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Considering scale within optimization procedures for water management decisions: Balancing environmental flows and human needs

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ABSTRACT

A key issue in optimization model development is the selection of spatial and temporal scale representing the system. This study proposes a framework for reasoning about scale in this context, drawing on a review of studies applying multi-objective optimization for water management involving environmental flows. We suggest that scale is determined by the management problem, constrained by data availability, computational, and model capabilities. There is therefore an inherent trade-off between problem perception and available modelling capability, which can either be resolved by obtaining data needed or tailoring analysis to the data available. In the interest of fostering transparency in this trade-off process, this paper outlines phases of model development, associated decisions, and available options, and scale implications of each decision. The problem perception phase collects system information about objectives, limiting conditions, and management options. The problem formulation phase collects and uses data, information, and methods about system structure and behaviour.

1. Introduction

Water management is challenged by socio-economic (e.g. rising demand, sectoral competition) and climate change pressures (e.g. droughts, extreme events) (EEA, 2017; Grizzetti et al., 2017; Tonkin et al., 2019) threatening water security (Kennen, Stein and Webb, 2018) and river biodiversity (Vörösmarty et al., 2010). Despite increasing awareness of river ecosystems' needs (Arthington et al., 2018), water allocation goals typically still aim "to provide water to people when and where they most need it and not when and where it would naturally be available" (Daniell and Barreteau, 2014). However, addressing the challenges of climate change and increasing demand will require a range of strategic actions, including those that directly protect and restore the environment (Pittock and Lankford, 2010; Thompson et al., 2014; Liu, Liu and Yang, 2016; Salik et al., 2016). Failing to adequately incorporate ecosystem values and underestimating the potential cross-scale impacts of water use and climate change on freshwater ecosystems (McCluney et al., 2014) fails to acknowledge the benefits that freshwater systems generate for the wider community (Richter, 2009).

The implementation of environmental flows is one action that is already applied (Mendoza and Martins, 2006; Le Quesne, Kendy and Weston, 2010; Poff et al., 2010; King et al., 2015; Horne, O'Donnell and Tharme, 2017) to better protect freshwater and related ecosystems from modifications caused by river regulation (e.g. dams, weirs, diversion channels) (Poff et al., 1997; Arthington, 2012) and high-intensity use (EEA, 2012). The approach to implementing environmental flows and the accompanying water management decisions varies according to governance level, spatial extent and temporal scale of the desired outcome: broad-scale long term environmental flows (e-flows) management typically employs a 'top-down' approach by imposing limits to additional hydrological alteration (e.g. caps on water abstraction, license conditions for water users, environmental water rights, see Horne et al., 2018), whereas a 'bottom-up' strategy (e.g. conditions on storage operators, environmental reserve established legally) that considers ecologically-relevant components of the flow regime and their ranges is implemented at finer scales and generally prioritizes short term effects (Pahl-Wostl et al., 2013; Gopal, 2016; Horne, Webb, et al., 2017). Current incorporation of e-flows within integrated water resource management (IWRM) expresses environmental water requirements as quantity, quality and timing of water flows, in the short term at point-scale to limit impact propagation towards broader spatial scales in the long term (Vörösmarty et al., 2013; Evers, 2016; Arthington et al., 2018). As a consequence, water governance seeks to implement enhanced management and infrastructure systems that can regulate

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river flow at multiple spatial and/or temporal levels (Daniell and Barreteau, 2014; Stewardson et al., 2017) in the light of changing consumptive water needs.

Scale-specific investigation tools are often used to inform successful river management (Volk et al., 2008). Case study-level applications show that some management problems envisage several objectives and hence multi-objective optimization can be used to address water management needs at different spatial scales, such as hydropower facility, reservoir, reach, sub-basin and basin and different temporal horizons (e.g. Shang, 2015; Yin et al., 2015; Fallah-Mehdipour, Bozorg-Haddad and Loáiciga, 2018). The optimization of a set of desired objectives related to water abstraction or release (e.g. species survival, hydropower production, domestic supply, irrigation) seeks to find optimal solutions. These solutions are searched across a range of criteria that allow the identification of trade-offs and synergies, and, as a result, the definition of compromises among conflicting goals (Horne et al., 2016; Cord et al., 2017; Gunantara, 2018). The opportunity to explore compromise solutions might better support decision-making processes than single-objective modelling, as it has been shown in other resource allocation problems (e.g. Lautenbach et al., 2013; Kaya et al., 2016; Kaim et al., 2018).

However, modelling these decisions in water management is made challenging by the fragmentation and hierarchy of hydrological scales (Moss and Newig, 2010). A key obstacle is related to the consideration of the different scale-specific hydrological and ecological characteristics and processes (Volk and Ewert, 2011; Davies et al., 2014; Thorp, 2014). Indeed, the effective representation of connections (e.g. ecological, hydrological and geomorphological) on each temporal and spatial scale of the river network remains a core challenge in e-flow assessments (Poff, Tharme and Arthington, 2017). Another problem is related to the reference hydrological scales used in the classification of river spatial extent. The spatial mismatch between physical and socio-political

Box 1

Definition of terms

Environmental flow	The quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being (Arthington et al., 2018; (Artinghton, 2018)).
Management objective	Specific statement about the intents of the water management approach (e.g. in relation to ecosystem services, processes and components) as a result of engagement between multiple stakeholders and managers. In the case flow management it relates to water allocation for environmental purposes. (adapted from Horne et al., 2017)
Optimization objective	Function to be either maximized or minimized, corresponding with ‘outcomes of interest’ of the optimization problem. Depending on the problem formulation, optimization problem constraints can substitute/complement objectives. (adapted from Maier et al., 2019)
Management decision	Mechanism through which a management objective is achieved (e.g. control of diversion and release, flow alteration reduction). High-level management decisions are tied to larger scales (e.g. provided through planning or regulatory instruments) while implementation decisions reflect management choices for periodic objectives at finer spatial and temporal scales. (adapted from Horne et al., 2018)
Optimization decision variable	Input parameter of the optimization problem that is measurable and controllable (e.g. reservoir water level, release timing, energy production), providing a quantitative representation of a management decision (adapted from Coello et al., 2007).
Problem perception phase	The stage consisting of the consideration and interpretation of all the factors and processes (i.e. spatial, temporal, environmental and operational) involved with the implementation of the considered management decision (adapted from Beven, 2012).
Problem formulation phase	Encompasses all the actions related to the translation and modelling of the perceived problem into functions (i.e. objectives and constraints). Involves also the consideration of data needs to appropriately represent the area of interest of the water management problem (adapted from Maier et al., 2014, 2019).
Optimization problem	Or optimization model is the formulation of the management problem within a simulation/modelling context. This is the mathematical formulation of the water management problem.
Optimization framework	Structured set of steps and considerations used for the formulation of an optimization problem. In this study it is applied in support of optimization problem definition for environmental water management, highlighting the role of each step in defining the resulting scale of the assessment.
Optimization scenario	Captures a degree of variability in the optimization problem to reproduce system behaviour under different possible circumstances (e.g. operational, climatic, and hydrological). The concept of an optimization scenario is intended to capture variations of the decision problem formulation, which can include alternative climate projections or decision variables, and their resulting outcomes.
Infrastructure operation	The time steps of the scheduling (frequency) of infrastructure operations’ set.
Planning horizon	The timeframe upon which management decisions are taken. From a water management perspective, it usually corresponds with one management cycle and is linked with the previous (management objectives) and the following (monitoring outcomes) management cycles (adapted from Horne et al., 2018). From an infrastructure management perspective, can also be associated with the frequency of updating an operational management plan.
Spatial scale	The spatial bounds of the events and processes considered in the optimization problem (in relation to a management problem) (adapted from Iwanaga et al., 2021). Common spatial scales used in water management related to hydrological units and flow altering structures (see Table 2 and Fig. 4).
Temporal scale	The temporal horizons of the events and processes of the considered optimization problem (in relation to a management problem) (adapted from Iwanaga et al., 2021). Levels of temporal scale (e.g. days, months, years) can relate to the temporal resolution of hydrological data (adapted from Daniell and Barreteau, 2014). In water management optimization it can also refer both to the infrastructure operation cycle time steps and the planning horizon time window.

boundaries poses a challenge for the definition and implementation of management objectives (Moss and Newig, 2010; Daniell and Barreteau, 2014; van den Belt and Blake, 2015; Opperman et al., 2018); Lastly, chosen e-flow parameters can be employed for studies at small scales and can show effects in the short term (e.g. population size), but can also be ecologically relevant for wider areas (e.g. basin-scale) and support processes that manifest at longer temporal scales (e.g. nutrient cycling) (Poff, Tharme and Arthington, 2017). This requires the consideration of a range of flow events (e.g. pulses, 30-day minimum flow) and diverse processes (e.g. water production, sediment delivery and vegetation dynamics, ecological stages, land cover influence) (Gurnell et al., 2016; Opperman et al., 2018).

In this study, we present a framework that describes the conceptual and operational steps of optimization model development to support e-flows and the related spatial and temporal scale considerations. The framework draws on a review of the state-of-art in this field of water research. Clarity about the role of scale improves our ability to model across scales and as a consequence, provide more reliable predictions of decision outcomes at the scales of interest.

