CHAPTER 23

Flow management through a resilience lens: Allocation of an environmental water budget using the Functional Flows Adaptive Implementation Model

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Introduction

In the Anthropocene, rivers are seen as socio-ecological systems where human societies are connected to the functioning of river ecosystems (Naiman, 2013; Dunham et al., 2018, Chapter 17). Riverine landscapes provide extensive ecosystem services for people, including provisioning (e.g., freshwater, food) and regulating (e.g., water purification) services, often linked to widespread water infrastructure (Brauman et al., 2007; Arthington et al., 2010; Cooley et al., 2021). As a result, regulated rivers are prevalent globally and are increasing in both number and extent as human demands expand (Lehner et al., 2011; Grill et al., 2019). Impacts from dams, diversions and floodplain levees on aquatic ecosystems have disrupted river ecosystems and impaired water quality, resulting in dire conditions for over 85% of freshwater species globally and reduced ecosystem services for people (Vorosmarty et al., 2010; Reid et al., 2019; van Rees et al., 2021). At the same time, many aquatic ecosystems below dams are now dependent on the flows provided by reservoirs (Null et al., 2022). Ongoing climate stress from increasing temperatures and extreme weather events such as droughts and floods (Swain et al., 2018; Brunner et al., 2021) is forcing water managers and societies to adapt and transform to improve riverine ecosystem functionality, sustain ecosystem services and build resilience to future uncertain disturbances. We therefore ask: *Can flow regimes below dams be re-regulated to restore functionality and build river resilience?*

Recent studies highlight a need for more comprehensive holistic approaches to river management that focus on understanding and supporting river ecosystem functions (Poff et al., 2010; Meitzen et al., 2013; Palmer and Ruhi, 2019). This requires understanding interdisciplinary river processes and interactions that vary over temporal and spatial scales (Dollar et al., 2007; Yarnell and Thoms, 2022). Water management approaches that focus solely on the needs of a single species or a narrow range of water quality conditions rarely succeed, as dynamic interactions between physical, biogeochemical and biological processes over time are not accounted for (Williams et al., 2019; Tonkin et al., 2021). Further, when simplified and homogenised river systems (like regulated rivers) are disturbed, they lack flexibility to respond adaptively and can easily move across a tipping point to a new regime where desired conditions may be harder to achieve and the ability to provide ecosystem services is reduced (Poff et al., 2007; Parsons et al., 2016). River resilience comes from the ability of a system to evolve, dynamically adapt over time and maintain ecosystem services (Parsons and Thoms, 2018; Fuller et al., 2019). Water management in regulated rivers can enhance river resilience by maximising aquatic ecosystem functionality thereby supporting the ability for the river to adaptively respond to changing conditions.

One avenue for improving the ecosystem functionality of regulated rivers is to take a functional flows approach to river management (Yarnell et al., 2015; Stein et al., 2021; Yarnell and Thoms, 2022). The approach focuses on identifying functional flow components, which are discrete aspects of the flow regime that have documented relationships with ecological, geomorphic or biogeochemical processes in riverine systems (Yarnell et al., 2015). Flow management in regulated rivers to retain these key flow components, such as flooding overbank flows and spawning migration pulse flows, supports the biophysical processes needed to maintain a river's ecological structure and function upon which native biological communities depend (Bestgen et al., 2020; Yarnell et al., 2020). The approach does not require the high density of data needed to develop flow—ecology relationships as in other methods (e.g., Poff et al., 2010) but rather considers how the natural flow regime interacts with physical channel conditions, floodplains, sediment regimes, thermal regimes and biologic and biogeochemical processes to support critical ecosystem functions (Yarnell et al., 2022; Yarnell and Thoms, 2022). As such, the implementation of a functional flows approach supports and enhances river resilience, where resilience is defined both as a *property* of the system — the capacity of an ecosystem to continuously self-organise and adapt so as to withstand a regime shift, and as *approach* — an overarching way of thinking about sustainability and stewardship in a world characterised by change, uncertainty and complexity (Chapter 1).

In practice, a functional flows approach can be adaptively implemented with an environmental water budget that allocates water in time and space to support river processes and functions (Grantham et al., 2020; Null et al., 2022). Here, we demonstrate how to implement a functional flows approach in a heavily regulated river with a water budget operations model that allocates environmental water in real-time based on changing monthly flow forecasts.

Case study — Allocating an environmental water budget in a Mediterranean-montane watershed using the Functional Flows Adaptive Implementation Model

A functional flows approach provides an effective method to apportion limited water budgets to support ecosystem processes. This chapter presents an example from a hypothetical Mediterranean-montane watershed (catchment) in California, USA, of how an environmental water budget, established as a percentage of annual flow volume, can be allocated as a functional flow regime throughout the year, while adaptively managing for uncertainty as the expected water budget changes over the year. The water budget concept evaluated in this hypothetical watershed is loosely based on and adapted from the Lower San Joaquin River seasonal flow objective that was adopted in 2018 (California State Water Resources Control Board, 2018). At the start of the year, the total available flow volume for the budget is unknown, yet information on runoff to date as well as probabilistic forecasts of future runoff is available to inform flow release decisions. The Functional Flows Adaptive Implementation Model (FFAIM) is a seasonal operations model that recommends environmental flows as runoff conditions evolve. It assesses risk related to various functional flow regimes associated with the forecast runoff volumes and optimises the outcome to provide a recommended flow schedule for the river. As additional runoff information becomes available and annual flow volume becomes more certain, FFAIM incorporates the new information and updates flow recommendations. Although flow magnitudes may change as runoff conditions increase or decrease with climate over time, the ability to translate runoff to a functional flow regime ensures that foundational ecosystem functions are maintained even as conditions shift within a season.

Context

Our hypothetical watershed is a mixed rain-snowmelt driven system typical of many Mediterranean-montane rivers in California. The wet season begins in autumn (October-early December) and typically extends through winter and spring to early June, followed by an extended dry season with little to no precipitation from June to September. Large winter precipitation events (typically December to March) fall as snow at higher elevations and rain at lower elevations, which creates flashy high magnitude winter flow pulses at lower elevations. Snow from the higher elevations melts in spring as air temperatures increase, creating a distinctive and predictable snowmelt pulse and recession that can last into July. Flows continue to decline into the warm, dry summer months such that flow magnitudes in September are several orders of magnitude less than higher flows in the winter wet season.

Like most watersheds in California, our hypothetical watershed includes a large lower elevation reservoir that captures both winter runoff and spring snowmelt for later release during the dry season to lowland areas. The lowlands are largely agricultural with several urban areas that depend on reservoir releases for their water supply. The river through the lowlands also supports a diverse native aquatic community adapted to the strongly seasonal climate and streamflow conditions but is highly impacted by anthropogenic development that alters both the natural seasonal flow regime and downstream channel-floodplain habitat. Like many arid and semi-arid regions where population and water demands are increasing, competition for limited surface water runoff is growing, particularly with warmer and drier climate conditions (Grantham et al., 2013).

