of operations from strictly peaking, to reregulating, to run-of-river, and two tier-2 MOPs, representing diversion and integral dam-powerhouse configurations. Although MOPs differed in physical characteristics and energy production, classification trees had low accuracies (≤62%), which suggested that accurate evaluations of MOPs may require individual attention. MOPs and dam storage explained 20% of the variation in downstream subdaily flow characteristics and showed consistent alterations in subdaily flow patterns from reference streams. This standardized classification scheme is important for future research including estimating reservoir operations for large-scale hydrologic models and evaluating project economics, environmental impacts, and mitigation. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: large dams; subdaily hydrology; reservoir operation; dam classification; hydrologic model

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INTRODUCTION

The functional significance of dams within aquatic environments relies heavily on how they influence hydrology. Changes in hydrology that depart significantly from natural flow regimes have many adverse consequences on river ecosystems, including loss of floodplain habitat and function, changes in biotic and abiotic process, and alterations in river community structure (Bunn and Arthington, 2002). While some generalities exist with regard to how dams modify hydrologic regimes (Poff *et al.*, 2007), much of the literature suggests that dams have unique operational regimes that complicate the development of rules-of-thumb with respect to their influence on hydrologic conditions (McManamay, 2014). This is not surprising given that dams vary considerably in their size, purpose, and socio-economic importance, all of which influence operations, i.e. the nature in which dams store and release water (Poff and Hart, 2002).

A key challenge to understanding ecological and hydrologic responses to dam regulation (i.e. modification of stream flow regimes) is the absence of a universally transferable classification framework that adequately captures the variety of ways dams are operated (Poff and Hart, 2002). Such a classification would provide many basic and applied outcomes, including stronger predictive capacity for hydrologic models (McManamay, 2014), a better understanding of how dams organize ecological communities (e.g. Mims and Olden, 2013), determining dam operational flexibility (Uría-Martínez *et al.*, 2015), determining the potential for environmental flows (Lessard *et al.*, 2013), and balancing social demands with environmental needs. While seemingly a simple concept, developing a classification system for dam operations is complicated by varying classification criteria across different disciplines (Poff and Hart, 2002) and limited information. Dams have been most commonly classified according to size, and to a lesser extent classified according to purpose, construction design and material, potential safety hazard, and technology (Herschy, 2012; ICOLD, 2015c). However, such terminology is frequently used in an

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inconsistent manner, which makes generalization difficult. For example, size categorizations have been developed based on dam height, storage, or energy capacity, but these classifications are not consistent among institutions (e.g. WCD, 2000; Kibler and Tullos, 2013; Kao *et al.*, 2014; National Atlas, 2014; USACE, 2015). Despite their convenience, the physical attributes of dams do not necessarily translate into the magnitude of hydrologic effects or operations (McManamay, 2014).

Although databases ranging from national to global scales contain valuable information on physical, geopolitical, social, and regulatory characteristics of dams (Lehner *et al.*, 2011; ICOLD, 2015c; USACE, 2015), no openly accessible database exists on dam operations. As an example, the National Inventory of Dams (NID) database maintained by the US Army Corps of Engineers contains information on dams within the United States (USACE, 2015). Information includes dam and reservoir size, ownership, purpose, construction material, year built, safety hazards, congressional authorization, and regulatory authority. The most relevant of these attributes to operations is the Congressional authorized purpose (e.g. hydropower, flood control, etc.). Although some consistencies in hydrologic regimes have been observed downstream of dams that share the same purpose (Mims and Olden, 2013), purpose is not synonymous with mode of operation (e.g. peaking, run-of-river) (Poff and Hart, 2002; McManamay, 2014).

Second only to irrigation, hydropower dams are extremely common, comprising 20% of large dams worldwide (Herschy, 2012) and 24% of the world's electricity (ICOLD, 2015a). To our knowledge, however, there is no standardized, widely accepted classification for how hydropower dams operate. Functionally, dams have two broad purposes related to hydropower: to store water and raise water levels (McCully, 1996; Poff and Hart, 2002). However, the most common operational categorization is storage versus run-of-river, with storage dams having larger volumes, longer residence times, and hence, more control over the release of water downstream (Poff and Hart, 2002). ICOLD further partitions hydropower operations into three installation types (storage, run-of-river, and pumped storage), which are as much related to infrastructure than operation (ICOLD, 2015b). However, there is little consistency among these classifications, as entities may use different terminology to define similar operations (e.g. TVA, 2004; BOR, 2015).

Understanding how dams influence hydrology is essential for optimizing the balance of multiple demands on water (Yeh, 1985), accurately modelling hydrology across large spatial scales (Hanasaki *et al.*, 2006), assessing downstream ecological effects (Petts, 1984), and making environmental flow recommendations (Richter and Thomas, 2007; Lessard *et al.*, 2013). Our objective was to develop a classification framework to capture the diversity of modes of operation (MOPs) for US hydropower facilities. To justify our approach and data organization, we first provide an overview of the complex nature of hydropower infrastructure and useful terminology. To determine the diversity of MOPs present in the current US hydropower fleet, we mined federal documents, internet sources, and open-access data repositories. Given the effort required to manually classify dams according to MOPs, we examined whether MOPs could be accurately predicted using available information on physical characteristics, location, and project economics (generation). Part of the justification of developing a classification of MOPs is the assumption that dams influence hydrology differently depending on operations, which should provide a more accurate prediction of downstream hydrology than purpose, as defined by NID. However, purpose is commonly used to build reservoir operation algorithms (Hanasaki *et al.*, 2006). Hence, we evaluated consistencies in hydrologic responses to dam operations in comparison to NID purpose.

COMPLICATED NATURE OF HYDROPOWER DAM INFRASTRUCTURE AND TERMINOLOGY

Our approach to defining MOPs is directly related to the complex nature of hydropower infrastructure and associated terminology. We structure our database and terminology according to the hierarchical organization of hydropower dams and powerplants compiled through the National Hydropower Asset Assessment Program (NHAAP) at Oak Ridge National Laboratory (ORNL, 2014). NHAAP is a data integration effort that provides a compilation of information on all US hydropower facilities (ORNL, 2014).

Classifying hydropower dam MOPs is complicated, in part, because infrastructure is routinely designed to minimize construction costs while maximizing energy within highly variable natural hydrologic settings and valley topographies. For the most part, hydropower dams, their powerhouses, and associated water transport infrastructure (e.g. penstocks, tunnels) are collectively called developments (ORNL, 2015) (Figure 1). A classic example of a typical hydropower development is only one dam and one associated powerhouse, as in the case of the Kingsford Dam and Powerhouse on the Menominee River, Wisconsin (Figure 1). However, in many cases, smaller dams and reservoirs may be constructed to support larger dams and reservoirs as to increase total storage and provide an additional level of flow control. We term these 'auxiliary' facilities and include them within the same development as the dams they support. For consistency, we define developments as a complex of one-to-many dams and any associated structures that collectively store, control flows, and convey water to generate electricity at a single powerhouse. In special cases, we define single dams (with no associated powerhouse) as individual
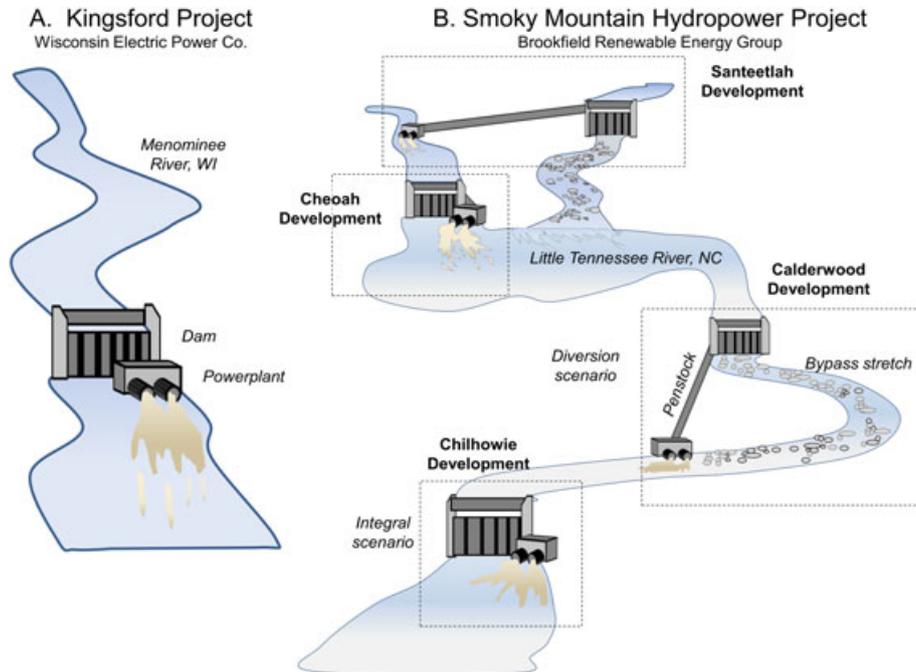
Figure 1. Conceptual model of different hydropower scenarios depicting (A) an integral dam and powerhouse and (B) a complex project consisting of multiple developments and a combination of integral and non-integral (i.e. diversion) dam/powerplant configurations. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

developments if they are considered separate developments by the Federal Energy Regulatory Commission (FERC). Typically, these dams constitute completely independent infrastructure from other facilities and provide highly-regulated releases to maximize hydropower production at dams and powerplants located a considerable distance downstream.