The paper first introduces water management decisions and their translation into optimization models (see Box 1 for the definition of terms) and provides the outline of the proposed framework showing the stages of optimization problem development (i.e. problem perception phase and problem formulation phase) (Section 2). The framework, mapping the scale related decisions and options linked to each development phase, is further described with reference to results from the review of selected studies in Section 3. Section 4 discusses the need for clarity of problem definition, strategies to implement desired assessment scales, and explicit discussion of trade-offs in problem development. Lastly, in Section 5 we provide recommendations to foster transparency throughout the optimization problem development phases.

2. A framework for incorporating scale within optimization modelling to support e-flows water management decisions

An optimization approach offers the opportunity to explore compromise solutions to support decisions about scarce water resources (Horne et al., 2016). It can be used to support environmental water management decisions while meeting conflicting water use objectives (e.g. hydropower generation, domestic supply, industrial supply, irrigation water). Environmental water objectives drive management actions that can be implemented at broader (e.g. control of diversion) or finer target scales (e.g. need to control reservoir releases). The timeframe of implementation also varies based on the management decision.

Water resources management, and in particular e-flows, sit within an adaptive management framework that reflects these different temporal and spatial scales (Webb et al., 2017). The selection of objectives and high-level policy decisions are made at a longer time scale and often for larger catchments or whole basins (see Horne and Konrad, 2017). However, implementation decisions are made at a shorter time scale and often for a specific site or location. Optimization to support these decisions therefore also lends itself to be framed within an adaptive management framework, providing the structure and technical capacity to support trade-offs and decision making at different scales (Fig. 1). Each stage of the adaptive management cycle has its own technical challenges. Similarly, the translation of management decisions into an optimization procedure needs to consider a range of factors to ensure the context and system is realistically represented. Table 1 uses a number of examples to demonstrate the importance of the type of management approach being considered (the columns in Table 1) for informing the approach to optimization model development. For instance, the decision to set a cap on abstraction can be tied to optimization at basin scale considering an annual or seasonal time frame; the optimization of release timing (at seasonal, monthly or daily scale) in response to the need to meet downstream ecological needs/target ecological indicators will be preferred for management decisions at smaller spatial scales (e.g. reaches or sub-basins) to match species ecological response timeframes and local hydrological conditions; at sub-daily scale it could be applied to reduce hydropeaking impacts at target locations.

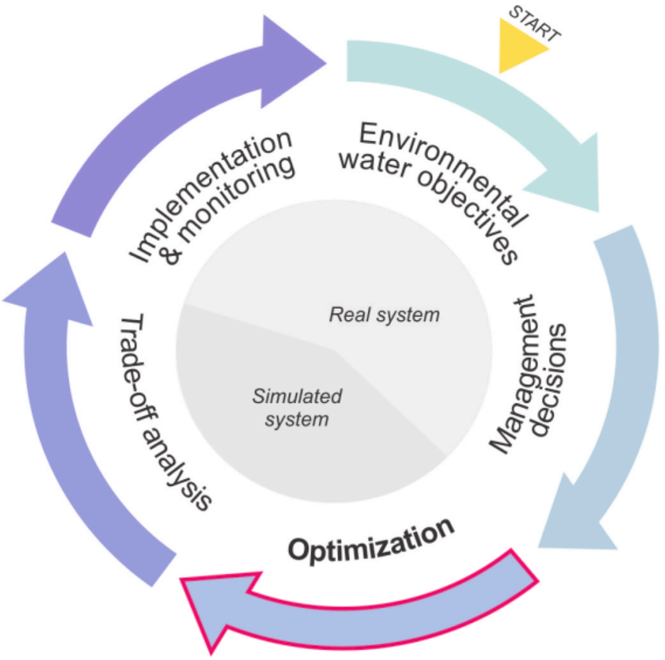

Fig. 1. Position of the optimization process within the adaptive water management framework (yellow triangle indicates the starting point for each management cycle).

The specific decision context dictates the target scales. However, translation of real-world management problems into a modelling framework presents some inherent challenges, either related to data availability, modelling or computational ability. The water management analyst dealing with optimization model development hence faces a range of trade-offs in model representation, in particular linked with choices of scale associated with the targeted problem and resulting modelled representation. Any optimization model development procedure to support e-flows decisions and water resource management will need to explicitly consider the implication and magnitude of these trade-offs for the spatial and temporal scales of the assessment, to foster transparency and understandability.

A general optimization process (showed in Fig. 2, left-hand side) first involves problem identification (or contextualization) and subsequently, requires input parameters definition and optimization environment creation (see Maier et al., 2014 for in-depth overview). As a first step, the system domain is defined by the water management problem and decisions which underpin the relevant objectives, constraints, and scenarios of the targeted spatial and temporal scales of assessment (Fig. 2, right-hand side). Once defined, the system characteristics, hydrological data, and other relevant information (e.g. ecological) are gathered to meet the requirements for representation at the targeted scales. Given that optimization assessments need to inform a decision making process (hence the output), the final scales of the assessment should appropriately match decision conditions and scales. Trade-offs in system representation arise when moving from problem perception phase to problem formulation phase as a consequence (see Section 2.2). Specifically, the trade-off can be resolved either by seeking additional information required to implement or by altering the problem perception to suit the information available. The precise process of achieving a trade-off is not well understood, and a variety of approaches and intermediate solutions may be possible (Fu, Guillaume and Jakeman, 2015). Fig. 2, together with Tables 3–7 in Section 3, provide a framework in support of model development in the interest of fostering transparency in the trade-off

Table 1

Overview of water management decisions underpinning optimization procedure definition. The table shows for every decision examples of the corresponding approach undertaken during optimization procedure development and the temporal and spatial scales of implementation. Note that in some cases also mixed approaches can be used.

Management Decisions	Control of diversion	Management planning	Control of releases	Impacts reduction
Examples	Setting a cap on maximum diversion	Incorporation of minimum environmental flow regimes into existing or new management plan	Optimization of reservoir release timing	Hydropeaking impacts reduction
Description	Specification of the maximum volume of diverted water that would allow maintaining the river regime at targeted levels	Incorporation of e-flow regimes into water management plan while meeting societal needs	Release timing adjustment to meet ecological water demand needs and/or reduce natural water flow alteration	Limitation of excessive water volume discharge downstream of the reservoir to mitigate adverse human and ecological effects
Type and frequency of flow modification	• Definition of specific % limits on the degree of allowable natural flow alteration • Definition of period-specific thresholds on river volume diversion	• Testing the feasibility of incorporating different minimum e-flows regimes into current schemes against a range of climatic or supply reliability scenarios	• Minimization of the deviation from reservoir storage and rule curves • Prescription of releases to meet specific downstream ecological needs • Reduction of the gap between natural flow and outflows	• Operational scheme synchronization of peak water volume releases with natural flooding or pulses
Targeted temporal scale	• Seasonal • Annual	• Annual	• Daily • Monthly	• Monthly • Seasonal
Targeted spatial scale	• Basin	• Basin	• Point scale (reservoir) • Multi-reservoir	• Basin • Sub-basin
Targeted ecological effects	• Long term effects at the ecosystem scale	• Long term effects at the ecosystem scale	• Population structure and size • Non-native species reduction	• Native community composition • Sediment budget
Comments	Participatory and/or multi-disciplinary workshops needed to define appropriate flow alteration	Would need the definition of plausible minimum e-flow regimes	Needs the definition of appropriate ecological indicators	Especially meaningful for large infrastructure

process around decision making and option selection during these two distinct phases of optimization model development.

2.1. Data collection

The proposed framework (see Tables 3–7 in Section 3) for assessing scale within optimization modelling to support e-flows was developed through a detailed review of existing literature that applied optimization in this context. We analysed existing literature and the options presented for each modelling element in the framework (Fig. 2), the targeted spatial and temporal scales, and the assets considered.

Data collection for the analysis was carried out by performing a literature search. The focus was set on studies that applied optimization of water diversion or impoundment to environmental water management decisions while meeting human water needs at different spatial and temporal scales. Keyword combinations were used in the ‘Web of Science’ search engine (i.e. multi-objective optimization, multi-criteria optimization, optimization, environmental flows, e-flows) to generate the initial set of literature. The collected studies were filtered for water management and the final selection was based on the criterion that they had to address both ecological and societal water use. Studies were excluded mainly due to their character (e.g. framework, review) or because of the study objective (e.g. focused on land use). In a few cases, studies focusing only on a single objective function but considering both needs (i.e. ecological and anthropogenic) have been included in the analysis, due to their compliance with the aim of the review and to stimulate discussion. A final collection of 27 case studies applying optimization procedures at different targeted scales was analysed (see references in Table A1, in the Annex). The overall objective of the review process was to highlight existing decisions and options for each phase of model development and to feed into the guidance framework for scale implications of modelling decisions.