Flow management of many large Californian reservoirs and lowland river reaches typically focusses on water storage and delivery of water for agricultural and municipal water users during the dry season and flood protection during the wet season. Minimum environmental flow releases to maintain perennial streamflow for downstream aquatic communities do occur and are sometimes supplemented with modest brief seasonal flow pulses that vary by water year type (wet, moderate or dry) to support anadromous fish migration. This type of baseflow and species-specific focussed environmental flow prescription is common throughout California but has provided limited success in supporting the diversity of native aquatic species, including the threatened and endangered species it was designed to sustain (Williams et al., 2019; Leidy and Moyle, 2021). A functional flows approach to environmental flow management offers an enhanced holistic strategy that incorporates natural flow variability within and across years similar to that in which native species evolved, supports foundational riverine ecosystem functions and processes and provides ecological resiliency to disturbances (Yarnell et al., 2015; Yarnell and Thoms, 2022). Our environmental flow strategy thus centres on using a functional flows approach implemented with an environmental water budget established as a fixed percentage of unimpaired – natural without regulation or diversion – runoff, expressed here as an annual unimpaired flow volume.

Development of FFAIM

The process and general steps for how we developed FFAIM for our hypothetical river are summarised in Fig. 23.1 and described in more detail in the sub-sections below. In brief, step 1 includes computing functional flow metrics (FFMs) that quantify the variability of flow characteristics of each functional flow component. Step 2 includes determining which FFMs correlate to the annual flow volume and thus are well-suited to be represented by an index — termed a Functional Flow Regime Index (FFRI) — that can be used to scale the annual flow volume to the value of the metric within the optimisation model. Any alterations to the FFMs to account for factors that may limit the effectiveness of the natural range of FFMs to support ecosystem functions, such as physical habitat alterations, biologic interactions from non-native species, or water quality impairments, are accounted for in step 3. Step 4 includes development of FFRIs where suitable (step 4a) and development of alternative rulesets to relate FFMs to annual flow volume for those FFMs that were poorly correlated with annual flow volume (step 4b). The resulting relationships between FFMs and annual flow volume, expressed as FFRIs or rulesets from steps 4a and 4b, respectively, are then input to FFAIM (step 5), along with probabilistic forecasts of the total annual flow volume, to recommend a daily flow schedule for the current modelled time period and the range of possible flow schedules for the remainder of the year. As updated forecasts become available, FFAIM can be re-run, allowing for updated recommended daily flows and reservoir outflow decisions as the annual water budget develops over time.

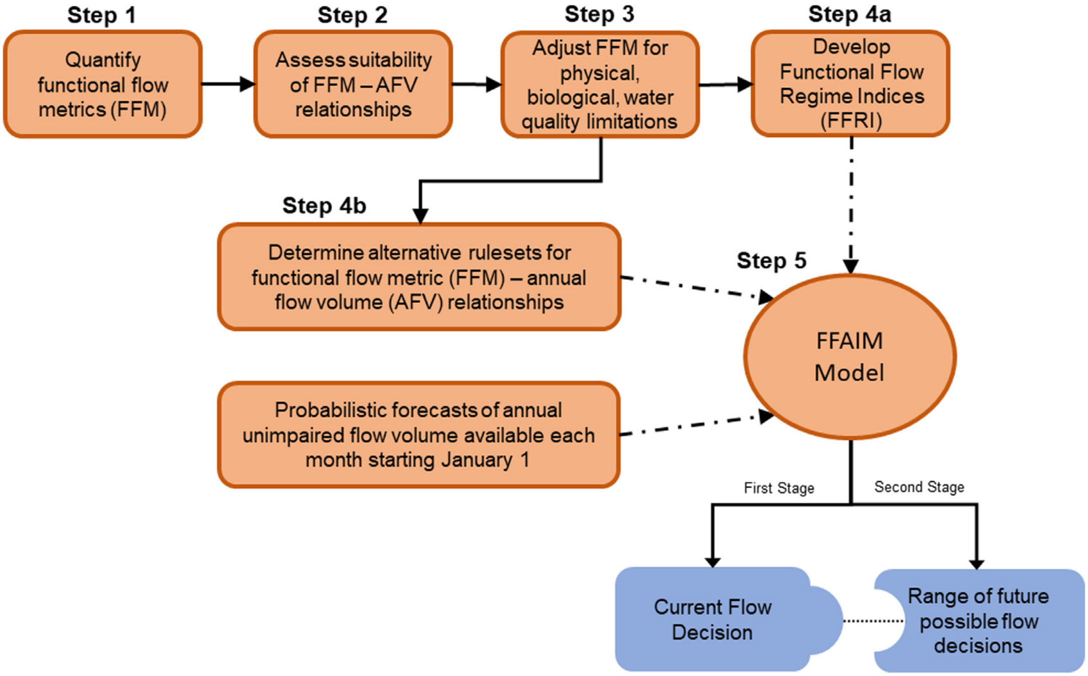
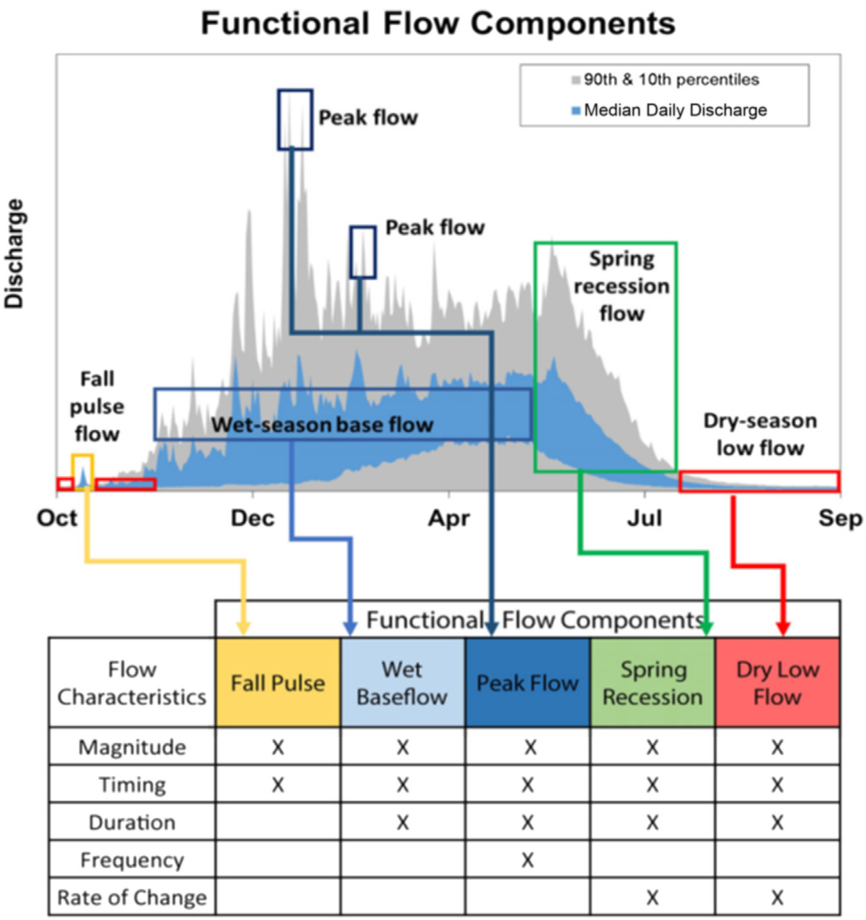


FIGURE 23.1 Process diagram for developing the Functional Flows Adaptive Implementation Model (FFAIM) for a stream location. See text for further details on each numbered step.