Another layer of complexity is diversion scenarios. Hydropower dams and powerhouses may be integral (connected as two elements of the same structural entity) (Figure 1A) or they may occur miles apart, such as in cases where water is diverted from the dam around a stream reach (termed a bypass stretch) to a downstream powerplant (Figure 1B). Steep mountain terrains often favour the use of diversions because head (i.e. potential energy) can be increased without the expense of constructing large dams with extensive reservoirs. Developments may include both integral or diversion designs with various configurations of water conveyance systems to connect different structural components.

Many times, multiple developments are managed as groups, often called projects, because they are either owned by the same entity, making regulatory requirements more efficient, or are part of a larger infrastructure meeting a specific authorized demand (e.g. Rio Grande irrigation project, Bureau of Reclamation (BOR)) (Figure 1). Once again, however, this terminology is not consistently used as FERC defines 'projects' as any single development or

group of developments having one owner (e.g. Figure 1A) and occurring within close proximity on the same river system (Figure 1B). We use the more strict definition of projects as multiple developments that are managed collectively. An example is the Brookfield Smoky Mountain Hydropower Project (historically termed Tapoco Project), located on the Little Tennessee River System in North Carolina. The project has four developments, all depicted in Figure 1B, which comprise a complex network of separate but interrelated facilities that maximize power production; hence, these developments are best managed collectively as a single project.

Given the complexity and regulation of hydropower infrastructure, the question arises, 'At what level of organization should we classify hydropower dams into different MOPs—the project, development, or individual level?' Because projects span multiple tributaries and include multiple developments, defining mode-of-operations for the project as a whole may be misleading. Although the Brookfield Smoky Mountain Hydropower Project operates all four developments in tandem to efficiently produce power during peak demands, different developments have different configurations and different MOPs. Additionally, river environments within different locations of the development may experience dramatically different flows. For example, diversion-bypasses are sections of streams where upstream flows have been diverted to downstream powerhouses thereby 'bypassing' a given segment of river (Figure 1B).

While these segments experience partial or complete dewatering, they are not exposed to the fluctuating high flow events below a given powerhouse (i.e. tailrace) (Figure 1B). Because river environments below dams may be very different than those below powerplants in situations of diversions, classifying both dams and powerplants is needed.

METHODS

Classification approach overview

We determined that classifying mode of operation separately for dams and powerplants at the individual level was the most appropriate. Using the NHAAP database (ORNL, 2015), we constructed a hierarchical database of projects, developments, and facilities (e.g. dams, powerhouses). We excluded dams and power plants constructed on canals (e.g. for irrigation) and conduits. We then used literature and web sources (see next section) to designate mode of operations. Given different sources of information, we took great care to ensure that classes were not simply an artifact of terminology from different agencies, but true differences in operation. We developed a two-tiered mode-of-operation classification scheme separately for dams and powerplants based on (i) how flows were stored and controlled within the upstream reservoir(s), and (ii) whether water was diverted around the natural stream bed. Mode of operation for each individual dam, whether the main controlling structure or an auxiliary structure, was classified separately according to the two-tiered scheme (e.g. Tier 1 = Type of Flow Regulation, Tier 2 = Diversion or Non-Diversion). Mode of operation for powerplants was somewhat easier as this was dependent upon the operation of main dams contributing flow to the powerplant. Powerplants were classified as diversions if they received diverted flow from the main dam immediately upstream; however, diversions upstream of power plants have no bearing on downstream hydrology, but are useful for classification.

Mining FERC e-library

Approximately, 50% of hydropower facilities in the USA are regulated by FERC and subject to periodic licensing and renewal (FERC, 2014). FERC publishes order approvals issuing new or subsequent licenses for hydropower projects, which contain adequate descriptions of project facilities and operations. All orders issuing licenses since 1995 (*n* = 369) were obtained from the FERC elibrary website (FERC, 2015) and we reviewed 278 of these documents. Only the latest order approval was considered for each dam and power plant. The project description, project facilities, current and proposed project operations, and articles mentioning flow requirements were reviewed for each

document. If these sections failed to describe the mode of operation, key-word searches were conducted within the document including 'mode' and 'operate'. However, we also viewed sections of orders entitled 'Headwater Benefits' to provide an indication of spatial layouts of dams and powerplants with respect to other hydropower projects. Headwater Benefits indicates possible compensation that a project may owe upstream hydropower projects (private or federal), in cases where the project was harnessing energy (i.e. benefitting) from upstream hydrologic regulation (e.g. flow pulses). This classified operations for projects correctly, such as cases where dams were classified as run-of-river, but inflows resembled flow pulses from upstream peaking facilities.

The description of the project and its facilities provides a spatial arrangement of different developments, dams, and powerplants within each development, including penstocks, tunnels, and canals (PTCs), all of which are relevant to determining diversion scenarios. The spatial layout, connectivity, and length of PTCs are typically provided in written form (project facilities) to describe how water is conveyed from dams to powerplants. We summed the total length of PTCs being careful to avoid duplicated values from parallel structures (several penstocks for multiple generators at powerplants). To determine diversion scenarios, we reviewed project facility descriptions and looked for keywords, such as 'diversion' or 'bypass'. In cases where descriptions were too vague, we validated the presence of diversions using Google Earth. We defined diversion scenarios as situations where a dam and powerplant were completely separated (i.e. powerplant and dam were not integral structures and powerplant was not at the immediate base of dam). However, in cases where dams and powerplants are not integral, releases of water from powerplant tailraces may pool up to the base of the dam leaving little-to-no exposed stream bed. Given that our definition of diversion was also important for understanding energy capacity (based on elevation gradient, e.g. potential energy), these facilities were still defined as diversions with the realization that this may not be hydrologically meaningful. Thus, it was equally important to understand the length of diversion-bypass areas. Although some FERC orders provide lengths for bypass areas, lengths for PTCs are more commonly provided and can be used to predict bypass length. For each diversion scenario, we obtained an estimate of stream channel sinuosity (total stream length/straight line distance) from the National Hydrography Plus Dataset (NHD version 1) (horizon-systems.com/nhdplus). We then developed a linear regression using PTC length*Sinuosity to predict bypass length. We compared the PTC values among non-diversions and diversions and then compared these values to bypass lengths.

Federal hydropower operations review

The availability and accessibility of information on mode of operation for federal dams depended on each agency. The BOR provides a centralized web portal that allows users to search for each dam and powerplant, and obtain information on project purpose, infrastructure, mode of operation, and the presence of diversions (BOR, 2015). Tennessee Valley Authority (TVA) conducted a study of reservoir operations (TVA, 2004), from which we obtained mode of operation. For US Army Corps of Engineers (USACE) facilities, we conducted web searches using the dam name or power plant, or we directly contacted regional offices to request information. In cases of both TVA and USACE, we used additional internet searches or Google Earth to determine diversion scenarios.

Geographical distribution and statistical summaries

Once the classification framework was solidified, we plotted all dams by their GPS coordinates to visualize any geographic affiliations in MOPs. We tested for statistical differences in the distributions of dam and power plant characteristics according to mode of operation using Kruskal–Wallis rank-sum tests. Non-parametric multiple comparison tests among classes were conducted using the kruskalmc function in the pgirmess package in R (Giraudoux, 2015). For simplicity, we only evaluated comparisons among Tier 1 MOPs. In addition, pumped storage facilities were excluded to keep comparisons of plant and dam characteristics unbiased as to only consider conventional hydropower.

We tested whether mode of operation was associated with the Congressional authorized dam purpose provided by NID. The NID lists 11 different purposes for dams and each dam may one or multiple purposes, the order of which indicates the relative importance (USACE, 2015). For the dams in our dataset, there were 165 unique NID purpose combinations if the order of listed purposes was considered and 94 unique purposes if the listed order was disregarded. To simply the number of NID purposes, we created 12 new purposes based on hypothesized levels of increasing water control: Other (O), Recreation (R), Supply and Irrigation (S), Flood Control (C), Hydropower (H), Hydropower + Other (HO), Hydropower + Recreation (HR), Hydropower + Supply (HS), Hydropower + Navigation (HN), Hydropower + Navigation + any others (HNO), Hydropower + Control (HC), and Hydropower + Control + any others (HCO). We used a chi-square test to determine whether the frequency of MOPs and NID purpose were statistically significant. We then used Cramer's V as a measure of association between the two classifications.