2.2. Definitions of scales in multi-objective optimization procedures for water management

Defining comprehensible scales and their consistent use is still a key issue in systems modelling (Iwanaga et al., 2021). The interdisciplinary nature of water resource management exacerbates this with different spatial and temporal boundaries related to the multiple aspects of water management (i.e. administrative, hydrologic, management, etc.) (Moss and Newig, 2010; Daniell and Barreteau, 2014; Gleeson and Paszkowski, 2014). As policy decisions can be defined based on model outputs, Dabiri and Blaschke (2019) distinguished between the policy and the modelling scales, and associated the latter with the “dimension at which the data is acquired or derived” and in strict connection with the mathematical expression; similarly, Moss and Newig (2010) distinguish the ‘hydrological’ and the ‘political’ scales as central dimensions for water management modelling. On the other hand, in landscape ecology, scales are usually associated with patch extent or duration and grain or resolution (Withers and Meentemeyer, 1999). Most studies related to socio-environmental modelling consider the extent and resolution to define spatial and temporal scales (Moss and Newig, 2010; Daniell and Barreteau, 2014; Gleeson and Paszkowski, 2014; Dabiri and Blaschke, 2019; Iwanaga et al., 2021). Both spatial and temporal scale resolution is linked with data: grain size or cell size represent the smallest features of the spatial scale (particularly if the modelling is spatially-explicit); while time-steps represent the levels of the temporal scale (e.g. hours, days). In this study, we consider these notions to define spatial and temporal scales for optimization modelling for water management (see Box 1).

Studies optimizing water management usually indicate the targeted area for the assessment. Table 2 shows the spatial scale definitions we retrieved from the analysed studies. For each we provided a description of the features of the considered scales. While these definitions were linked with the focused assessment area and thus presumably belong to the ‘problem perception phase’, we found an ambiguity in the use of the terms sub-basin, multi-reach and river section scale. In fact they seem to be used interchangeably and possibly relate to modeller’s understanding of the system. However, this seems to be in accordance with the

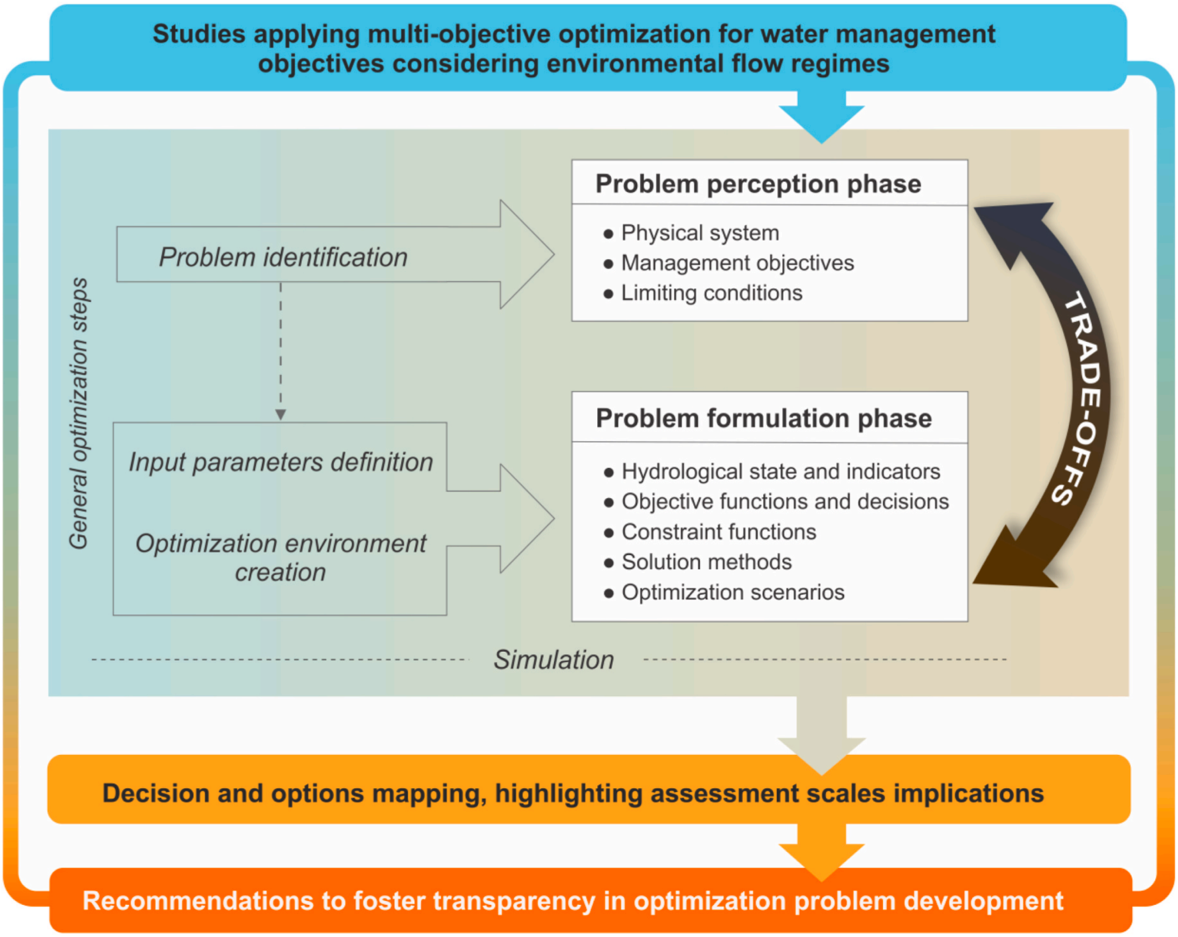

Fig. 2. Conceptualization of optimization process, as adopted in this analysis. Scheme of a stepwise general optimization procedure (left-hand side); Structure of the analysis applied in this paper (right-hand side): analysis of optimization procedure development for water management problems focused on two distinct phases, problem perception phase and problem formulation phase.

conclusions of Gleeson and Paszkowski (2014) who found that hydrological scales definitions are not used consistently among researchers. We use the definitions provided in Table 2 as mean of comparison throughout the paper.

3. Lessons from the literature: scales in multi-objective optimization procedures for water management

Environmental water management problems in regulated rivers can represent different issues related to the delivery of e-flows. For example, e-flows can be incorporated into an existing operational plan or infrastructure operation can be modified to reduce flow alteration (see Table 1 in Section 2). Modelling these management problems requires the definition of the targeted area and the available information during the 'problem perception phase' (Section 3.1) and the selection of the modelling approach in the 'problem formulation phase' (Section 3.2). Both phases are exposed to scale issues related with the data resolution, the temporal horizon for the operation plan and spatial boundaries of the system. Box 2 and Box 3 describe two example case studies. In the following sections, we elaborate on the framework by drawing on the considered literature to discuss the different stages within each phase with the aim of understanding the trade-offs between the management problem scales and the modelling problem scales.

3.1. *Problem perception phase*

3.1.1. *Physical system*

The concept of 'system' is expanded in water management to include the geographical, temporal and the socio-economic setting of the applied optimization procedure. The physical system can be defined in terms of the spatial area, including that involved in the generation of the water flow and the structural limits of the studied facility (e.g. a reservoir), and the temporal window of effect. Fig. 3 illustrates systematically the spatial and temporal scales that interest water management problems and highlights some of the major factors that have scale implications, based on the reviewed papers. The definition of spatial area and temporal window of effect provides the physical-temporal target reference for the following problem formulation phase. Here, we split the decision related to physical system perception into multiple decisions related to the flow alteration infrastructure: the type and number of flow altering infrastructures, and its operations; the definition of environmental assets; and, the definition of the management horizon (see Table 3). Temporal scales tend to be fairly well-defined by flow alteration type (impoundment, diversions), the management horizon, and the points of interest (and hence spatial scale). Points of interest include flow altering infrastructure, which affects how that infrastructure is operated, as well as e-flow target locations (e.g. river reaches, environmental assets).

Optimization assessments are developed to reflect operational schemes of impoundment and diversion structures at a range of management horizons. Considering all the resulting options related to the

Box 2
Case study: the Luis L. Leon reservoir (Big Bend reach) (Porse et al., 2015)

Management problem (perception phase)	Incorporation of environmental flow requirements into reservoir operation. Respect of supply requirements subject to international treaty. Demonstrating that environmental flow allocations can be increased.
Considered system:	River segment delimited by two reservoirs, with releases from one reservoir, tributary inflows, water extractions, flow at multiple gauges, inflows to second reservoir. Existing environmental flow requirements for basin and longer river segments could also have been used.
Operational timescale	Monthly reservoir releases, flows, and water extractions
Planning horizon	Multi-year; treaty works on 5 year cycles not explicitly modelled here.
E-flow approach	Prescribed hydrograph describing environmental flows monthly targets (base-flows, high flows and small/large floods developed from statistical analysis of hydrological record), scaled to vary total environmental flow volumes
Optimization problem (formulation phase)	Decision variables: monthly reservoir releases in two reservoirs Objectives: Minimization of total environmental flow deficits for all months Constraints: monthly mass balance continuity equations, total flow and minimum storage requirements approximating treaty stipulations; limits to storage and change in storage between months for operational constraints.
Input data	Flow record, water demands data, infrastructure operations from a prior water allocation model (1969–2009), e-flow requirements (literature) for BB reach
Optimization approach	Linear programming
Scenarios	Water availability scenarios – total environmental flow used to scale monthly environmental flow targets: (a) 600; (b) 800; (c) 1000; (d) 1100; and (e) 1200 mcm.
Our comments on spatial scale	Flows at one gauge assumed to be representative of environmental flow requirements along entire river section. Full implementation of treaty requirements and trade-offs with upstream and downstream EF requirements would need expansion of spatial scale. River segment focus demonstrates feasibility of local changes all else being equal.
Our comments on temporal scale	Multi-year management cycles are not explicitly modelled (management-implementation scale mismatch). Monthly rather than daily time step may not capture shorter term breaches of operational constraints. Expression of environmental flow as monthly average discharge conditions may not capture requirements at shorter timescales. Analysis assumed to make convincing case despite simplifications.

planning horizon, the selected facilities and the spatial range of their impact inevitably leads to a series of possible context-infrastructure combinations. In this case, system conceptualization benefits from the visualization of connections between assets, especially in large highly regulated river systems, as in transboundary river basins (e.g. Schlüter et al., 2005; Martin et al., 2017). Such visualization enables the definition of points where water movement is related to different causes (e.g. supply, inflow, storage), expressed as point sources (e.g. tributaries), releasing points (e.g. dams, hydraulic structures), and gauging stations facilitating optimization procedure development.