Step 1. Quantification of functional flow metrics

Five key functional flow components that support natural ecosystem processes have been identified for California's rivers and streams (Yarnell et al., 2020) (Fig. 23.2).

- **Fall pulse flow**, or the first major storm event following the dry season. These flows represent the transition from dry to wet season and serve important functions, such as moving nutrients downstream, improving stream flow water quality and signalling species to migrate or spawn.
- **Wet-season base flows**, which support native species that migrate through and overwinter in streams.



	Functional Flow Components				
Flow Characteristics	Fall Pulse	Wet Baseflow	Peak Flow	Spring Recession	Dry Low Flow
Magnitude	X	X	X	X	X
Timing	X	X	X	X	X
Duration		X	X	X	X
Frequency			X		
Rate of Change				X	X

FIGURE 23.2 Functional flow components for California depicted on a representative hydrograph, described by a suite of functional flow metrics highlighted in the table. Blue line represents median (50th percentile) daily discharge. Grey shading represents 90th to 10th percentiles of daily discharge over the period of record. *Reproduced from Yarnell et al. (2020).*

- **Peak magnitude flows**, which transport a significant portion of sediment load, inundate floodplains and maintain and restructure river corridors.
- **Spring recession flows**, which represent the transition from high to low flows, provide reproductive and migratory cues and redistribute sediment.
- **Dry-season base flows**, which support native species during the dry-season period when water quality and quantity limit habitat suitability.

These flow components are quantified by a suite of functional flow metrics that can be computed using signal processing algorithms to identify the *timing* of component transitions and the characteristics of each flow component (i.e., *magnitude, duration, frequency* and *rate of change*) (Patterson et al., 2020).

A 30-year historical time series of daily unimpaired flow estimates from the California Department of Water Resources (https://cdec.water.ca.gov/reportapp/javareports?name=FNF) was used to calculate the suite of functional flow metrics for each water year (October 1 – September 30) and the distribution of metrics across the period of record expressed as percentiles for our hypothetical river. These data became the basis for developing the functional flow regimes and inputs to FFAIM.

Step 2. Assessing suitability of functional flow metric-annual flow volume relationships

In most Californian streams, the range of functional flow metrics varies across water year types (Grantham et al., 2022). Wetter years typically have larger flows and longer durations of wet season and spring flows, while drier years have lower magnitude flows and longer dry season durations. Given the strong seasonality to the annual flow regime, the total annual unimpaired flow volume is strongly correlated with the flow volume of the baseflow and spring recession flow components and by extension their magnitude and duration metrics. When a predictable relationship exists between a functional flow metric and the annual flow volume, an index of this relationship, which we have termed a Functional Flow Regime Index (FFRI), can be used to scale the annual flow volume to the value of the metric. The FFRIs provide a means to translate a forecasted annual unimpaired flow volume to an indexed value of a functional flow metric, which is then used with other functional flow metrics to construct an annual functional flow regime. FFAIM constructs a range of functional flow regimes from the probabilistic forecasts of annual flow volumes and optimises for the most suitable flow release schedule.

We compared the range of each functional flow metric across the historical 30-year flow record with the total annual flow volume using general additive models (GAMs) to determine whether predictable relationships occurred. We found that the wet season baseflow magnitude, dry season baseflow magnitude and spring recession start magnitude correlated well (low standard error and higher R-square values) with total annual flow (see Fig. 23.3 for wet season baseflow magnitude relationship). The magnitudes of shorter event pulse flows, such as the wet season peak and fall pulse flows, and the timing to the start of the wet season were less correlated with total annual flow volume. We thus chose to develop FFRIs for the baseflow and spring recession magnitude metrics (see step 4a) and to develop rulesets for relating the remaining functional flow metrics to annual flow volumes (see step 4b).

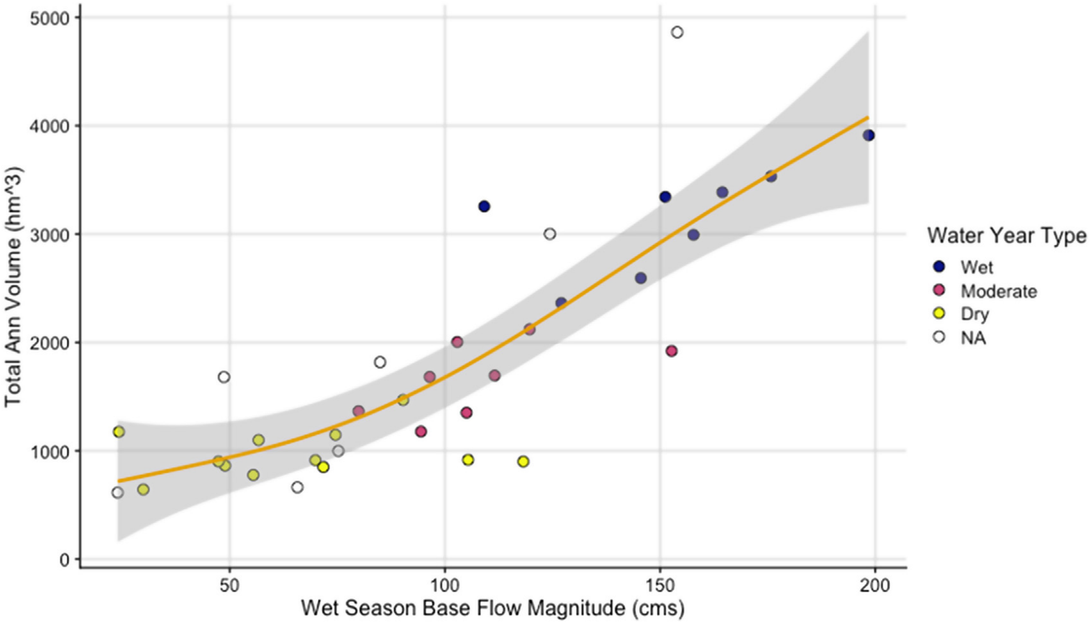


FIGURE 23.3 Relationship of wet season baseflow magnitude with annual flow volume for each year in the simulated historical period of record. Points are colour-coded by water year type: Wet (W), moderate (M), dry (D) and unknown (NA).