Predicting MOPs

Classification trees were used to determine whether mode of operation could be accurately predicted separately for dam and power plants based on relevant attributes. Because of reasons mentioned above, we only focused on predicting tier 1 classification schemes and not diversion scenarios; however, the presence of a diversion was included as a binary predictor variable in trees. In addition, pumped storage was excluded because of no way to differentiate auxiliary facilities for pumped storage from those of conventional hydropower in predictions. Tier 1 classes were simplified into coarser classes to determine if a simplified framework would improve predictive accuracy. Twenty-five variables were assembled (Appendix A) and ranged from natural basin characteristics and geography to facility size, ownership, and energy characteristics. Natural characteristics included drainage area, flow, and topography whereas hydrologic regions (i.e. two digit hydrologic units) were used to characterize differences in geography because of regulation, natural variation, and social values. Characteristics of dams included dam height, year built, dam storage (divided drainage area), reservoir surface area, residence time, and whether the dam was the main or auxillary structure. For power plants, we created cumulative variables that summarized all structures controlling flow upstream of the power plant within each development. Thus, we calculated the maximum height, maximum residence time, and cumulative surface area and storage among all dams contributing to each power plant. Regulatory requirements that might influence operational regime included who regulated each facility and whether the facility was licensed by FERC regulations. This becomes necessary in cases in which licensing may not be intuitive based on ownership, i.e. cases where private companies add power to federally owned structures. All variables were used in the rpart package in the R programming environment (Therneau et al., 2015) to predict detailed and coarse mode of operations for dams and power plants separately. Variable importance, a cumulative measure of goodness-of-split criterion for all variables in a tree, was used to assess the relative importance of all predictors based on their agreement values (classification accuracy) when used as primary and surrogate splitting variables (Therneau and Atkinson, 2015).

Subdaily hydrologic variation from MOPs

One of the central objectives in classifying dams by mode of operation is to understand how operations influence downstream hydrology. However, the temporal resolution of hydrologic variation is important when considering effects of dam regulation, especially with regard to hydropower

(Zimmerman *et al.*, 2010). Specifically, sub-daily hydrologic variation below hydropower facilities has been shown to be more meaningful than daily variation in generalizing dam-induced ecohydrologic effects (Zimmerman *et al.*, 2010; Bevelhimer *et al.*, 2015). We used six subdaily hydrologic statistics reported by Bevelhimer *et al.* (2015) to examine patterns in hydrology across mode of operation classes. The six metrics included: (i) daily CV (standard deviation of all values within 24-h period divided by the daily mean); (ii) Delta Q1 (daily delta, i.e. max–min over each 24-h period, divided by the daily mean); (iii) Hrly Ramp (hourly ramp rate, i.e. greatest hourly incremental change in flow during a 24-h period divided by the daily mean); (iv) Reversals (number of changes between rising and falling periods of the hydrograph within 24-h period, using a 10% threshold of change); (v) Rich Baker (Richards-Baker Flashiness index, i.e. daily path length of flow oscillations within 24-h period divided by the daily mean); and (vi) Rise Falls (difference between the number of hours of rising and falling flow as determined with each pair of consecutive flow values, ranges from −24 to 24).

We plotted dams and power plants by their GPS coordinates in ArcMap 10.1 and then used a spatial join procedure to find US Geologic Survey stream gauges within 15 km downstream. These gages were then filtered on the basis of whether they provided sub-daily information. The most recent four years of data were downloaded from the USGS instantaneous data archive (http://ida.water.usgs.gov/ida/) and top-of-the-hour observations were imported into a Microsoft Excel-based program (Bevelhimer *et al.*, 2015) to calculate indices. Four years of data were considered sufficient as they provide rich information (35 000 hourly observations) and avoid bias from year-to-year outliers (i.e. every gauge record will include at least one leap year). Hourly observations were used to keep all records consistent because gages provide a range of temporal resolutions (15 min – 1 h).

We attempted to ensure all mode of operation classes were represented by at least 10 stream gauges, and we achieved this except for storage-release dams (6 gages). In total, we collected subdaily discharge information from 133 stream gages influenced by dam regulation. To provide a reference comparison, we compiled subdaily discharge records for 35 reference-condition stream gauges across the US with little evidence of hydrologic modification and regulation by dams. Reference-condition gages drained watersheds with minimal hydrologic disturbance and were selected from a previous analysis (McManamay *et al.*, 2014). Hydrologic classes, representing 13 predominant natural hydrologic types across the US (McManamay *et al.*, 2014) were used to stratify reference gage selection to ensure a diversity of hydrologic types was represented. Cumulative frequency distribution (CFD) plots were used

to visually examine differences the distribution of subdaily statistics among MOPs and reference streams. We used a PMANOVA (non-parametric, Permutational Multivariate Analysis of Variance) from the vegan package in R (Oksanen *et al.*, 2015) to determine the amount of variation in hydrologic statistics explained by mode of operation (excluding reference gages), in addition to covariation explained by dam storage (adjusted by drainage area—Megaliters km^{-2}). As a comparison, we also assessed the variation in hydrologic statistics explained by dam purpose (reclassified as described above).

To examine patterns among stream gages in ordination space, a Principal Components Analysis was conducted using the six subdaily statistics. Statistics were $log(x + 1)$ transformed, centered, and scaled prior to analysis. The broken-stick method was used to determine the number of components to retain (Jackson, 1993). Gauges were plotted in ordination space according to different MOPs. Polygons were digitized representing the entire ordination space of reference streams and the ordination space occupied by the lower 90th percentile of reference streams (i.e. lower bounds for 90th percentile values of principle components).

RESULTS

We reviewed information for 721 dams and 597 power plants, which resulted in nine Tier-1 MOP classes and two Tier-2 MOP classes (Table I). MOP was determined separately for dams and power plants, as evident by the different sample sizes in each class (Table I). There were 18 Tier 1–2 combinations for dams and 14 Tier 1–2 combinations for powerplants (Table I). The most numerous classes were run-of-river and peaking dams and powerplants. Typically, dams outnumbered power plants within each class, with the exception of run-of-river and intermediate peaking facilities. These facilities, many of which were owned by BOR, have one dam feeding multiple power plants through diversions or interbasin transfers. While most dams were directly associated with power plants (either integrally or via diversion), over 15% were auxiliary facilities and did not have direct connections with power-generating facilities. For example, storage dams augment the total water stored for projects by storing and then spilling or diverting water to larger main dams or forebays, which then control water sent to power plants. In addition, storage-release dams act similarly to peaking dams, but have no associated power plants. Instead, these facilities are responsible for producing flow pulses to benefit energy production at downstream dams and powerplants. An interesting finding was that some dams have a combination of MOPs. For example, approximately 5% of dams operate as run-of-river facilities for seasons (e.g. during fish spawning) or the majority of the year and

Table I. Tier 1 and Tier 2 mode of operation classes defined for hydropower dams within the study. Classes were lumped together to provide a simpler, coarser classification system

Tier 1 mode of operation	Code	Dams	Plants	Description	Coarse class
Run-of-river	ROR	239	243	Discharges from the tailrace or dam approximate the sum of inflows to the reservoir at any given time. Hydroelectric generation is dependent upon natural incoming flows. Minimal fluctuation of the reservoir surface elevation.	ROR
Peaking	PK	213	194	Stores and releases water (high flow releases) for hydroelectric generation. Typically large reservoir fluctuations because of seasonal drawdowns.	PK
Storage	STOR	63	—	Auxiliary facility that stores (seasonally or daily) and controls water (moderate flow releases) for downstream hydroelectric generation. No generation capacity.	STOR
Storage releases	STOR-R	48	—	Stores and releases water (high flow releases) for downstream hydroelectric facilities. No generation capacity.	PK
Run-of-river/upstream Peaking	ROR-UP	44	44	Operates as a run-of-river facility but harnesses inflows from upstream storage releases or peaking operations to generate electricity.	ROR
Intermediate peaking	INT-PK	38	45	Stores limited amounts of water for occasional releases or moderates the intensity of peaking for hydroelectric generation.	PK
Run-of-river/peaking	ROR-PK	34	32	Operates as run-of-river for periods of time or seasons (e.g. during fish spawning) and then operates as a peaking facility the remainder of time.	ROR
Reregulating	RERG	20	20	Stores and releases water to stabilize flow fluctuations from upstream peaking or storage release facilities and generates electricity. Mitigation facility.	PK
Pumped storage*	PS	22	19	During periods of low energy demand, water is pumped to higher elevation auxiliary storage reservoirs using lower-cost energy generation. During high energy demand, water is released from high-elevation reservoirs through tunnels to powerplants and operated as a peaking facility.	PS
Tier 2 mode of operation					
Integral*	NDIV	408	333	Water flowing into power-generation facility enters intakes and flows through a powerhouse integral with the dam or is discharged over spillway. Water flowing into a non-powered facility is either spilled over spillway or stored and released through tunnels to base of dam.	—
Diversion*	DIV	313	264	Water flowing into facility is diverted through penstocks, tunnels, or canals to downstream reservoirs, other diversion structures, or to a separate powerhouse bypassing the natural river channel. Incoming flow that exceeds intake capacity is discharged over spillway.	—
Total		721	597		

*indicates class was excluded from multiple comparisons and classification trees

then operate as peaking facilities for other parts of the year. In other cases, some dams were classified as run-of-river operations according to project descriptions in FERC documents, but after careful consideration of upstream flow regulation, these dams were correctly classified as run-of-river/upstream peaking operations.

For the most part, the distribution of MOPs according to dam owner/operators followed the distribution of the entire sample size, with peaking and run-of-river dams being the most common (Table II). However, there were some noticeable differences. USACE and TVA dams were the least diverse in types of operations. In addition, none of the USACE-operated dams were diversion scenarios; however, non-federal operators utilizing USACE facilities did include diversions. A large portion of BOR dams were intermediate-peaking. Compared to other owners, non-federal dams were the most diverse, but also the most numerous, and utilized a far higher proportion of auxiliary dams to support power generation. Run-of-river-upstream peaking, run-of-river-peaking, and reregulation were

common operations at non-federal dams, but virtually absent at federal dams, with the exception of reregulation at USACE dams. Many run-of-river-upstream-peaking operations at non-federal dams harnessed peaking flows from federal facilities.