The wide variety of possible network configurations means that the targeted hydrological scale can range spatially from reach or river sections (e.g. Mullick, Babel and Perret, 2013; Fleifle et al., 2014) to sub-basins and multi-reach systems (e.g. Xevi and Khan, 2005; Shiau and Wu, 2013) or an entire basin (e.g. Suen and Eheart, 2006; Shiau and Chou, 2016). The consideration of the number of assets and their location as well as the scale of effect influences the final size of the spatial domain. Fig. 4 illustrates the different targeted assessment scales as emerged from the analysed studies.

A key challenge in the problem formulation phase is articulating the target for environmental outcomes. Environmental assets can include not only in-river values but also attributes of wetlands and floodplains (e.g. Szemis, Maier and Dandy, 2012; 2014; Szemis, Dandy and Maier, 2013). The environmental objective can be represented in several ways, for example as the provision of habitat or as the provision of ecosystem services. This clear articulation of environmental outcomes (as opposed to hydrological indicators) has been more evident in Australian case studies and management contexts. It is acknowledged that this need to define a-priori the targeted environmental assets during the optimization model procedure is a significant challenge, however, it represents good practice for system definition.

Lastly, management context decisions relate to operational horizon or release schedules. Infrastructure operational horizon can be tailored both at sub-daily or daily scale as this supports the identification of the best option based on hourly flows or how much water is to be allocated. The management horizon should also be consistent with the frequency of need to update the management plan. We identified studies using management horizon that were monthly, seasonal, single, and multi-year. When targeting single or multi-year management horizon, water releases are assessed for different single years, differentiating by wet, normal, dry, allowing to implement the best releases or abstraction operations based on the yearly hydrological conditions type (e.g. Steinschneider et al., 2014; Chen and Olden, 2017; Dai et al., 2017; Lewis and Randall, 2017). Policy testing could require the definition of multiple alternative management horizons. Conception of alternative legislative contexts can consider the prioritization of different combinations of objectives (e.g. Shiau and Wu, 2013).

3.1.2 Management objectives

The definition of optimization objectives reflects a range of management objectives or goals that can then be assessed for compromises in water allocations or other water release variables (see Table 4). There is a range of different formulations of system objectives, e.g. maximization satisfaction of consumptive demand (or minimization of shortfalls), optimization of structural performance, the maximization of economic benefit, or minimization of the hydrological disturbance. The way the objectives are expressed is linked to the spatial extent but can reflect end-user needs. For example, the need for controlling floods is more pressing at the basin scale and can be managed by considering the difference between inflows and outflows (e.g. Porse, Sandoval-Solis and

Box 3
Case study: the Peishih Creek (Shiau and Wu, 2013)

Management problem (perception phase)	Plan release environmental water for three interconnected reaches (subject to various degree of hydrological alteration) while ensuring domestic water supply and hydropower production
Considered system	Reservoir connected to river section (with weir diversion), performance measured for 1, 2 and all 3 reaches
Operational timescale	Hourly flows, with release decisions spread through the day, and flow indices aggregated to multiple scales
Planning horizon	Multi-year
E-flow approach	Measurement of natural flow alteration through 5 hydrological indices: RBF*, daily flow, monthly flow, annual 7-day minimum flow and 5-year floods.
Optimization problem (formulation phase)	Decision variables (15): 2 environmental flow proportions, 3 three-period release parameters, 3 hedging coefficients, and 7 compelling release parameters. Objectives: TOPSIS (technique for order preference by similarity to ideal solution) transforms multi-objective problem into single objective. Reservoir performance objectives: minimization of long term shortage ratio, mean annual deficit duration, maximum 1-day shortage ratio; maximization of mean annual hydropower production, flood attenuation. Environmental water objectives: minimization of difference to pre-impact RBF, difference to daily hydrograph, difference to pre-impact monthly flow, difference to pre-impact annual 7-day minimum flow, difference to pre-impact 5-year floods. Constraints: only limits on decision variables. Routing model used to simulate flow.
Input data	Flow record (1998–2008) of reservoir inflows and Nanshih Creek's river flow.
Optimization approach	Genetic algorithm in simulation-optimization framework
Scenarios	Operation scenarios: (a) 1-reach scenario with 10 objectives, (b) 2-reach scenario with 15 objectives, (c) 3-reach scenario with 20 objectives.
Output	Hourly reservoir releases; weir diversion volumes at Nanshih Creek, and post-impact flows at the three study reaches.
Our comments on spatial scale	Exploration of multiple scales; bottom of system defined implicitly in figures as junction with larger watercourse. Reaches defined based on nature of hydrological alteration provides natural segmentation while recognizing that ecosystem response has not been addressed. Selection of reaches significantly affected results.
Our comments on temporal scale	Inclusion of hydrological alteration at multiple scales as objectives, then reduced to single objective by comparison to ideal point such that trade-offs are not explicitly explored. The planning horizon of infrastructure operations is not clear, especially in relation to projected demand magnitude, as the only available information is the data timeframe (10 years).

Notes: *Richards-Baker flashiness index (RBF).

Lane, 2015; Shiau and Chou, 2016).

Studies aiming at maximizing water supply seek to ensure water supply maintenance over time by adjusting to flow fluctuation, rather than aiming to abstract the greatest possible amount of water at a single time-step. The operational scheme of the facility (i.e. impoundment or diversion) affects the approach for the definition of supply reliability. Targeted reservoir releases for downstream ecological needs are sought in the case of impoundment. In such cases water collection represents the prioritized supply method for human use and optimization objectives aim to maximize the 'collection capacity' of the reservoir. Water abstraction optimization, on the other hand, focuses on the withdrawal of water from the flowing river (e.g. diversion). An alternative for assessments targeting large basins that encompass several abstraction points is to define a 'supply objective' for each abstraction point in the considered system before defining the cumulative objective.

Hydropower generation objectives are typically considered for assessments targeting reservoir- (e.g. Shiau and Wu, 2013; Wang et al., 2015; Fallah-Mehdipour, Bozorg-Haddad and Loáiciga, 2018) or basin-scales (e.g. Paredes-Arquiola et al., 2013; Shiau and Chou, 2016; Hassanjabbar, Saghafian and Jamali, 2018). Hydropower production optimization objectives require the consideration of infrastructure operations and the infrastructure capacity in energy generation. When optimization objectives are focused on the economic aspect of hydropower generation from a reservoir, metrics such as net benefit or revenues are considered.

Definition of environmental objectives within the optimization procedure is connected to the environmental water management decisions (see Section 2) and usually considers the natural hydrograph or specific water volumes for ecological processes. Compliance of the regulated hydrograph with the natural discharge is based on the consideration of the natural flow regime as a pristine hydrological reference (Acreman, 2016). Despite increasing awareness of the need to advance the natural flow regime paradigm, whether or not species can adapt or are already adapted to flow alteration caused by man-made infrastructures (e.g. dams) remains difficult to assess and needs an 'expanded e-flow science foundation' (Poff, 2018). This leaves the natural flow regime alteration reduction as the easiest choice for many optimization assessments (Wang et al., 2015). Moreover, this approach does not explicitly prioritize specific species over others as in the ecological flow regime paradigm (e.g. (Suen and Eheart, 2006). Within the optimization procedure, gauge data at reference points can set the target conditions of the ideal flow regime (e.g. Torabi Haghighi and Kløve, 2015). Shiau and Chou (2016) for example minimized the differences between the monthly flow hydrograph and the monthly discharge; similarly, Schlüter et al. (2005) minimized water flow changes across several intake points. However, the use of gauge data should be based on appropriate considerations regarding the location of the gauging station and the river section it is related to (e.g. drainage area or length of river segment), as this could affect the resulting scale of the assessment. As alternative to real flow data and to the flow-alteration-reduction approach, simple algorithms

Fig. 3. Temporal and spatial scales that define water management optimization problems. This figure is based on the results of our analysis. It illustrates the different spatial and temporal scales in relation to certain factors which challenge optimization procedure development by means of decision and option selection complexity, and definition of the resulting system boundaries.

such as those in the Global Environmental Flow Calculator (GEFC) can rapidly calculate e-flow requirements for the main rivers worldwide (e.g. Hassanjabbar, Saghafian and Jamali, 2018). This information can be then used within the optimization problem for developing targeted releases or 'designer flows'. The designer flows approach is gaining momentum for preservation of river ecosystems (Poff and Olden, 2017) and has been embraced for example by Chen and Olden (2017) to prioritize native over non-native species in regulated rivers.