Step 3. Adjusting functional flow metrics for physical, biological or water quality limitations

Anthropocene rivers are heavily modified by extensive human activities and are unlikely to be restored to their historical or pre-human disturbance condition. However, in these novel ecosystems, there remains the opportunity to sustain aquatic communities, build resilience and provide the ecosystem services upon which societies rely by preserving and restoring stream ecosystem functionality (Thoms et al., 2020). Within a functional flows approach, anthropogenic impacts that may limit the effectiveness of the natural range of functional flow metrics to support ecosystem functions can be accounted for by adjusting the metrics to compensate for these limitations (Stein et al., 2021). For example, extensive channel incision limits the ability for the natural range of wet season peak flows to inundate the floodplain and provide functions such as riparian succession or geomorphic adjustment. Greater wet season peak flow may be needed to inundate the floodplain under such incised conditions.

To illustrate how these realistic limitations can be addressed within the development and use of FFAIM, we imposed channel constraints on our hypothetical river common to many developed rivers in California's lowlands. We adjusted the channel dimensions to be more channelised with limited overbank and floodplain connectivity. Floodplain connectivity was defined as beginning at 100 m^3s^{-1} (cubic metres per second) and reaching a maximum at 900 m^3s^{-1}, beyond which flows would begin to inundate adjacent cities and communities established in the historical floodplain. In the historical unimpaired 30-year flow time series, the 2-year and 5-year flood recurrence flows were 1425 m^3s^{-1} and 2250 m^3s^{-1}, respectively, and the spring recession start magnitudes ranged from 375 m^3s^{-1} to 2070 m^3s^{-1}. These natural flood flow magnitudes and higher spring recession flows would be too high to provide the desired functions based on limitations of our modified river channel. We therefore adjusted the desired range of wet season peak flow magnitude and spring recession start magnitude to remain between 500 and 850 m^3s^{-1} and 125—850 m^3s^{-1}, respectively, and to vary between these bounds in a similar fashion as the natural range (approximately linearly).

We also adjusted the wet season baseflow as the modified incised channel conditions have reduced channel complexity such that the upper end of the natural range of baseflows (24 m^3s^{-1}—200 m^3s^{-1}) within the simplified channel would provide velocities too high to support anadromous fish spawning or backwater slow areas for resting and rearing. Thus the range of wet season baseflow was modified to be 25 m^3s^{-1}—75 m^3s^{-1}. The resulting suite of FFMs, including both the adjusted wet season and spring recession magnitude ranges and the natural ranges of the remaining metrics, were then evaluated in step 4.

Step 4a. Developing functional flow regime indices

The strong relationship between the annual unimpaired flow volume and the baseflow and spring recession magnitude metrics (both natural and adjusted ranges) supports an index (FFRI) that translates a forecasted annual flow volume to a value for each functional flow metric. We defined the FFRI as a linear relationship between the functional flow metrics and the annual flow volume expressed as a percentile over the period of record (Fig. 23.4).

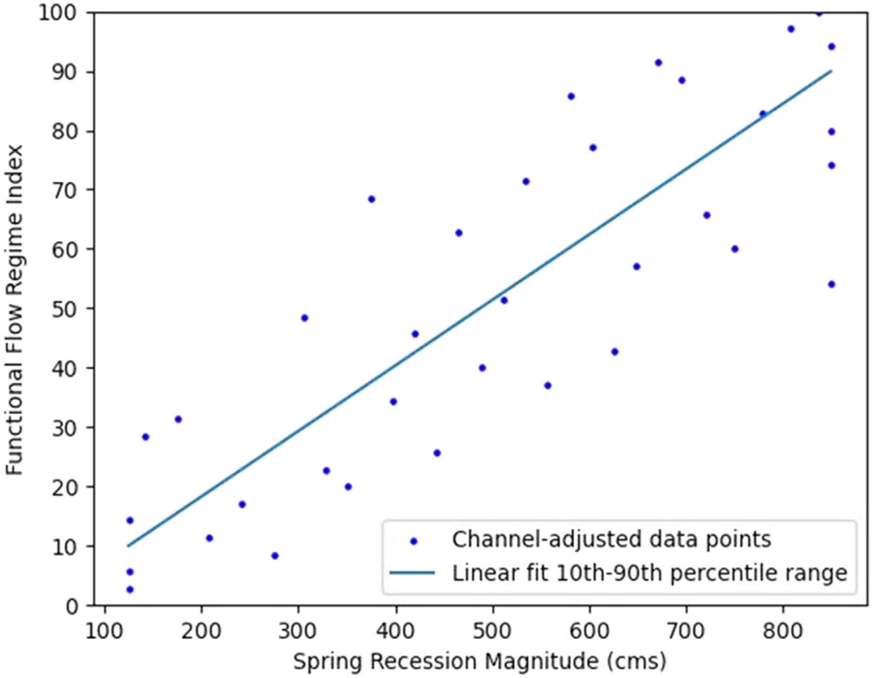


FIGURE 23.4 FFRI, expressed as a percentile of annual flow volume over the period of record and limited to the 10th-90th percentiles, for the spring recession start magnitude in cubic metres per second (m^3s^{-1}).

The use of a percentile of annual flow allows for a continuous scaled linear relationship between an FFM and the annual flow volume conducive to the optimisation method in FFAIM. This linear relationship also provides the full interannual variability of flows over time versus the limited number of flow regimes resulting from discrete categorisation of flows into only a few climate types, such as wet, moderate or dry. For example, drier years will range from FFRIs of 10 to approximately 40 (10th to 40th percentiles of all flow volumes), while wetter years will range from FFRIs of approximately 60–90. We limit FFRIs to the 10th to 90th percentile range to avoid extreme climate conditions, such as critically dry drought or extreme flood years, that would be difficult for the optimisation model to run and would likely need to be managed individually. Finally, the FFRIs provide a means for interpreting variable climate conditions and associated flow volumes in a manner that is transferable and adaptable across watersheds as needed.

Step 4b. Determining alternative rulesets for relating functional flow metrics to annual flow volume

For metrics poorly correlated with total annual flow volume, such as the magnitudes of shorter event peak or fall pulse flows and the timing of the start of the wet season, we developed alternative rulesets for relating metric values to the annual flow volume. The peak flow magnitude, timing, duration and frequency were determined similarly to rules provided by Willis et al. (2022) (Table 23.1). The frequency of peak flows was based on the annual flow volume, such that peak flows did not occur in drier years (annual flow volumes less than the 50th percentile) but did occur in wetter years (greater than the 50th percentile). While in many rivers, the frequency of a 2-year or 5-year flood event within a year also varies such that multiple peak flows tend to occur in wetter years, we chose to release one peak flow of varying duration (3–10 days) in wetter years for simplicity. Similarly, we manually input the timing of the peak flow release as February 1, which is when the first flow recommendation was made; however, in practice, the timing of peak flows could be hydrologically driven and coordinated with naturally occurring high flow events (see Willis et al., 2022). For example, operators could choose to let the first peak flow event of the season pass through the reservoir unimpeded provided dam release valve configurations were suitable. Due to

TABLE 23.1 Custom ruleset for defining hydrologic characteristics of wet season peak flow release recommendations based on annual flow volume percentile range.