Of the diversion scenarios in our analysis, 89% (284) of those were dams regulated by FERC. Of those dams, 74% (211) provided sufficient information to determine a PTC length or bypass estimate. Pentsock-Tunnel-Canal (PTC) length, when combined with sinuosity, predicted bypass length with fairly high accuracy (Figure 2A). Thus, in cases where bypass length was not provided, we could predict these estimates provided that PTC length and sinuosity was available. PTC lengths for non-diversion scenarios averaged (SE) 0.26 km (0.07) and were much smaller than those for diversion scenarios, 2.93 km (0.34) (Figure 2B). Small PTC lengths arose for two reasons: (i) all diversion infrastructure may have not been provided, or (ii) small private hydropower operations (e.g. saw mill) have little infrastructure when diverting flows from smaller river systems. Bypass lengths averaged (SE) 3.74 km (0.54) and ranged from 14 m to 45.1 km. In only four cases, bypass lengths for dams were less than 50 m of stream. Of the diversion scenarios regulated by FERC, only 51% of bypass lengths were >1 km (Figure 2C).

Geographical distribution and statistical summaries

Typically, MOPs showed little geographical affiliation to different regions (Figure 3). However, intermediate peaking dams (primarily BOR) were more common in the western US whereas pumped storage and peaking pumped storage dams were more common in the Southeast and Southwest. Reregulating dams showed some affiliation to coastal areas (or Great Lakes), an indication of flow reregulation to estuaries.

Intermediate peaking and peaking dams had significantly higher dam height, higher storage, and created reservoirs with more surface area than the majority of other classes (Figure 4). Although storage and storage-release dams were located on smallest river systems, they had significantly higher residence times than most classes (Figure 4). Intermediate peaking and peaking powerplants also had the highest energy capacity (MW) and energy production (MWh), significantly higher than run-of-river and run-of-river/peaking plants. Plant factor was significantly lower at run-of-river plants, but otherwise similar among most classes (Figure 5).

Mode of operation and NID dam purpose were statistically independent ($X^2 = 435$, df = 117, $p < 0.0001$) and displayed little association (Cramer's $V = 0.259$, with 1 indicating perfect association) (Figure 6). Sixteen percent of dams had either no NID purpose provided or provided a purpose other than hydropower, 28% listed only hydropower as the purpose, and 56% listed at least one other purpose besides hydropower (Figure 6B). The diversity of mode-of-operation types within each NID purpose was a function of sample size (i.e. the number of dams with each purpose) rather than the purpose category itself (Figure 6C). This was unlikely an artifact of our assessment, as our subsample of dams matched the overall distribution of dams very well (Figure 5A).

Predicting MOPs

Overall, classification tree performance was poor with classification accuracies ranging from 39 to 62% and cross-validation errors ranging from 60 to 71% (Figures 7, 8).

Table II. Number of dams within different mode of operation types according to dam owner/operator

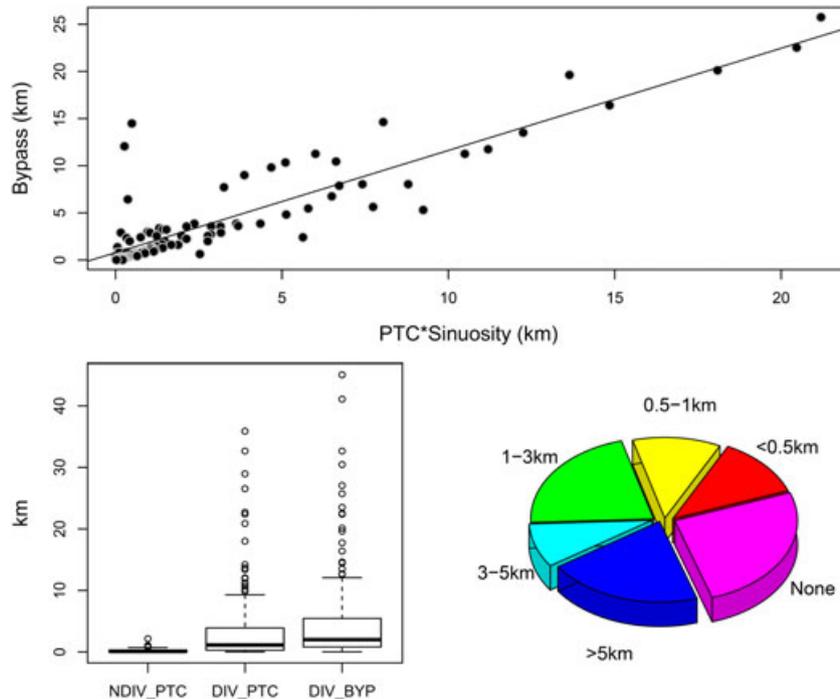| Mode of operation	Non-fed	USACE	BOR	TVA	Non-fed-USACE	Non-fed-BOR
Tier 1						
ROR	187	20	9	8	14	1
PK	142	30	13	20	5	3
STOR	55		5	1		2
STOR-R	47		1			
ROR-UP	43				1	
INT-PK	16		21		1	
ROR-PK	32	1	1			
RERG	14	6				
PS	9	3	4	2	1	3
Tier 2						
NDIV	261	60	40	27	13	7
DIV	284		14	4	9	2
Total	545	60	54	31	22	9

Figure 2. Analysis of diversion-bypass at hydropower dams ($n = 284$) regulated by the Federal Energy Regulatory Commission. (A) Summed values of lengths for penstock, tunnels, and canals (PTC) were multiplied by channel sinuosity and compared to empirical values of bypass ($n = 103$) using linear regression. (B) Lengths were compared among PTCs for non-diversion scenarios, PTCs for diversion scenarios, and diversion-bypass lengths. (C) The distribution of bypass lengths among diversion scenarios were examined only for FERC hydropower dams. 'None' indicates that length values were not provided for PTCs or bypasses in FERC documents. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

For trees predicting detailed MOPs, classification accuracies were 41% and 39% for dams and powerplants, respectively; however, accuracy increased in both cases when coarse MOPs were predicted with accuracies of 51% and 62%, respectively. Cross validation error rates for detailed mode of operations were 71% and 68% for dams and plants, respectively, whereas error rates dropped for coarse trees at 60% and 63%, respectively.

Residence time, dam height, dam storage, and regulation type were consistently important variables for dam MOP trees (Figure 7, Appendix A). Similarly, maximum residence time, maximum dam height, cumulative dam storage, cumulative surface area, and energy capacity (MW) were important variables for plant MOP trees (Figure 8, Appendix A). Height and residence time (including cumulative variables) were primary splitting variables, indicating these explained the most variation among MOPs.

Subdaily hydrologic variation from MOPs

Hydrologic statistics were statistically significant among mode of operation classes (PMANOVA, $F = 2.67$, $df_{num} = 8$, $df_{dem} = 123$, $p = 0.001$). Dam storage (Ml km^{-2}) also explained significant variation in hydrologic statistics

(PMANOVA, $F = 9.36$, $df_{num} = 1$, $df_{dem} = 123$, $p = 0.005$). Together, both MOPs and storage explained 20% of variation in hydrologic variables (mode of operation = 13.9%; storage = 6.1%). In comparison, hydrologic statistics were marginally significant among NID purposes (PMANOVA, $F = 1.64$, $df_{num} = 8$, $df_{dem} = 123$, $p = 0.06$). Dam purpose and storage explained 13.4% of variation in hydrologic variables (purpose = 9.0%; storage = 6.4%).

Peaking, intermediate-peaking, run-of-river-upstream-peaking, and run-of-river/peaking displayed the largest changes in hydrology compared to reference streams (Figure 9). Peaking dams had the largest influence on daily CV, hourly ramp rate, and Rich Baker index whereas intermittent peaking, run-of-river-upstream-peaking, and run-of-river/ peaking had greatest effect on reversals (Figure 9). Additionally, run-of-river-upstream-peaking had considerable influence on Rich Baker index.