3.1.3. *Limiting conditions*

Decisions about the range of limiting conditions to consider for the targeted assessment system can be distinguished based on their nature: (1) physical-environmental conditions, which refer to the environmental status of the system, e.g. conservation of mass; (2) supply-related, linked to the magnitude, timing, and type of demand; (3) infrastructure-related, that are influenced by the design or operational capacity of the flow modification structure (e.g. dam, hydropower plant); and (4) regulative, which are defined based on policies or normative requirements (see Table 4).

Physical-environmental limiting conditions reflect a certain environmental availability of water within the considered system and are usually described using a water balance equation or hydrological model. Our analysis showed that physical-environmental limitations are directly linked to the scale of the assessment. The location of the facility (i.e. dam, reservoir, hydropower plant, and weir) within the assessed area (e.g. basin, sub-basin, reach) influences the definition of the reference flow conditions and the number of inflow points. The targeted scale of the assessment is physically defined by the input location receiving the flow and an output location releasing the flow following the course of the river. Continuity equations are often used to capture and assure the balance between the inflows and the outflows (e.g. Xu et al., 2017; Hassanjabbar, Saghafian and Jamali, 2018). The definition of the continuity equation requires the consideration of the dynamics of inflows, hence of both location and timing. For example, the water quantity in a reservoir (dam) at a certain point in time (that depends on the considered timescale) is a function of the water contained in the reservoir (dam) at the previous time step (e.g. day, hour) and of the outflow and inflow water quantity at the current time step (e.g. Chen and Olden, 2017). The 'water budget' within a reservoir also needs to account for losses due to evaporation (e.g. Porse, Sandoval-Solis, and Lane, 2015). This is particularly relevant if the system is exposed to severe temperature fluctuations, dry conditions. Flows to and from groundwater systems and the hyporheic zone may also be relevant.

Limiting conditions can also reflect water or energy delivery requirements to meet sectoral needs (e.g. domestic, industrial, agricultural). Infrastructure operations optimization requires consideration of structural limitations on infrastructure capacity and releases. The number of infrastructure facilities and their management influences required scale and the corresponding constraints. Minimum (maximum) reservoir storage capacity or in- and outflow volumes are frequently implemented for water impoundment management, for example to avoid reservoir wall overtopping. This suits a daily or sub-daily scale optimization through the definition of the minimum and maximum allowable volume fluctuations (e.g. Chen and Olden, 2017) with respect to demand magnitude and risk of downstream bankfull flows or floods (e.g. Xu et al., 2017).

Water use agreements, treaty stipulations, and legal water rights can appear as limiting conditions depending on how the river network intersects with national or other jurisdictional borders (e.g. Porse, Sandoval-Solis and Lane, 2015; Wang et al., 2015). Quality standards (e.

g. for irrigation, drinking water) are also common.

3.2. Problem formulation phase

3.2.1. Hydrological state and indicators

The decisions within the problem formulation phase specifically account for model, data, and computational limitations, contrasting with the ideal problem perception that stakeholders might prefer in absence of these limitations. In this phase, the definition of environmental water requirements establishes limits to the modification of water flows. We identified a series of crucial decisions related to the setting of environmental water requirements: the consideration of the preferred e-flow assessment approach, the inventory of the available sources of information, environmental water requirements establishment, and the location of the gauging stations and selection of the hydrological metric (see Table 5 for summary).

Environmental water requirements definition through empirical estimation of e-flow ranges is an option at finer scales (e.g. reach) and on short term planning (e.g. seasonal) when direct data (e.g., species, habitat-level data) is accessible. These ranges reflect hydrological or habitat needs (e.g. Mullick, Babel and Perret, 2013) of key species and can be defined through hydro-ecological models or regression techniques: for example, regression-based approaches to define fish-flow relationships for native and non-native species preferences (e.g. Chen and Olden, 2017) or by using the physical habitat simulation models (e.g. PHABSIM, Bovee et al., 1998) to retrieve minimum e-flows requirements for phenological stages (e.g. Shang, 2015). Mixed assessment approaches are more complex to implement as exploit multi-disciplinary instruments based on collaborative interactions between scientists, management analysts, and stakeholders (e.g. Porse, Sandoval-Solis and Lane, 2015).

Once the preferred approach is identified, multiple methods can be applied to obtain the necessary eco-hydrological information. Literature review and experts' involvement in the definition of water requirements for targeted species can be used for modelling and optimization of spatially complex systems (e.g. involving non-linear relationships and multiple predictors) as alternatives to massive data collection. Participatory workshops to set hydrological thresholds are underpinned by knowledge coming from different sources (e.g. Paredes-Arquiola et al., 2013; Xevi and Khan, 2005), possibly measured at different scales in

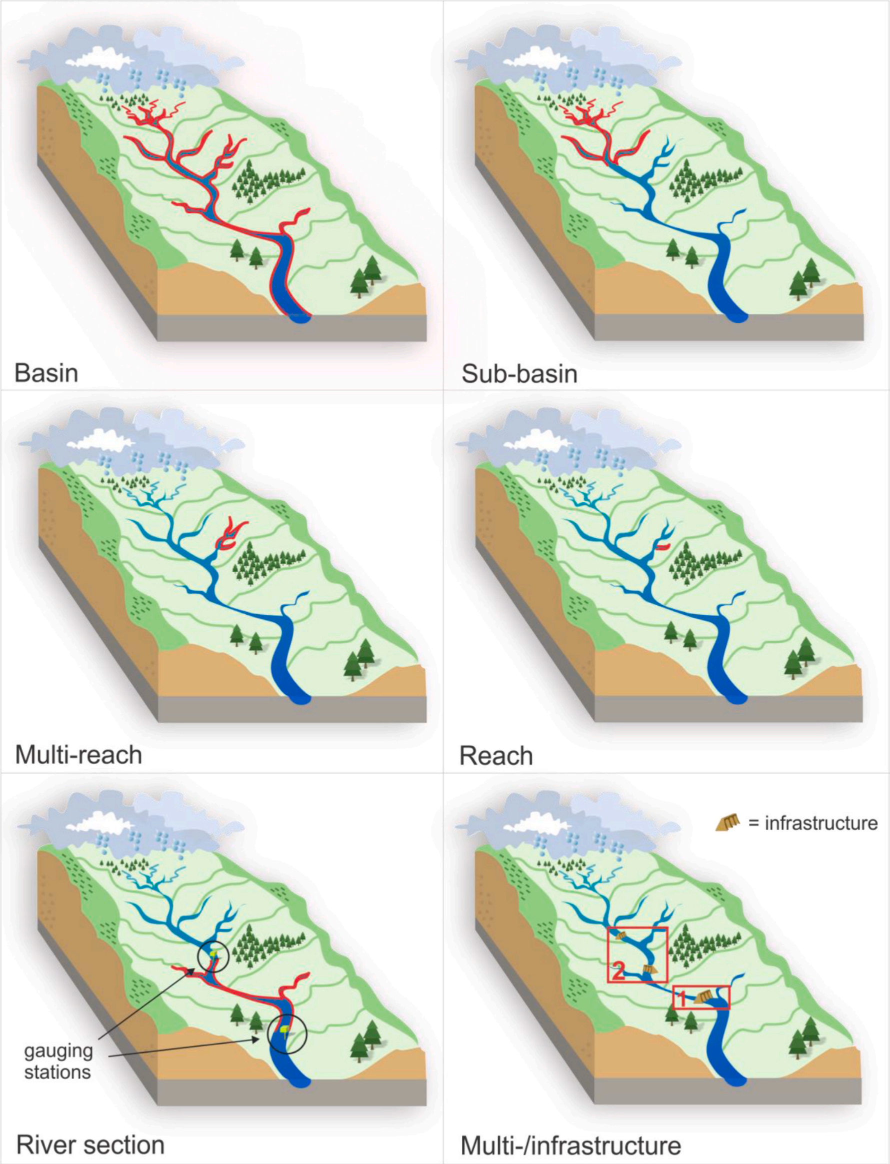

Fig. 4. Illustration of different spatial scales considered in the reviewed studies. For description see Table 2.

Table 2

Spatial scales used for optimization modelling applied to water management. We identified a set of recurrent definitions in the reviewed studies that refer to the targeted assessment areas and their meaning.