Annual flow volume percentile range	Magnitude (m^3s^{-1})	Timing	Total duration (days)	Frequency (number of events)
10–49	N/A	N/A	0	0
50–66	Same as spring recession	Feb 1	3	1
67–74	Same as spring recession	Feb 1	5	1
75–90	Same as spring recession	Feb 1	10	1

imposed channel limitations as discussed above in step 3, the magnitude of the peak flow equalled the magnitude of the spring recession in wetter years, varying with annual flow volume from 500 m^3s^{-1}–850 m^3s^{-1}.

The remainder of the functional flow metrics was determined either manually or calculated from the other metric values as appropriate. For illustrative purposes, the timing of the start of the wet season baseflow was set to February 1, when the first flow release decision was made, and the timing of the spring recession start magnitude was set to May 3, when greater certainty of available snowmelt and runoff created a notable increase in forecast certainty. As with the peak flow releases, the timing of the spring recession flow could in practice be hydrologically driven, such that it varied with spring climate conditions (e.g., based on natural reservoir inflows) providing more natural interannual flow variability than shown in this case study. The timing and duration of the fall pulse was manually input as October 15 and 2 days, respectively, and the magnitude of the fall pulse was manually input as a linearly increasing relationship with the annual flow volume, ranging from 2.6 m^3s^{-1}–20 m^3s^{-1}. The duration of the baseflows was not explicitly input to the model but was resultant from the timing of the flow components, and for the spring recession, the duration resulted from the combined effect of the start timing, magnitude and rates of change. For example, in wetter years, the spring recession duration was inherently longer as a result of higher magnitudes, and subsequently, the dry season baseflow duration was shorter.

Step 5. Compilation of inputs to FFAIM

Together, the results from steps 4a and 4b provide the inputs needed for FFAIM to define a series of potential functional flow regimes from which to choose. Table 23.2 summarises the various functional flow metrics and rules used to establish metric values under differing climate conditions. Fig. 23.5 shows the range of functional flow regimes described by the metrics and rules for this case study, encompassing the range of FFRIs from 10 to 90. In this case study, all functional flow components are prioritised or weighted equally in all years. A functional flow regime with an FFRI of 90 represents the magnitude and timing of flows expected to support ecosystem functionality given the available water budget in very wet years, while a functional flow regime with an FFRI of 10 represents the flows expected to maximise ecosystem functionality given a reduced water budget in very dry years. While these rules provided a simple decision set to defining functional flow regimes, the ability to modify any of the rules with more or less specificity highlights the flexibility of the approach.

FFAIM also requires input of probabilistic forecasts of water availability to define potential annual flow volumes for the water budget. Here, we used forecasts of the total annual unimpaired flow volume provided as distinct exceedance probabilities updated monthly (Table 23.3). Our environmental water budget for a functional flow regime was 40% of total annual unimpaired flow. The water budget concept evaluated in this hypothetical watershed is loosely based on and adapted from the Lower San Joaquin River flow objective that applies from February through June and requires 40% of unimpaired flow as a 7-day running average or as a total 5-month volume of water (budget) released on an approved schedule (California State Water Resources Control Board, 2018). Beginning January 1, an updated forecast was available each month as the flow volume the prior month became known. Over time, the environmental flow budget becomes more certain, narrowing

TABLE 23.2 Summary of rules used in FFAIM to determine functional flow regimes.

Flow component	Metric	Rule-type (FFRI, ruleset, manual input)	Description
Wet season baseflow	Magnitude	FFRI	Varies with annual flow volume; m^3s^{-1}
	Timing	Manual input	Start of 1st decision period
	Duration	Calculated	Until start of spring recession
Peak flow	Magnitude	Ruleset	Magnitude of spring recession in 1st decision period
	Timing	Manual input	February 1 (for illustrative purposes, but can be moved to coincide with actual hydrology)
	Duration	Ruleset	0, 3, 5, or 10 days
	Frequency	Ruleset	0 or 1 event
Spring recession flow	Magnitude	FFRI	Varies with annual flow volume; m^3s^{-1}
	Timing	Manual input	May 3 (for illustrative purposes, but can be moved to coincide with actual hydrology)
	Duration	Calculated	Until start of dry season
	Rate of change	Manual input	13% per day upramp 7% per day downramp
Dry season baseflow	Magnitude	FFRI	Varies with annual flow volume; m^3s^{-1}
	Timing	Calculated	When spring recession equals baseflow magnitude
	Duration	Calculated	Until start of wet season baseflow
	Rate of change	Manual input	Held constant
Fall pulse flow	Magnitude	Ruleset	Varies with annual flow volume; m^3s^{-1}
	Timing	Manual input	October 15 (for illustrative purposes, but can be moved to coincide with actual hydrology)
	Duration	Manual input	2 days

towards the finalised water budget on June 30 when subsequent summer precipitation is rare, and thus, the total annual runoff is typically known (Fig. 23.6). Together, the forecasts of total annual unimpaired flow volume and the data to calculate potential functional flow regimes (from steps one to four above) are the key inputs required by FFAIM to suggest an optimal river flow for the current month and a range of potential flow regimes for upcoming months.

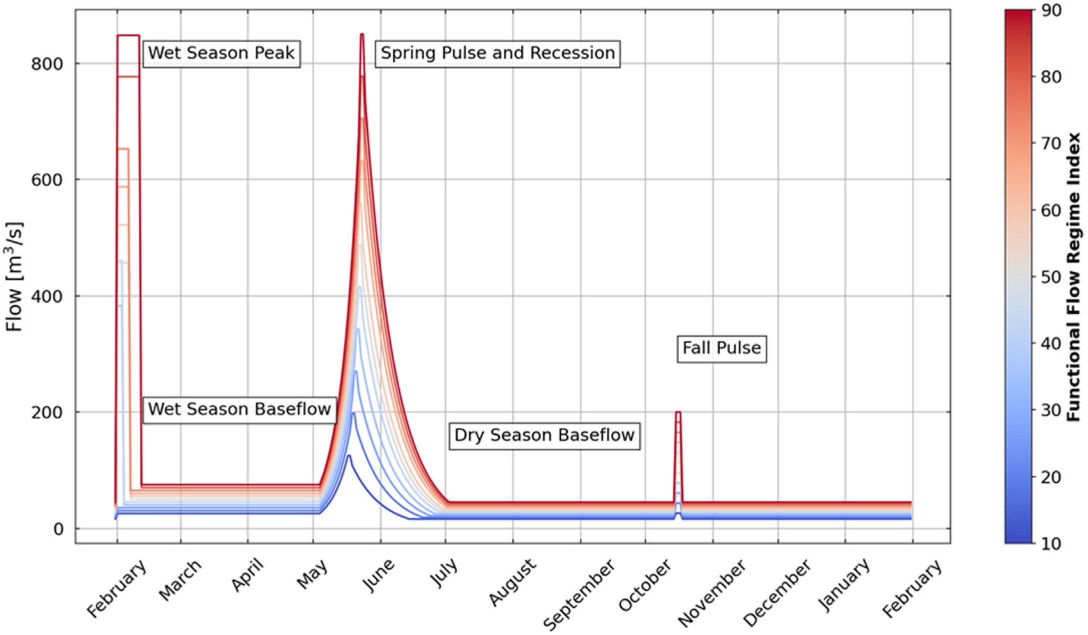


FIGURE 23.5 Full range of functional flow regimes considered by the model for this case study. Lines show 11 functional flow regimes evenly distributed across FFRIs ranging from the 10th to 90th percentile, out of 80 possible FFRIs.