According to the broken-stick rule, the first two principal components (PC) were significant and explained 92.8% of the overall variation in hydrologic statistics (Figure 10). The first PC explained 75.7% of the variation and driven by the following variables (loadings): daily delta (-0.460), daily CV (-0.457), Rich Baker index (-0.455), hourly ramp rate (-0.448), and reversals (-0.414). Similar values
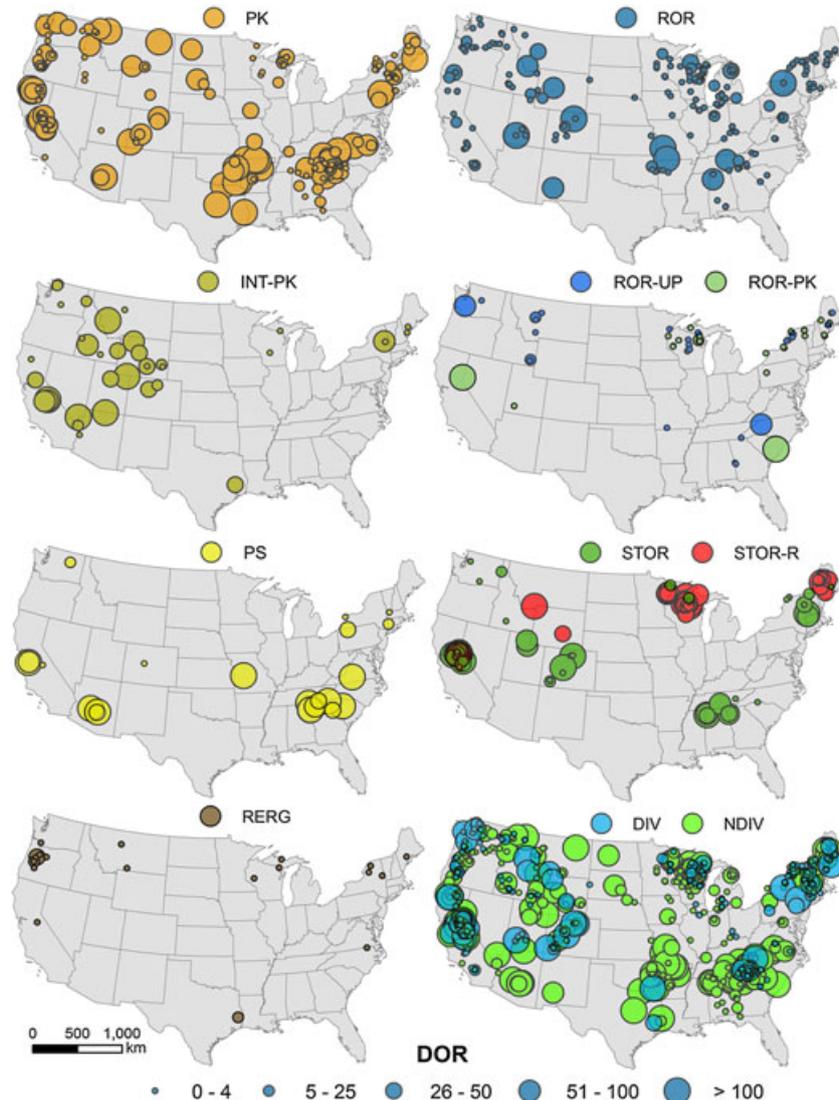
Figure 3. Spatial distribution of dams according to mode of operation classes and degree of regulation (DOR = storage / annual flow × 100). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

for variable loadings suggested strong correlation among metrics. The second PC explained 17.3% of the variation and was primarily related to rise and falls (−0.979). Peaking, run-of-river-upstream-peaking, and run-of-river peaking displayed more variation along PC1 whereas the other classes showed more variation along PC2 (Figure 10). Only 31% of dam regulated gages fell within the two-dimensional polygon-cluster outlining 90% of the reference-gages (Figure 10). The highest percentage of gages (based on abundance of gages within classes) was diversions (64%), storage dams (55%), and run-of-river dams (38%). When considering the polygon outlining all reference gages, 56.3% of dam-regulated stream gages fell within the two-dimensional space.

DISCUSSION

Our results revealed a continuum of operation modes of hydropower facilities that range considerably in dam characteristics, energy production, and the extent of hydrologic modification. Considering that hydropower dams represent less than 4% of all dams in the USA, the degree of variation in MOP classes within our analysis is surprising and suggests that the full suite of dam operation types across the entire USA may be quite large. Based on our experience of reviewing dam operations on a case-by-case basis, the level of effort required to develop a classification of dam operations is the most probable reason that a comprehensive assessment of dam operations did not previously exist.
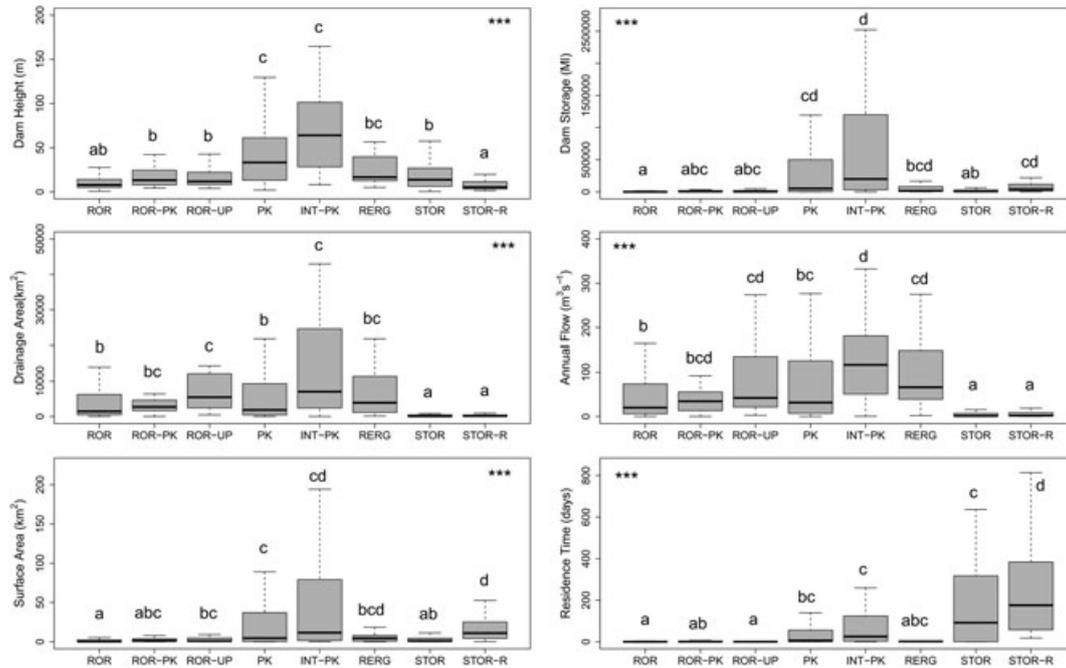
Figure 4. Box and whisker plots of characteristics for dams according to modes of operation (MOPs). *, **, and *** represent statistical significant among MOPs at the 0.05, 0.005, and 0.0001 levels using Kruskal–Wallis tests. Different letters represent statistical significance of non-parametric pair-wise comparisons at the $p < 0.05$ level

Interestingly, we found that MOP classes were not synonymous with NID purpose, which suggests that in many cases, dam operations are somewhat flexible as long as they meet the needs of Congressional authorized purpose for development (Uría-Martínez *et al*., 2015). Many dams within our assessment had NID purposes that excluded hydropower; thus, given their non-obvious linkage to downstream power-generating facilities, investigators may incorrectly assume operations for these facilities have little influence on hydrology. For example, storage dams and storage-release dams were included in our analysis despite not having any direct generation capacity; however, storage-release dams display considerable effects on hydrology. Furthermore, project descriptions provided by various agencies may be misleading and lead to underestimating the true nature of hydrologic regulation. As one example, FERC orders classified many dams as run-of-river operations despite receiving pulsed flows from upstream storage-release or peaking dams. These facilities are appropriately classified as run-of-river-upstream-peaking types and display hydrologic responses more similar to peaking dams than run-of-river dams.