Definition	Description
Multi-basin	A series of adjacent basins.
Basin	The hydrological delimitation of the river domain, formally defined as the land area that collects the rain or snow water generating the flow and the river network. Can refer to the whole river network.
Sub-basin	An area of the river network (as part of a defined basin) that encompasses a series of adjacent and interconnected reaches. The latter can eventually merge with a bigger tributary.
Multi-reach	Several reach sections of the same river. It can encompass multiple tributaries throughout the river network. Depending on the number of considered reaches (and their proximity) this may be similar to a sub-basin scale or river section.
Reach	A section of the river that presents similar hydrological characteristics (e.g. discharge, depth). Usually it represents short river portions or small tributaries. Sometimes it can be associated with the river section scale.
River section	A portion of the river network of variable length that is arbitrarily defined by the user. It could encompass the portion of the river stretch included two key points (e.g. gauging stations, dam, and connection to another tributary).
Reservoir	Body of water artificially impounded by a dam, commonly with potential for controlled releases
Infrastructure	Human assets linked to the river flow (e.g. dams, reservoirs, weirs) that are used to supply water or energy for human consumption, regulate the floods or provide navigation.
Multi-infrastructure	A series of infrastructure located in different sites of the river network. Can refer to a number of in-series infrastructures (i.e. consecutively positioned on the same river section) or on multiple reaches.

different locations, and hence require a more careful statement of the final scale of applicability of the assessment. Another option is the use of existing e-flow calculation software packages (see Section 3.1.2). However, the modelling process can affect the spatial and temporal resolution of their output data and thus the final scale boundaries.

To define the reference hydrological conditions, and the monitoring of the targeted environmental assets, historical and actual data from gauging stations are used, potentially with hydrological model simulations. Flow data includes inflow data to reservoirs or dams when studies focus on optimizing release timing (e.g. Shiau and Wu, 2013). Whilst the number and location of gauging stations vary based on the study site type and the general purpose of the assessment, observations from gauging stations located downstream of the reservoir are useful for the assessment of water release alterations in single (e.g. Yin, Yang and Petts, 2012) or multiple reservoirs in series (e.g. Dai et al., 2017). Moreover, analyses for multiple-reaches benefit from a sound gauging station network at the rivers and their tributaries as they enable the analysis of the variability of historical flows (e.g. Fleifle et al., 2014), while optimizing reservoir- or dam-series requires reporting or modelling of dam outflows (e.g. Yin, Yang and Petts, 2012; Shiau and Wu, 2013).

Our analysis showed that among the considered flow components, flow magnitude class parameters are widely used as hydrological indicators of ecosystem health within optimization studies as they reflect conditions that shape habitat availability and suitability for species (Richter et al., 1996; Poff and Zimmerman, 2010; Rolls, Leigh and Sheldon, 2012; Rolls and Bond, 2017). Measures of the magnitude of monthly and annual flow conditions (e.g. median value of the mean monthly flow, minimum monthly flow) are used to describe the prevailing behaviour of the flow across the year or uncover major hydro-climatic cycles among different years (e.g. average yearly flow) but are unable to deliver sufficient information of local characteristics (e.g. reach-level behaviour). In this case, disaggregating of monthly average flows into site-specific minimum monthly flows allows the consideration of the hydrological spatial variability at a sub-regional scale (e.g. Paredes-Arquiola et al., 2013). The water impoundment planning horizon (e.g. Wang et al., 2015) or the characterization of a multi-reach system's behaviour (e.g. Shiau and Wu, 2013) can drive the choice of the selection of indicators defining the timespan and intensity in water flows (e.g. for low flow conditions). Similarly, baseflow indicators (often subdivided into wet, dry and extreme baseflow) are linked to reservoir outflow or diversion scheduling (e.g. Yin, Yang and Petts, 2012; Yin, Yang and Liu, 2014; Yin et al., 2015; Dai et al., 2017).

Water quality indicators (i.e. temperature, dissolved compounds, oxygen) are less frequently considered when addressing environmental flows problems (e.g. Fleifle et al., 2014; Xu et al., 2017). Nevertheless, these indicators are usually associated to the flow parameters to the extent of being affected by changes in the regime.

3.2.2. *Objective functions and decision variables*

The previous problem perception phase creates the conditions for the translation of assessment objectives into objective functions. The general optimization problem is defined by the equation $f(x)$ that we seek to *minimize* or *maximize*, in which x is the decision variable in question (or vector of decision variables). In addition to deriving from the management objective, objective functions can differ considerably depending on data availability and the type of flow alteration type (e.g. run-of-river hydropower, storage-based power generation) (see Table 6). Selection of optimization objectives remains highly dependent on analyst choice and revolves around two main options: on one hand, a higher number of objectives (i.e. more than one) can favour a more comprehensive representation of the system while promoting an increased understanding of existing trade-offs; on the other hand, due to the structure of the applied technique, the optimization of multiple objectives is often hampered by limited computational capacity or difficult visualization of complex results (Lautenbach et al., 2013). Despite the existence of optimization tools able to model a higher number of objectives (see Reed et al., 2013), studies tend to keep the number of simultaneous objectives low (e.g. ≤ 4) as well as considering few decision variables (see Section 3.2.4). In this case, the assignment of different weights to decision variables (e.g. Schlüter et al., 2005; Xevi and Khan, 2005) or the judicious use of constraints can reflect a range of stakeholders' preferences or policy decisions while at the same time reducing the computational effort. Further discussion on the number of objectives is presented in Section 3.2.3 and 3.2.4.

The availability of exact and updated water consumption data for the targeted infrastructure can be challenging to obtain. Expressing water supply objectives as the minimization of shortage indices (e.g. long term total shortage ratio, mean annual deficit duration, maximum 1-day shortage ratio) allows the indirect consideration of demand by relying on daily reservoir releases (Shiau and Wu, 2013). Finer scale representation of water supply objectives, e.g. water demand-type at river network nodes (i.e. intake points) (e.g. Schlüter et al., 2005) allows a more refined optimization for complex reach systems. An alternative approach uses a composite function (e.g. an index) composed of different indicators for water use purposes, such as domestic, industrial, and agriculture supply (e.g. Suen and Eheart, 2006). Shares of abstracted water can sometimes be retrieved from regional and local databases, which may need to be downscaled or extrapolated to areas of interest.

The most straightforward way to optimize power production is through the maximization of water releases or available water volume for hydropower generation (e.g. Arslan, 2015; Xu et al., 2017) or inversely by minimizing the gap between generated hydropower and the installed capacity during operational periods (e.g. Fallah-Mehdipour, Bozorg-Haddad and Loáiciga, 2018). Yin et al. (2015) for instance, aimed at maximizing the mean annual revenue of hydropower generation concerning specific degrees of flow regime alteration. Likewise, economic objectives can be also set for studies targeting irrigation water demand (e.g. Xevi and Khan, 2005; Lewis and Randall, 2017).

In section 3.2.1 we discussed hydrological indicators used to define

Table 3
Framework 1/5. Summary of the decisions and options, and related scale considerations for the 'Physical system' step during the 'Problem perception phase'.

Assessment phase	Modelling element	Decision	Description	Related options	Spatial scale relation	Temporal scale relation	Relationships between options
Problem perception phase	*Physical system* (Section 3.1.1)	Definition of flow alteration type	Definition of the flow altering infrastructures that belong to the considered regulative unit and consideration of their functioning	• Diversion • Impoundment	Need to consider the scale of effect and nature of flow alteration	Need to consider infrastructure operations	This step influences the incorporation of the management decision
		Definition of the number of flow altering infrastructures	Consideration of all the assets in the target unit	• Single-infrastructure • Multi-infrastructure • Single with mixed-use (e.g. impoundment with power generation)	Affects the scale of representation of the infrastructure network	Need to consider operative conditions (schemes) of all the assets. Hence could affect the final timeframe.	This step influences also the choice of the solution approach (number of decision variables or objectives). Requires awareness of possible influences between assets
		Definition of infrastructure operations	Consideration of the operative scheme of the selected infrastructure	• Monthly • Daily • Sub-daily	Spatial scale of effect is influenced by timeframe	This relates to the timeframe of the operation cycle, involving both flow alteration type and configuration of infrastructure assets	Option selection could affect the choice of the scenario (Section 3.2.5)
		Definition of environmental assets	Consideration of the type and characteristics of the targeted environmental assets and their location	• Ecosystem type (e.g. wetlands) • Ecosystem services (e.g. habitat provisioning areas)	Affects the scale of representation	Needs to consider infrastructure operations and flow alteration type	This step could influence scenario definition
		Definition of the management horizon	Consideration of the frequency of needs to update the management plan	• Monthly • Seasonal • Annual • Intra-annual	Spatial scale of effect is influenced by management timeframe	Affected by uncertainty in driving conditions and system knowledge, as well as the ability to adapt plans over time	This step could influence the type of scenarios and hence trade-offs analysis

ecological needs. Here we present ways to employ those indicators within the optimization model. Environmental outcomes can be directly used as objective functions. In fact, e-flows objectives within the optimization problem are commonly expressed as specific share of incoming flow (usually expressed as volume) that reflect environmental requirements (e.g. Arslan, 2015; Xu et al., 2017). At the scale of river

Table 4
Framework 2/5. Summary of the decisions and options, and related scale considerations for the 'Assessment objectives' and 'Limiting conditions' steps during the 'Problem perception phase'.