TABLE 23.3 Example probabilistic annual unimpaired flow volume forecasts available each month starting January 1.

Exceedance probability	**Forecast annual unimpaired flow volumes (hm^3)**					**Known annual unimpaired flow volume (hm^3)**
	Jan	Feb	Mar	Apr	May	June
0.99	10.7	24.0	17.2	18.8	19.4	21.8
0.90	18.6	33.4	23.7	22.6	20.9	21.8
0.75	26.9	39.4	29.0	26.1	22.4	21.8
0.50	37.5	45.5	33.9	29.5	24.3	21.8
0.25	53.5	55.2	41.6	34.7	27.0	21.8
0.10	68.0	65.4	49.0	39.5	29.4	21.8

The total annual unimpaired flow volume available was finalised by June 30.

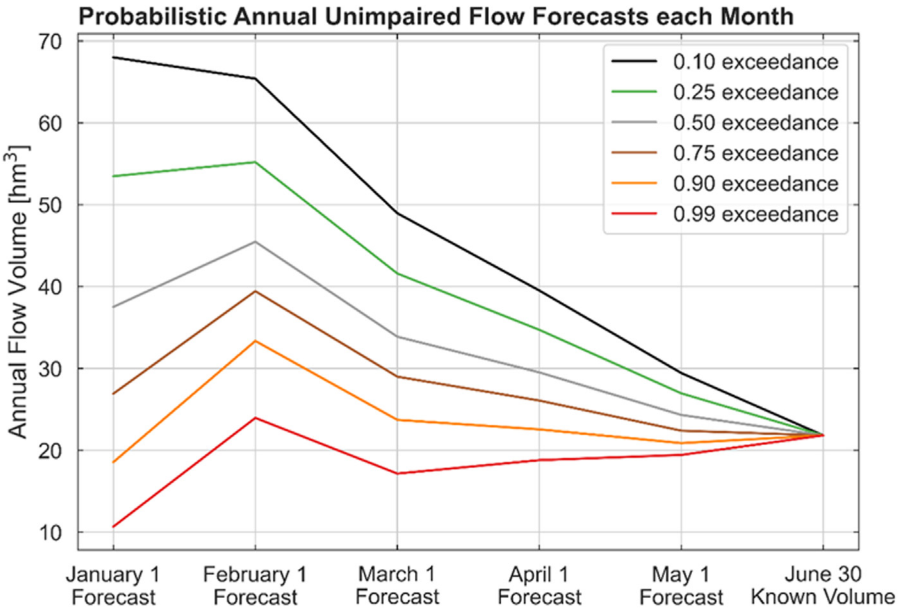


FIGURE 23.6 Example of evolution of monthly forecasts as they converge towards the known environmental flow budget by June 30.

Adaptive implementation of FFAIM

The Functional Flow Adaptive Implementation Model balances benefits of decisions needed today against the risk of not having enough water for the future by using a stochastic two-stage optimisation approach implemented in python (*pyomo* package). The primary model objective is to balance the achievable functional flow regime in the current decision period (first stage) with the potential functional flow regimes in the remaining time periods (second stage), so that flow commitments made early in the season do not excessively restrict ability to provide flow functionality later in the year. Specifically, the optimisation balances the highest achievable FFRI in the first stage with the potential FFRIs with flow forecasts for later periods such that the highest possible FFRI is achieved across the entire year given the available water budget. As the season progresses and flow decisions are made with each updated forecast, the model accounts for the water budget already allocated as it optimises for possible future flow regimes in remaining time periods. If at any point the model finds an FFRI below 10 is needed for the remaining time periods due to unexpectedly dry conditions, the model suggests a river flow associated with the 10th percentile to avoid adverse ecological impacts with the hope that future forecasts will have sufficient water to meet this requirement. Similarly, if more water is available than would be required for the 90th percentile flow volume, then the model allocates the additional flow to the future as 'carryover storage'. Although simplistically applied in this case study, rules for carryover storage could be adjusted in practice to allow for small carryover volumes in wetter years (e.g., 60th to 90th percentile years) that would help to hedge against dry early season conditions in subsequent years.

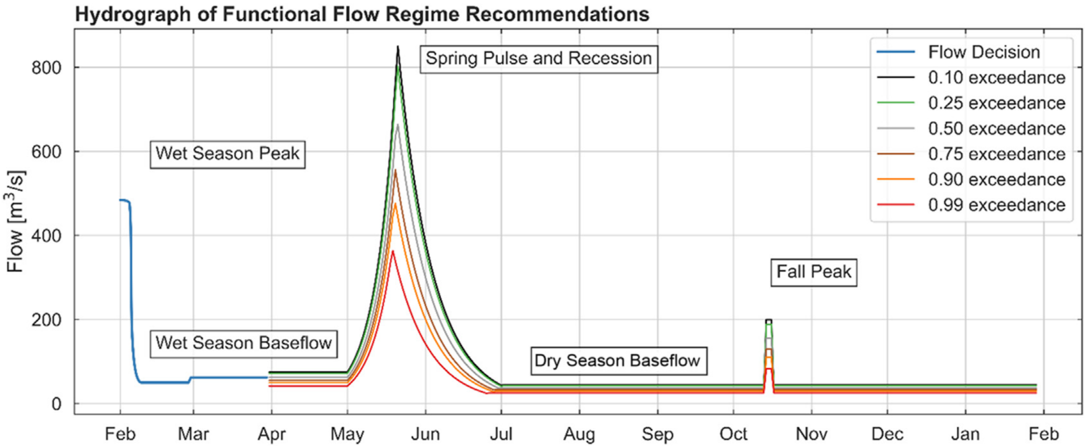


FIGURE 23.7 Output from FFAIM for an April annual flow volume forecast showing possible future flow regimes accounting for flow release decisions made in February and March.

In this example, the model was run each month with an updated annual flow volume forecast and known past monthly river flow decisions. Fig. 23.7 shows an example of FFAIM output for the month of March, where the February flow recommendation was already made, March flows were allocated (first-stage) and a range of potential future flow regimes were determined based on the forecasted annual flow volumes (second-stage). Once the final environmental flow budget was known on June 30, the model was run a final time to optimise a functional flow regime for the remainder of the year. Additionally, using the final environmental flow budget as a known volume, the model was re-run over the entire year (starting January 1) to identify the functional flow regime that could have been provided with perfect hydrologic foresight. Comparing the perfect foresight model outputs with the adaptive model outputs highlighted the impact of imperfect forecasting on model results.