Despite having a relatively large predictor ensemble, model performance in predicting MOPs was poor. Ultimately, this suggests that dam operations are complex, context-specific, and determined by multiple factors including the local regulatory context, energy generation supply needs, environmental needs, and social pressures from stakeholders. Hence, we conclude that frameworks for coarsely classifying dam operations across large spatial scales will likely have limited application; thus, to accurately assess operations, individual attention may be required by reviewing documentation or using reservoir operation algorithms (inflow/outflow data). Besides the complexity and contextual nature of mode of operations, other reasons for low model accuracy are numerous. For instance, we attempted to avoid biases from institutional differences in terminology, but these artifacts may still be present because some agencies define operations on the basis of meeting energy demands (e.g. BOR, 2015) as opposed to control over hydrology (e.g. TVA, 2004). In many cases, a considerable number of hydropower projects have changed operations in recent years. For example, a review of 233 FERC-licenses renewed between 1998 and 2000 revealed that 13% (28) moved from peaking to run-of-river operations in response to environmental concerns from stakeholders (Jager and Bevelhimer, 2007). Given the operational flexibility of facilities (Uría-Martínez *et al*., 2015), the physical characteristics of dams do not inevitably suggest operation type. Predictive performance could have increased had we considered other variables, such as social drivers (stakeholder participation), regulatory demands from federally listed species, energy demand, or the diversity of the local energy-portfolio (e.g. fossil fuel, nuclear, non-hydro renewables, etc.). However, the effort required to assemble variables that provide additional dimensions to the
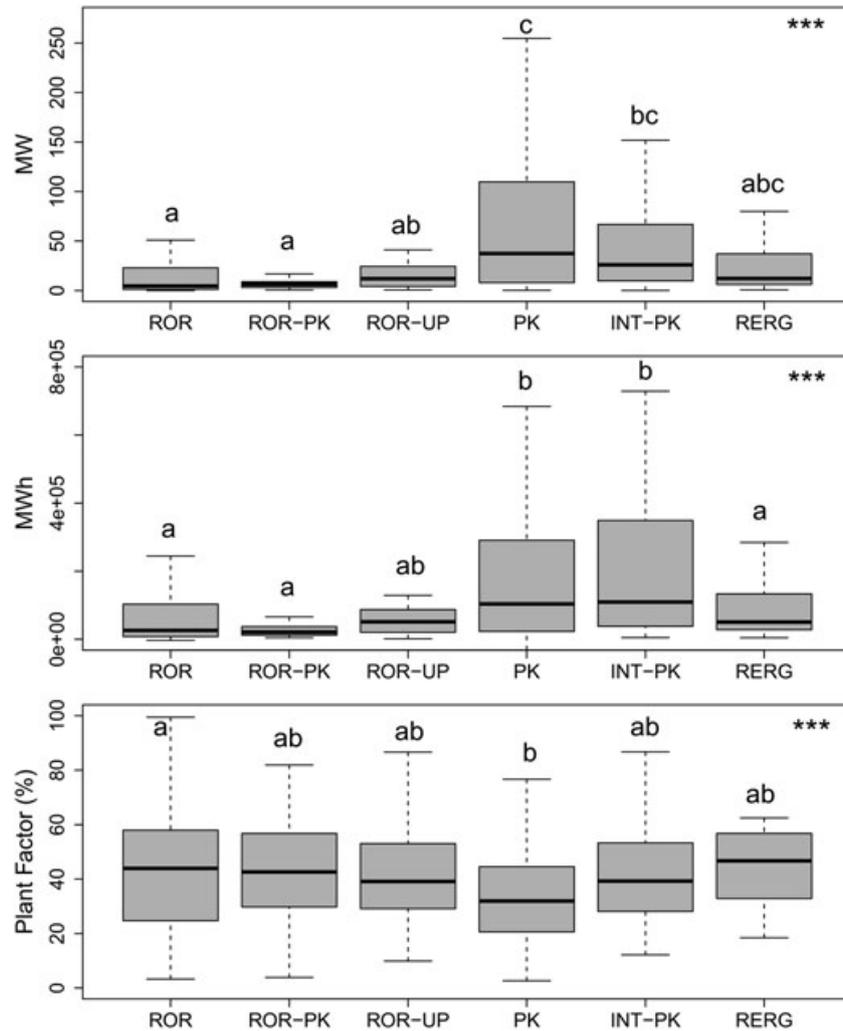
Figure 5. Box and whisker plots of characteristics for power plants according to modes of operation (MOPs). *, **, and *** represent statistical significant among MOPs at the 0.05, 0.005, and 0.0001 levels using Kruskal–Wallis tests. Different letters represent statistical significance of non-parametric pair-wise comparisons at the $p < 0.05$ level

model should be balanced with the effort of evaluating each individual facility on a case-by-case basis.

Although hydrologic responses to dams were highly variable, they predictably followed MOP classes. MOPs and dam storage explained 20% of the variation in six subdaily hydrologic metrics, notably higher than the variation explained by dam purpose. In comparison, sophisticated statistical models with hierarchical structure and 18 predictors only explained 10–30% in daily hydrologic responses (McManamay, 2014). The degree to which MOPs influenced hydrology varied according to the MOP and subdaily metrics. Peaking and run-of-river-upstream-peaking dams had the largest and most consistent deviations in subdaily hydrology, followed by smaller but noticeable effects of intermediate-peaking and run-of-river/peaking dams. Peaking and dams tended to influence

measures of variation (daily CV, hourly ramp rate, and Rich Baker index) whereas the other MOPs influenced reversals. Similarly, Zimmerman *et al.* (2010) found that peaking dams exhibited the largest alterations in subdaily flows, but also observed significant changes in subdaily flows below run-of-river plants.

The fact that run-of-river-upstream-peaking (ROR-UP) dams share similar hydrologic effects to that of peaking dams also suggests that coarse evaluations of MOPs can be misleading. FERC classifies these facilities as run-of-river dams as they have little storage and outflows approximate inflows. Careful attention to the spatial orientation of multiple dams is needed to determine the true nature of hydrologic effects depending on the application. Process-based hydrologic models (e.g. SWAT) produced for entire basins may not need to account for differences between ROR and
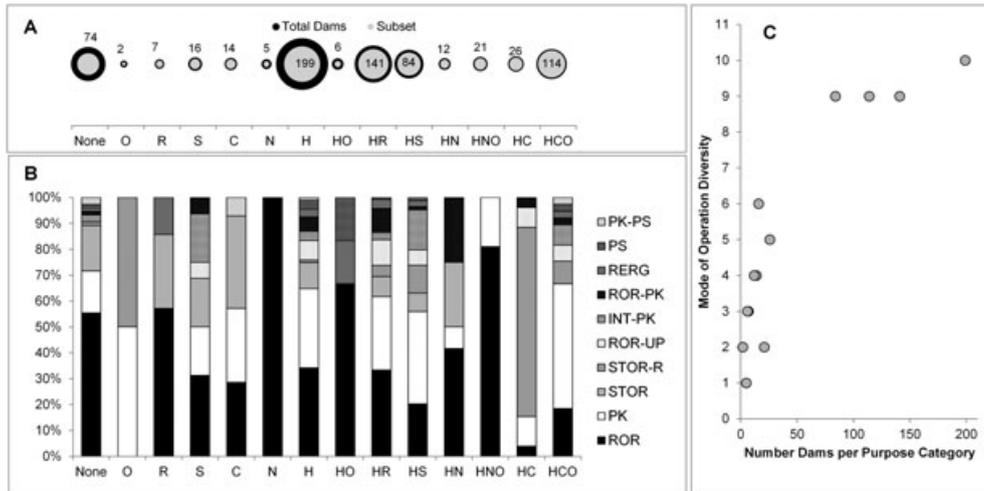
Figure 6. (A) Distribution of all hydropower dams and the subset examined in our study across different dam purposes, (B) comparison of dam purpose with modes of operations (MOPs), and (C) comparison of sample size within each dam purpose to the number of different MOPs represented within each purpose
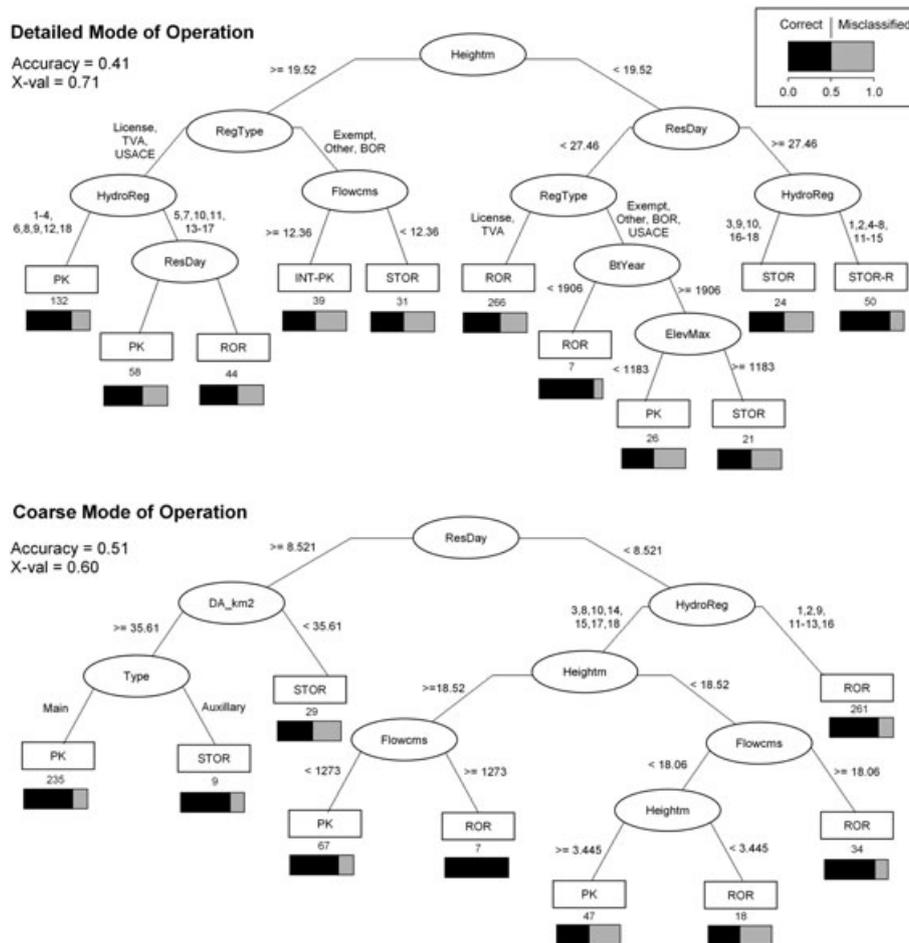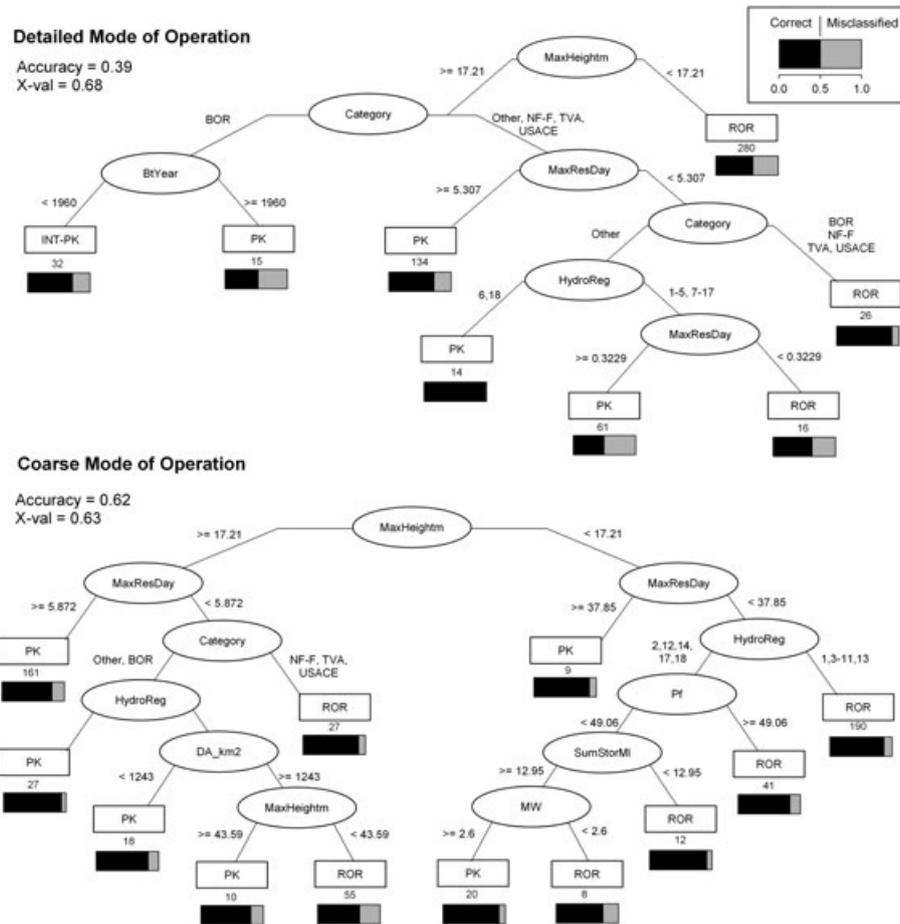