Assessment phase	Modelling element	Decision	Description	Related options	Spatial scale relation	Temporal scale relation	Relationships between options
Problem perception phase	*Management objectives* (Section 3.1.2*)*	Classification of water uses	Define water use objectives that are linked to the considered water flow alteration	• Energy generation • Water supply • Flood attenuation • Environmental health	Some objectives can be more strongly related to one scale (e.g. water supply or flood attenuation)	Need to consider the management horizon	This decision can be influenced by the decision on the extent of the assessment scale
		Contextualization of objectives	Consideration of the implication of objectives implementation within the case study area	• Participatory workshops with relevant stakeholders • User-defined • Regulations • Treaty stipulation	System boundaries do not change but need to consider the spatial scale in regulative terms	Could present different temporal needs in resource use (e.g. demand)	/
	Limiting conditions (Section 3.1.3)	Definition of the limiting conditions	Definition of the factors that can affect the nature of the considered objectives or the representability of the target system	• Natural phenomena • Structural limitations • Operational limits • Demand fluctuations • Hydrological continuity	Physical parameters (that can be spatially bounded e.g., hydrological continuity equation)	Consider time-dependence of some variables (especially demand, hydrology)	These conditions border the search space, allow the output of more realistic outcomes and reduce computational time

Table 5

Framework 3/5. Summary of the decisions and options, and related scale considerations for the ‘Hydrological state and indicators‘ step during the ‘Problem formulation phase’.

Assessment phase	Modelling element	Decision	Description	Related options	Spatial scale relation	Temporal scale relation	Relationships between options
Problem formulation phase	*Hydrological state and indicators* (Section 3.2.1)	Consideration of the preferred e-flow assessment approach	Selection of the suitable e-flow assessment approach defining environmental water requirements	• Habitat approach (habitat requirements of relevant species) • Phenological approach (life-history stages) • Holistic approach (mixed approach)	Need to consider the nature of targeted ecological endpoints (e.g. instream elements). Mixed approaches could be linked to multiple spatial scales and multiple resolutions	Needs to consider the targeted ecological outcome manifestation within the planning horizon	This decision could be linked to the decision on the considered number and nature of flow alteration structures (Section 3.1.1)
		Information inventory and method selection	Consideration of the available source of information	• Empirical estimation • Expert judgement • Web-tools • Literature • Participatory workshops	Data format could affect spatial scale. Need to consider the model resolution (if spatially explicit).	As for spatial scale, data resolution and empirical method could affect the temporal scale	This decision is directly linked with the previous decision on e-flow assessment approach. Could also affect scenario definition.
		Definition of reference hydrological conditions	Definition of the location of the monitoring or gauging stations as a source for natural flow values and hydrograph data	• Upstream of the reservoir • Downstream of the reservoir • Multi-reach	System spatial boundaries could change when including gauging station location	Could be affected by historical data timeframe and temporal resolution	Represents mainly a data source, but can be linked with environmental asset location decision
		Selection of hydrological and non-hydrological indicators	Definition of the hydrological metrics (statistics) for the definition of threshold conditions (e.g. flow magnitude and frequency/timing)	• Flow magnitude • Frequency and timing • Extreme events • Water quality indicators	Infrastructure size could influence the extent of flow alteration	Indicator selection could be affected by the length of the considered timeframe (e.g. annual statistics can be used for multi-year planning)	This decision is linked to planning horizon needs, the nature and area of effect of flow alteration type as well as the scenario choice

Table 6

Framework 4/5. Summary of the decisions and options, and related scale considerations for the ‘Objective functions and decision variables ‘step during the ‘Problem formulation phase’.

Assessment phase	Modelling element	Decision	Description	Related options	Spatial scale relation	Temporal scale relation	Relationships between options
Problem formulation phase	*Objective functions and decision variables* (Section 3.2.2)	Consideration of the number of objectives	Definition of objectives number based on the computational effort	• Single-objective • Multi-objective	Objectives for different water uses are often on different spatial scales or extents	Objectives calculated on longer timeframes often need to be complemented with objectives that capture shorter-term variability	Relates mainly to computational resources but can be influenced by the solution method decision.
		Consideration of the nature of objectives	Definition of the type of objective function that can solve assessment needs	• Supply reliability indices • Shortage indices • Composite functions (weights assignment) • Gap reduction	Requires knowledge of the environmental asset	Requires knowledge on management horizon and information on demand nature	Relates to the solution method and is mainly methodological.
	Constraint functions (Section 3.2.3)	Consideration of the nature of constraints	Selection of the type of constraints that would allow the best representation of the targeted system	• Upper and lower limits on decision variables (e.g. storage capacity) • Search-related constraints	Requires knowledge of infrastructure operations, location, and type of flow alteration	Need the consideration of the management scenario and planning horizon	Relates to the decision on the type and number of objectives

Table 7

Framework 5/5. Summary of the decisions and options, and related scale considerations for the ‘Solution methods’ and ‘Optimization scenarios’ steps during the ‘Problem formulation phase’.

Assessment phase	Modelling element	Decision	Description	Related options	Spatial scale relation	Temporal scale relation	Relationships between options
Problem formulation phase	*Solution methods* (Section 3.2.4)	Solution search approach	Selection of the solution approach based on the nature of the considered decision variables and related functions	• Mathematical-based • Stochastic	Complex problem formulations covering multiple spatial scales may not be computationally feasible, requiring simplification	Longer management horizons and finer-scale operations may require longer model run times	This decision is highly linked with the decision on the number and nature of objective functions (and computational resources availability)
	Optimization scenarios (Section 3.2.5)	Definition of the uncertainty sources/ external conditions	Consideration of the major source of uncertainty in optimization outcomes	• Climatic conditions • Hydrological • Operational horizon • Legislative	Need to consider the extent of the river network and the type of facility	Connected to management horizon, if set at an annual scale could highlight inter-annual patterns	This step is influenced by the optimization model purpose (i.e. updating an existent plan or propose a new one)

sections, habitat-level data availability allows optimizing specific river flow conditions for the benefit of target species (Chen and Olden, 2017). Depending on the targeted ecological endpoint, data collection and hence function definition can be more or less straightforward to perform. Reduction of the proportional deficit between a prescribed point-diversion and the river regime (e.g. Chen and Olden, 2017) suits assessments of finer-scale hydrological systems such as rivers and river sections. This also applies for assessments at reservoir-scale aiming at ensuring continuity between water inflows and outflows (e.g. Yin, Yang and Petts, 2012; Shiau and Wu, 2013; Steinschneider et al., 2014).

Lastly, the fitness of certain solutions to the objective function for the environmental water requirements can be conceptualized based on the assumptions of the analyst in relation to ecological response functions (Fu and Guillaume, 2014). For example, Suen and Eheart (2006) considered the intermediate disturbance hypothesis assumption as basis for the definition of the fitness function for six eco-hydrological indicators to maintain the livelihood of aquatic ecosystems.

3.2.3. *Constraint functions*

The general objective function presented in Section 3.2.1 is usually subject to some constraints. In the general case, $f(x)$ is subject to $g(x) < 0$, in which $g(x)$ represents the constraint function. Constraint functions can significantly influence the optimization outcomes, allowing the output of more realistic results with respect to the considered system scale and other factors (Strauch et al., 2019) in mathematical optimization approaches, whereas they commonly represent "decision maker preferences rather than physical laws" in simulation-based optimization (Clarkin et al., 2018). For the general definition of constraints and their effect on the objective function, see Coello et al. (2007).

Constraint definition can be a modelling-intensive phase if the system considers a high number of input points, diversion points, and facilities. If data used in the optimization problem is not yet spatially explicit (i.e. georeferenced), spatial boundaries are usually represented by considering intake and outtake points location.

While consumptive requirements can also be set as objectives (e.g. by defining a minimization function aiming at minimizing the gap between the target consumptive amount and the optimized amount), the translation of consumptive requirements into constraint functions requires knowledge of the nature of demand. Stable demands over time are easily expressed by estimating an amount of water that captures all the possible consumptive uses in the considered system. However, this choice will be more suitable for short time frames or long term averages, for example management plans for maintaining the native ecological communities in river sections (Chen and Olden, 2017). Alternatively, differentiating among demand types by setting a minimum water supply ratio can ensure compliance of reservoir operation with specific supply objectives, for example for irrigation purposes (e.g. Wang et al., 2015). On the other hand, a series of unpredictable factors (e.g. climate, social behaviour, and daily patterns) can also make the demand level uncertain. In this case, defining a reliable quantity of stored water for consumptive use or energy generation allows satisfying fluctuating needs over a longer period. In this case, a minimum storage constraint or supply reliability constraint may be used. The latter, in the case of municipal supply, can be also considered as objective depending on the problem structure (e.g. Yin, Yang and Petts, 2012).

Hydropower plant optimization objectives are frequently constrained by capacity thresholds limiting the range of decision variables such as the control gate operations, turbine release, ramping, power tunnel, and grid capacities defining power output limitations (e.g. Steinschneider et al., 2014; Dai et al., 2017).

Optimization process-related constraints have the purpose of facilitating the search phase by setting specific conditions that will influence the fitness value based on the degree of violation (e.g. Dai et al., 2017). Penalty functions are an example of constraint handling techniques, where a constraint function is transformed into a penalty that is directly added to the objective function (Coello, Lamont and Veldhuizen, 2007; Ruhul, Masoud and Yao, 2012). For example, penalties can be set based on the frequency of falling outside of the target range for each e-flow parameter (e.g. Wang et al., 2015). However, the values of the penalties should not be set to very large values to avoid interfering with the identification of the ideal fitness values (Dai et al., 2017).