FFAIM results for example years

The model was run for 3 years that represented dry, moderate and wet conditions to highlight the use of FFAIM. In each case, FFAIM provided a flow schedule that preserved essential functional flow components scaled to the available environmental water budget (Fig. 23.8). The probabilistic hydrologic forecasts changed through each year as highlighted by the difference between the adaptive flow release and the perfect foresight flow release schedules. We also show the daily 40% of unimpaired flows to compare model results with the daily unimpaired flow pattern.

In the dry year, despite very low streamflow, FFAIM was able to adaptively balance river flows so the final recommended flow regime provided acceptable functionality for every flow component (Fig. 23.8A). The annual flow volume forecast on February 1 projected that the unimpaired flow volume, and its 40% environmental flow budget would be less that what is required to meet the minimum functional flow regime for the year (i.e., FFRI <10). As a result, FFAIM recommended the minimum acceptable flow release associated with an FFRI

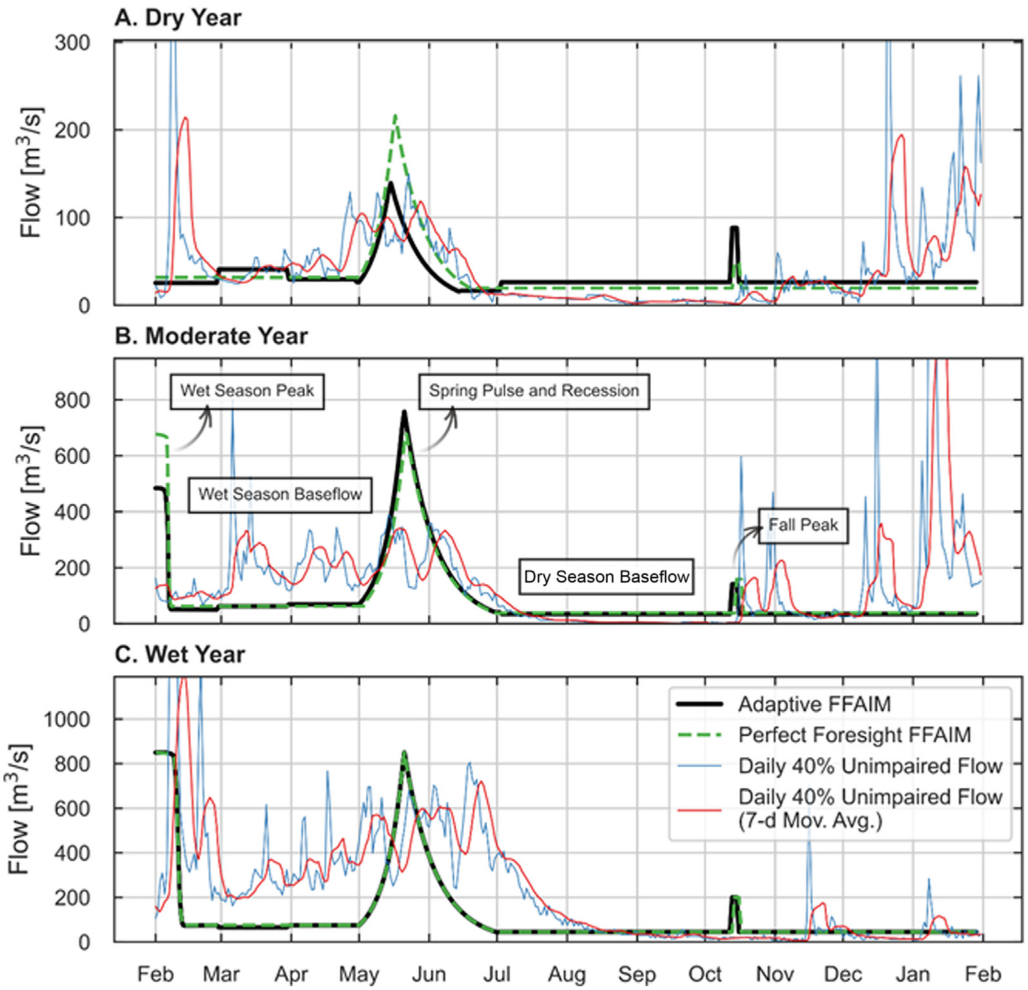


FIGURE 23.8 Flow release schedules recommended from FFAIM for three different years illustrating model outputs under adaptive implementation and perfect foresight. The daily 40% of unimpaired flow is shown for comparison. Y-axis scales differ for each water year. The dry year (A) has an FFRI of 20 with no wet season peak flow release; the moderate year (B) has an FFRI of 71 with a 3-day wet season peak flow release; the wet year (C) has an FFRI of 90 with a 10-day wet season peak flow release and carryover storage.

of 10 for February. The increased unimpaired runoff observed in February (shown in the 40% unimpaired flow hydrograph) resulted in higher forecasted annual flow volumes on March 1, and FFAIM adjusted accordingly recommending a higher flow release for March (FFRI = 35). However, continued dry conditions in March lowered the April 1 forecast of annual flow volume. Accounting for the already released flows in February and March, FFAIM balanced the volume of these previous releases with probabilities of future available water in the budget and recommended a lower flow release for April (FFRI = 17). As climate conditions remained dry through April and runoff remained low, FFAIM recommended lower flow releases during the spring recession in May and early June (FFRI = 12). However, by June 30 when the total environmental flow budget was known and additional runoff in late May and early June occurred, FFAIM recommended a dry season baseflow associated with an FFRI of 39.

A comparison of the adaptive functional flow regime with the perfect foresight functional flow regime highlights how FFAIM responded to changing seasonal flow forecasts over time. For the known environmental water budget (perfect foresight), FFAIM recommended a functional flow regime associated with an FFRI of 20; however, with adaptive implementation where flow releases were adjusted with each updated monthly forecast of annual flow volumes, FFAIM recommended flow regimes that ranged between FFRIs of 10−39. When forecasts predicted lower annual flow volumes early in the year, the model hedged against potentially dry conditions in the future and recommended lower river flows. As forecasts varied between March and April, model recommendations varied similarly. As flow conditions improved in late May and June after the spring recession flow had been released, FFAIM recommended higher dry season flow releases to use the remaining environmental water budget.

In the moderate year, forecasts of annual unimpaired flow in February were sufficient to warrant release of a wet season peak flow of 3 days duration (Fig. 23.8B). The forecasts for March through May remained relatively consistent slightly increasing in flow volume over time as runoff conditions improved. As a result, the adaptive functional flow regime (FFRI ranged 50−81) was similar to the perfect foresight functional flow regime (FFRI of 71), with only slight differences in the magnitudes of the wet season peak and spring recession flows. Under adaptive implementation, FFAIM hedged against future drier conditions by recommending a slightly lower wet season peak flow magnitude than under perfect foresight and, subsequently, a slightly higher spring recession flow as climate conditions remained relatively consistent and water was available in the environmental flow budget.