Figure 7. Classification trees predicted detailed modes of operation (MOPs) and coarse MOPs for dams. Numbers below each node represent sample sizes. Accuracy refers to % of samples accurately classified. X-val refers to cross-validation error rate

Figure 8. Classification trees predicted detailed modes of operation (MOPs) and coarse MOPs for powerplants. Numbers below each node represent sample sizes. Accuracy refers to % of samples accurately classified. X-val refers to cross-validation error rate

ROR-UP dams as reservoir operation algorithms in these models can account for highly modified incoming flows.

One potential limitation of our study was that we did not evaluate patterns using daily discharge data. While dam purpose may explain interpretable trends in daily discharge (Mims and Olden, 2013), daily hydrologic responses to dam regulation are difficult to predict (McManamay, 2014). Bevelhimer *et al.* (2015) found that subdaily hydrologic statistics were superior at distinguishing hydropower dam operation types from each other and from unregulated streams as compared to daily hydrologic statistics. Compared to daily statistics, subdaily statistics seem to be more sensitive and responsive to hydrologic alterations (Zimmerman *et al.*, 2010). This was apparent in our study as 69% of stream gauges regulated by hydropower dams fell outside the 90th percentile range of subdaily flow variation represented by reference stream gages.

In contrast to our analysis, the most common method of assessing dam operations is by using dam purpose and/or constructing reservoir operation algorithms (Yeh, 1985;

Wurbs, 1993; Labadie, 2004). At the most basic level, these algorithms require compiling or simulating inflow or outflow information for each reservoir, but also include other mechanisms such as dam purpose(s), storage, estimated losses because of evaporation, and additional water demands (if different than purpose) (Hanasaki *et al.*, 2006; Zhang *et al.*, 2010, 2011) Appropriate calibration of reservoir operation algorithms is resource-intensive; thus, the most appropriate applications have been at the scale of individual dams or basins (Labadie, 2004; Zhang *et al.*, 2010, 2011), with only a few applications at large scales (Döll *et al.*, 2003; Hanasaki *et al.*, 2006). Our analysis provides important considerations for the development reservoir operation algorithms in multiple ways. First, we show that there is a wide diversity of MOPs when only considering hydropower dams (a subset of the entire population of US dams) and that NID purpose either incorrectly classifies dams (hydropower is not listed as a purpose) or is poorly associated with MOPs. Thus, algorithms that rely on dam purpose for calibration should be carefully evaluated as to
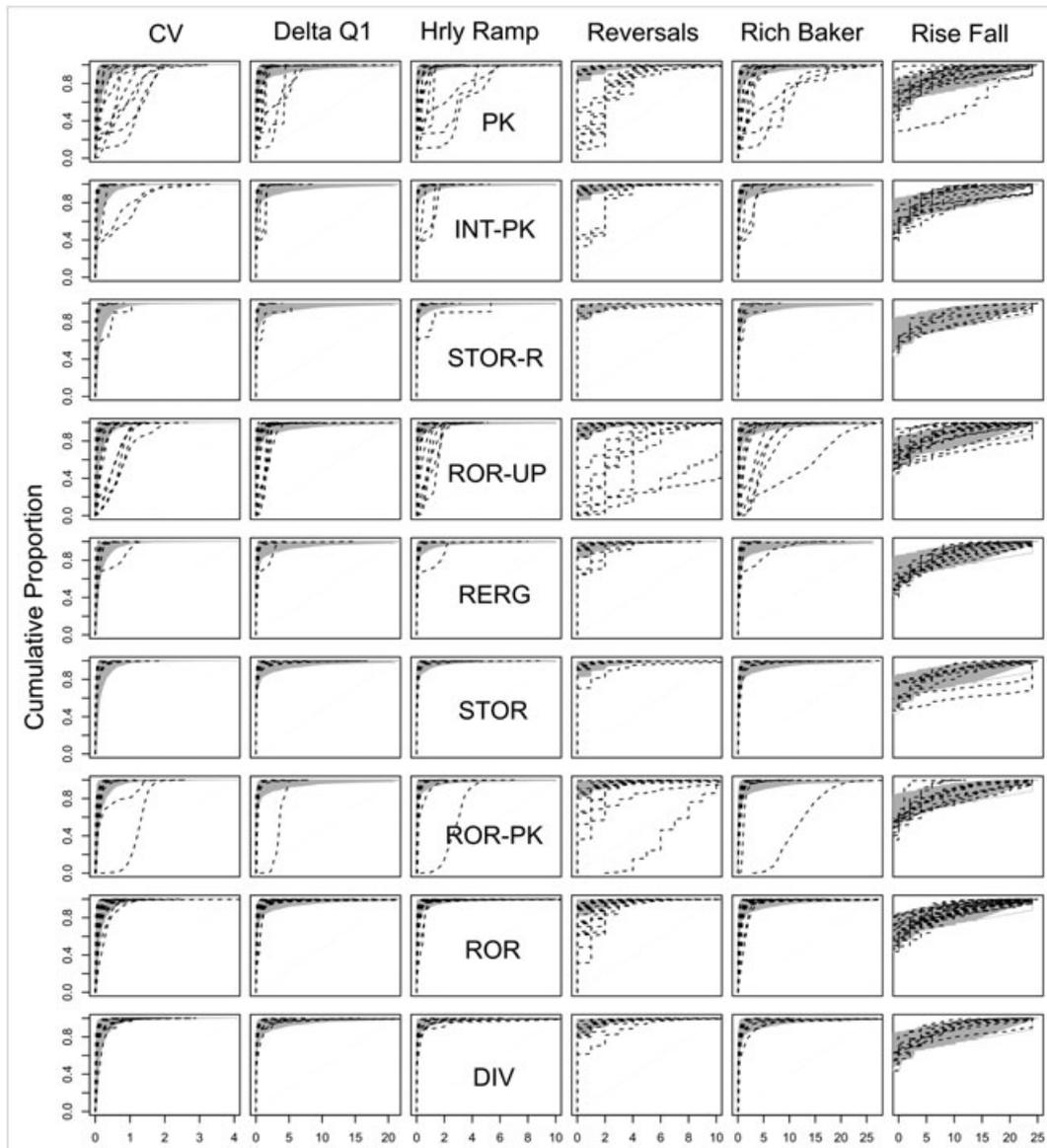
Figure 9. Cumulative frequency distribution (CFD) plots of six sub-daily hydrologic indices (columns) and nine modes of operation (rows). Each line represents a separate CFD for an individual stream gauge over four years. Grey shaded region represents the maximum and minimum of the 95th percentile values for 35 reference streams across the US

ensure operations have some bearing on authorized purpose. Secondly, MOPs were difficult to predict using a suite of variables that are commonly used to calibrate reservoir operation algorithms. This suggests that the true nature of dam operations would be difficult to predict at large spatial scales (e.g. Hanasaki *et al.*, 2006) without considerable uncertainty. Last, we found considerable, but predictable variation in subdaily hydrologic variation according to MOP classes. However, the vast majority of reservoir operation algorithms (including those for hydropower dams) are created on the basis on daily discharge (Yazicigil *et al.*, 1983; Xu *et al.*, 2015; except see Shiaul and Wu, 2013). While subdaily

hydrologic variation may be irrelevant to non-hydropower dams, energy production at hydropower dams relies on operational flexibility of within-day variation (Jager and Bevelhimer, 2007), in addition to variable day-to-day or seasonal operations (Shiaul and Wu, 2013). For algorithms to be most relevant to multi-objective optimization, especially regarding power production, subdaily temporal scales should be considered.

The utility of MOPs in informing environmental flow assessments is most relevant for analyses conducted at basin or regional scales. Determining the potential for modifying dam operations to improve downstream hydrologic
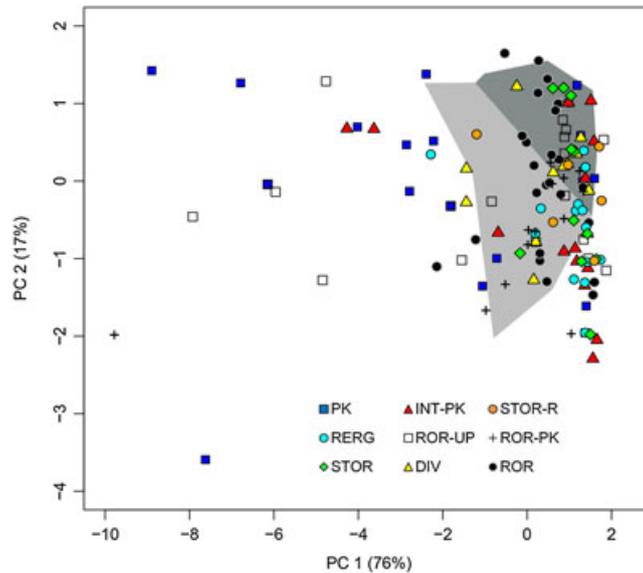
Figure 10. Ordination of stream gages regulated by different dam operations using Principal Components Analysis (PCA) on six subdaily flow metrics. Dark polygon outlines the smallest multidimensional space occupied by 90% of the reference streams. Lighter polygon outlines the entire multidimensional space occupied by all reference streams. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

conditions requires some knowledge of project flexibility (Richter and Thomas, 2007; Lessard *et al.*, 2013); thus, MOPs can help prioritize hydropower projects where reoperation is the most feasible. For example, MOPs can be partitioned into groups of high and low flexibility (Uría-Martínez *et al.*, 2015), where peaking, intermittent-peaking, and run-of-river-upstream peaking provide more flexibility in operations and run-of-river, run-of-river-peaking, and reregulation dams are far less flexible (Figure 11). In addition, the most flexible operations typically induce the most significant deviations in downstream hydrologic and ecological behaviour from natural conditions (Jager and Bevelhimer, 2007). Thus, environmental flow assessments could be prioritized for regions or specific projects with the highest flexibility but most significant hydrologic effects (Figure 11). For example, Roanoke Rapids Dam has received considerable attention with regard to improving ecohydrologic conditions in the last free-flowing stretch to the estuary (Figure 11) (Richter *et al.*, 1997; Pearsall *et al.*, 2005); however, Kerr Dam (USACE owned) has almost 42 times the storage capacity of Roanoke Rapids Dam and has more operational flexibility. Because the size and operation of Roanoke Rapids is limited in the extent to which peaking flows from upstream can be reregulated, environmental stakeholders have negotiated new operations for Kerr Dam (Pearsall *et al.*, 2005). An important consideration, however, is that energy production is partially attributable to flexibility in operations, as generation can increase during periods of peak energy demands. Compared to other energy sources (including other renewables), the strength of hydropower is that it offers flexibility and reliability, and thus security, to the electricity grid. Therefore, environmental flow assessments must seek a balance to restoring key components of flow regimes while meeting energy demands.

Our analysis suggests that diversion scenarios for hydropower are relatively common in the landscape, making up 43% of dams in our analysis. While this would suggest that diversions have pervasive hydrologic effects, roughly half of diversions (only considering FERC data) have bypass lengths less than 1 km or are not reported at all. This suggests that while diversions are common designs for hydropower energy production, many of the bypasses are relatively short; however, this is not to suggest that short diversions are ecologically insignificant. While some diversions are likely small, the cumulative effect may be quite large. For example, we estimate that the total length of bypassed streams for 211 hydropower dams with data is 975 km. While tempting to extrapolate the cumulative length of diversions for all hydropower dams in the US, the context-specific nature would preclude any analysis with acceptable uncertainty.

One important consideration is that our classification offers the capability of high-resolution-spatially autonomous hydrologic modelling assuming Tier 1 and 2 classes are used correctly when evaluating changes in hydrology at high spatial resolutions, such as within specific stream reaches. For example, in the case of diversion scenarios, the Tier 1 operation type will likely have little influence on the hydrologic condition of bypassed (i.e. diverted) stream reaches, but will be directly relate to hydrologic conditions in stream reaches downstream of power plants. In contrast, Tier 2 operations
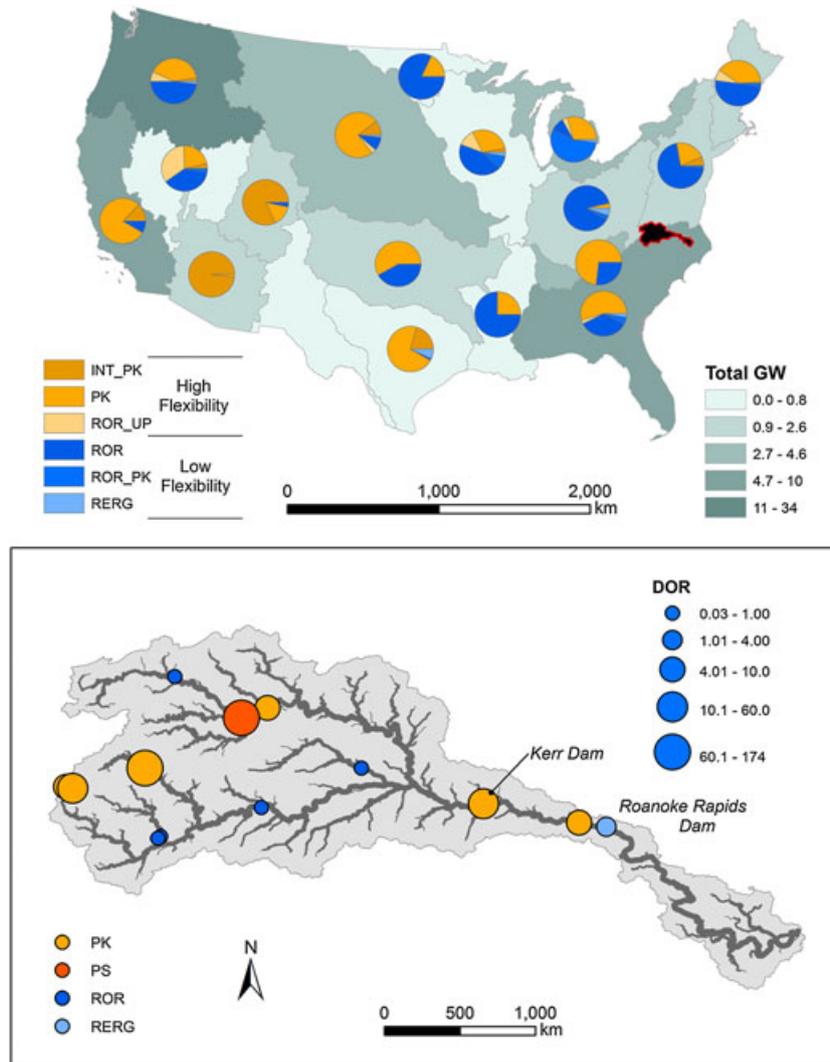
Figure 11. Flexibility in hydropower dam operations across the conterminous US (top). Pie charts represent proportion of gigawatt (GW) capacity represented by each mode of operation. Hydropower dams in the Roanoke River Basin according to operation and degree of regulation (DOR). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

will have little influence on hydrology below power plants (i.e. tailraces), but will have direct relevance to dewatering in bypassed reaches. In some cases, Tier 1 operations may influence reservoir fluctuations to an extent that water availability limits or provides for spillage into bypassed reaches (for environmental flows). For the most part, this is an exercise in water partitioning of reservoir storage.

There are approximately 2160 hydropower dams in the conterminous US; thus, we believe our subset (33%) is fairly representative of the entire population of hydropower facilities and the diversity of different MOPs. Realistically, operations at dams represent a continuum of different types and likely do not follow discrete categorizations, as is evidenced by low accuracy in classification trees and range of hydrologic responses. Nonetheless, our classification is a

useful for a number of reasons, including use as predictors in large-scale hydrologic models and for use in evaluating project economics, environmental impacts, and mitigation. As an example, our MOP classification has already been used to characterize the operational flexibility of the existing hydropower fleet to provide a quantitative baseline of energy characteristics to industry and policy makers (Uría-Martínez *et al.*, 2015). An alternative approach to our study is using downstream hydrologic responses to classify dams into different operational categories as opposed to relying on project descriptions from a variety of sources, each of which may be prone to uncertainty and differences in terminology. Future research should include more detailed evaluations of downstream hydrologic and ecologic responses to different MOPs for all types of dams

in order to find sustainable balances between services provided by those dams and environmental impacts.

Appendix A

Variables used in classification trees for dams and power plants. Values represent variable importance (see methods). Top 6 variables indicated in bold and shading for each tree. '---' indicates variable was not included in predictor ensemble for a given tree.

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