In the wet year, the adaptive functional flow regime and perfect foresight functional flow regime were identical as the forecasted annual flow volumes and environmental water budget were large enough throughout the season to provide the maximum modelled flow regime associated with an FFRI of 90 (Fig. 23.8C). It also shows that in the wettest years, additional water beyond the modelled functional flow regimes was available within the environmental flow budget. FFAIM allocated the additional environmental water volume into a ‘carryover’ allocation that might augment flows in later years or support additional flow allocations in the current year, such as higher wet season baseflows in April, additional wet season peak flow events in March (provided they remain below the channel capacity limits) or extended spring recession flows into July as might occur with unimpaired flow conditions.

Adaptively managing functional flows

The results from this example show the establishment of environmental flows from an environmental water budget following a functional flows approach, including limitations from channel modifications, and demonstrate their adaptive management over the course of an operating season with real forecast uncertainties. FFAIM provided flow recommendations that maximised flow ecosystem functionality for varying monthly conditions across a variety of water year types from dry to wet. The results from the dry year highlighted the sensitivity of model outputs to forecast uncertainty, while the wet year results highlighted opportunities for supplemental flow allocations to further benefit the stream ecosystem. In all example years, the functional flow regimes show the advantage of shaping an annual water budget to increase ecosystem functionality, in this case by providing higher spring recession start magnitudes than the daily 40% of unimpaired flow regimes, thus potentially providing greater floodplain connectivity and extended duration of high flows during the ecologically important spring spawning and rearing period (Yarnell et al., 2010). Although there are trade-offs between setting flow decisions early in the season when forecast reliability is lower and setting flow decisions later when windows of opportunity for ecologically important higher flow releases may have passed, the flexibility to adjust the rulesets within FFAIM allows for monitoring and adaptive management via a collaborative process over time, which is critical to providing resiliency under changing climate conditions.

Functional flows and river resilience

Ecological resilience has traditionally been illustrated via a ball and cup diagram. In this diagram, movement of the ball within the cup represents the natural dynamics of an ecosystem responding to disturbance, and a disturbance large enough to move the ball past a 'tipping point' to another cup represents a threshold crossed, shifting the ecosystem to a new 'basin of attraction' or regime (Holling, 1978). Resilient systems are thus able to absorb disturbances, maintaining structure, function and feedbacks while remaining in the same regime (Biggs et al., 2015). The nature of the cup, or the 'stability domain', also influences the movement of the ball, with more 'ecologically resilient' systems depicted as wider cups conferring greater movement or dynamics (Gunderson, 2000, Chapter 1). 'Adaptive capacity' is the system's ability to remain in a single stability domain, even as the shape of the domain changes through time. In dynamic and complex riverine systems, temporal variability of flow is a key disturbance, represented as movement of the ball, while heterogeneity in geomorphic structure of the river landscape over different scales, represented as spatial diversity within the stability domain or cup, enhances adaptive capacity by providing varying and diverse responses to flow disturbance (Fig. 23.9). While thresholds exist within river systems and can act as tipping points between alternate stable regimes, river systems can have significant spatial and temporal variability at different scales within a stable regime (Van Looy et al., 2019). River resilience thus relates to the ability for river functions and forms to persist, transform and adapt in response to change, continuing to provide ecosystem services for societies (Parsons et al., 2016; Fuller et al., 2019).

A functional flows approach maintains not only the variability of flows (e.g., the predictable movement of the ball) but also the spatial heterogeneity of the landscape (e.g., the character of the cup) inherent to the dynamic nature of rivers (Chapters 1 and 10). When the natural functioning of rivers is maintained and supported, adaptative capacity is increased and the river system is less likely to cross a tipping point into a less stable or undesirable regime that no longer provides desired ecosystem services. Traditional environmental flow approaches may effectively 'move the ball around', but a functional flows approach highlights the diverse nature of the cup and the *interaction* of the ball moving around the cup over time, linking together the ball and cup in providing ecosystem responses. Similarly, landscape-centred approaches, such as increasing Room for the River (Warner and van

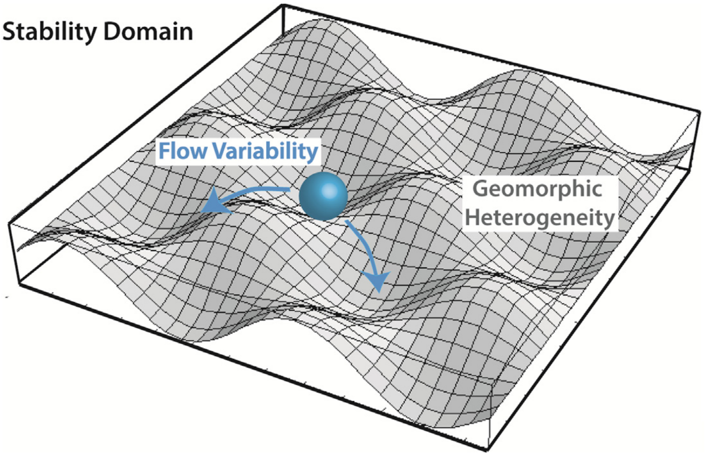


FIGURE 23.9 Conceptual representation of geomorphic heterogeneity as spatial diversity within a stability domain (or 'cup' in Holling's (1978) ecological resilience concept) and temporal variability of flow as movement of the 'ball'. Unlike previous representations of ecological resilience, valleys do not represent alternate basins of attraction, but rather complexity within a stable regime.

Buuren, 2011), may expand the diversity of the cup, but they often do not consider the response of flow (the ball) interacting with that landscape. A functional flows approach explicitly focuses on interactions between flow variability and landscape heterogeneity over time to promote ecological processes, ultimately supporting river resilience (Yarnell and Thoms, 2022).

The aim of functional flows is to promote dynamic riverine landscapes over space and time, to enhance high biodiversity and processes for self-rehabilitation. Resilience to future and current disturbances from climate change can only be achieved when rivers are dynamic, variable and have ability to naturally adjust. Maximising functionality in regulated rivers via varying functional flow regimes and habitat improvements enhances the adaptive capacity of riverine landscapes, thereby promoting resilience according to our understanding of river processes (Yarnell and Thoms, 2022). Dynamic interactions are linked across flow, sediment and biogeochemical regimes. If these linkages are supported and maintained, the river system can respond to changing conditions. Our current state of knowledge suggests this can be achieved by holistically looking at river processes and functions and working to restore the overall functionality of flows.

Changing climate conditions and extensive development have pushed many Anthropocene rivers past tipping points into alternate basins of attraction or regimes that no longer provide sustainable ecosystem services for communities (Reid et al., 2019; Thoms et al., 2020). Water managers and societies must adapt to improve riverine ecosystem functionality and build resilience to future uncertain disturbances if they are to safeguard or restore valuable ecosystem services. This example addressed how to support river resilience in regulated rivers with a functional flows approach using a dynamic operations model that allocates an environmental water budget in real time with uncertain flow forecasts. While the results demonstrated how to manage within-year water variability, this modelling approach could be expanded to explore longer-term environmental flow planning under projected changing climate conditions, such as multi-year droughts or extreme year-to-year climate variability. Similar flexible and adaptive approaches to water management are needed to promote river resilience, sustainability and stewardship in a complex and changing world.

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