Lastly, constraints can also reflect additional objectives thus reducing the number of objectives (e.g. to a single objective) (e.g. Torabi Haghighi and Kløve, 2015; Wang et al., 2015) but this does not necessarily mean that problem size would be reduced. Conversely, constraints can also be turned into objectives, thus increasing their number and eventually leading to many-objective problems. However, Kasprzyk et al. (2016) in their study of many-objective problems for water management showed that a higher number of objectives can be paradoxically easier to solve.

3.2.4. *Solution methods*

How a water allocation optimization problem is addressed across the different scales depends on its overall complexity. There is no direct relationship between scale and solution method as too many factors influence the selection of one technique over another. Moreover, problems can be approached with different degrees of complexity even if the considered assessment scale is fine (e.g. a single facility). However, since water allocation optimization is based on the mathematical conceptualization of the problem (e.g. linear, nonlinear, discrete, and continuous), knowledge about differences in solution approaches can contribute to the understanding of possible solving strategies for the considered scale (system) based on components (e.g. indicator types for objectives, nature for constraints). To illustrate the decision about the solution method, we distinguish between deterministic (or mathematical programming) and meta-heuristic optimization.

Our analysis showed that oftentimes water allocation problems are formulated as multidimensional, convex objective functions constrained by a series of rules. Since constraints influence the geometry of the feasible solution space, the solution can be found through the process of eliminating problem variables (Cavazzuti, 2013). For example, linear programming-based algorithms have been used for solving broad-scale optimization problems of system types involving dams and large reservoirs, showing a convexity both in the objective function and in the constraint functions (e.g. Xevi and Khan, 2005; Steinschneider et al., 2014; Porse, Sandoval-Solis and Lane, 2015; Chen and Olden, 2017). Problems envisaging variables with a high degree of nonlinearity (e.g. evapotranspiration, soil infiltration) can be solved by elimination-based nonlinear programming algorithms (e.g. Schlüter et al., 2005; Arslan, 2015). In the case of broad-scale optimization problems considering quadratic equations envisaging the relationship between streamflow and net economic benefit, sequential quadratic programming can iteratively search for the optimal solution (e.g. Mullick, Babel and Perret, 2013). When continuous function variables show discrete or integer values, mixed-integer linear programming is preferred instead. Wang et al. (2015) used this technique to optimize large scale reservoir operations carrying a binary value in the reservoir outflow parameter.

Metaheuristic optimization algorithms can handle problems characterized by a high number of objectives (Coello, Lamont and Veldhuizen, 2007; Maier et al., 2019). This could be the case of multi-purpose or multi-reach optimization problems. As a sub-group of metaheuristics, evolutionary algorithms provide good chances of approximating a globally optimal solution quite rapidly (Shahin, 2008; Cavazzuti, 2013) by generating initial random sets of variables and then by exploiting operators such as selection, mutation and cross-over to produce better solutions at each generation. For example, Fleifle et al. (2014) solved the minimization problem for the wastewater treatment costs and maximized water quality in a river section. Evolutionary techniques such as the non-sorted genetic algorithm (NSGA) are commonly applied for handling both basin and multi-reach scale optimization problems (e.g. Suen and Eheart, 2006; Dai et al., 2017; Martin et al., 2017; Xu et al., 2017).

3.2.5. Optimization scenarios

The definition of optimization scenarios is included in the problem formulation phase as it relates closely to the practicalities of providing useful information in the face of data, model, and computational limitations. In principle, a given problem formulation would ideally have a general solution, but in practice, it needs to be embedded in a specific context, and multiple variants of problem formulations may be possible. The context represents both environmental, operational and management conditions. Scenarios hence provide the opportunity to assess alternatives based on system behaviour under possible circumstances (e.g. on the effects of different release-schemes on hydrological variability or seasonal conditions on planned abstractions). This could contribute to reduce uncertainty about a specific management decision or to explore potential management decisions, under a range of operational, ecological and hydrological conditions. For example, Lewis and Randall (2017) considered dry, normal and wet hydrological conditions; Porse et al. (2015) considered different e-flow allocation targets to assess the trade-off with water supply; Wang et al. (2015) formulated scenarios representing combinations of objectives and constraints. While the reliability of optimization outcomes can be also linked with robustness and accuracy of output data, it also depends on prior knowledge about the considered system which is itself based on the overall system understanding (Sanchis, Martínez and Blasco, 2008). This means that some degree of conceptual bias arises from our lack of understanding of relationships between components. The size and type of investigated system influences the scenarios that have to be evaluated, because different needs, and thus ways to think objectives, can exist within that system domain. For example, if the system is large (e.g. river basin, sub-basin) multiple needs often need to be addressed due to the presence of different social groups and economic activities, policy requirements (e.g. Porse, Sandoval-Solis and Lane, 2015) or just the presence of multiple abstraction points (e.g. Paredes-Arquiola et al., 2013). Scenarios can be expressed differently for single facility systems. At the reservoir scale, alternatives could be represented by the compromises between the amount of released and impounded water flow concerning natural flow variability or e-flow requirements. Scenarios depicting trade-offs between a series of off-stream (e.g. irrigation) and instream benefits (e.g. fishery) can be assessed with and without e-flows as a constraint (Mullick, Babel and Perret, 2013) to promote the incorporation of e-flows within a water management plan.

4. Discussion

4.1. Need for clarity of problem definition

Complex environmental water allocation problems can be optimized for a range of regulated system types (e.g. river basins, reservoirs, reaches, hydropower plants) considering conflicting water management objectives (i.e. aquatic ecosystems livelihood and human supply). Overall, the definition of system scales and conceptualization within optimization procedures reflects a well-known problem-oriented perspective on the river system (van den Belt and Blake, 2015; Opperman et al., 2018), intended to meet the functions required for management purposes, and therefore requiring transparent documentation of the management problem.

The availability of optimization models that can be applied simultaneously to multiple scales is still limited. Studies would rather formulate the problem for one target area at a time. Hence, the applicability of an optimization framework is generally only suitable to the specific case study or systems with similar relevant features (e.g. the presence of a hydropower generator) (e.g. Yin, Yang and Liu, 2014). In general, this results in a limited reproducibility of a scale-specific optimization assessment for environmental water management - which could hinder the interpretation of results by decision-makers. This review and the resulting framework therefore highlight the need both for clear problem definition and efforts to develop the tools necessary to address multi-scale problems as defined.

4.2. Need for strategies to implement desired assessment scales

The size (i.e. temporal and spatial scale) of the assessment is intrinsically connected with the range of information needed for the development of the optimization procedure. Optimization of large systems (e.g. basins, transboundary rivers) and long planning horizons (e.g. multi-year planning) requires more complex decision making about suitable options as information could be nested and hence more challenging to obtain. Problems involving larger systems may be divided into smaller components by subdividing the system into shorter timeframes or sub-areas. This operation when possible may reduce both computational and modelling effort. Conversely, smaller systems (e.g. river sections, reaches) modelling require less difficult option selection but could still be as challenging as more demanding solution approaches (e.g. modelling ability) might be needed. However, mismatches between the scales of involved factors (e.g. management scale, hydrological scale) during modelling are frequent as scales are defined based on different needs (i.e. administrative, modelling). Overall, this can compound the difficulty of defining absolute assessment scales because of the many factors involved (see Fig. 3, Section 3). It may be hence more appropriate to speak of the targeted system 'boundaries' rather than scales more generally (van den Belt and Blake, 2015). Moreover, improved knowledge of the system connections (i.e. river system) at the basin scale would also be helpful to better understand the effects of local-scale flow regulation structures. This is especially meaningful if the final aim is to balance water needs as part of a wider system (i.e. basin) (Shiau and Wu, 2013)().

4.3. Need to make explicit trade-offs in model development

Decisions and option selection during optimization problem definition are usually nonlinear with respect to targeted assessment scales, as some trade-offs in data availability and modelling requirements need to be accounted for. This is due to the fact that the relationship between scale and available options is not one-to-one. The development of optimization procedures to solve water management problems requires the simultaneous consideration of multiple factors to representatively recreate the real context or system: the targeted scale from the management perspective (e.g. basin) on which a certain environmental goal applies (e.g. good ecological status); the number of involved infrastructures and their location; the location of gauging and monitoring stations within the management area; and the possibility for the considered system to cross geopolitical borders. Whilst the use of simulation data (e.g. synthetic hydrograph) can address the problem of input hydrological information, the main challenge for model development remains, and revolves around the need to gather sufficient information to be able to represent the targeted system; or, to adapt the assessment scale to the data available (i.e. reducing the problem size into smaller problems or 'nested' systems). Failing to clearly describe the optimization problem context (e.g. physical system, management horizon, and objectives) reduces the understanding of how to represent trade-offs and results in a less transparent treatment of scale, and therefore the ability to model across scales.

4.4. Need for increased modelling capacity

Solving water management optimization problems at different scales presents some challenges in relation to the nature of the decision variables, the increasing number of objectives and the nature of the functions (Reed et al., 2013). Whilst the fact that initial accessible information (i.e. in the problem perception phase) linking flows, infrastructure operations and environmental outcomes "is not readily available in a format suited to optimization" (Horne et al., 2016), a major impediment is represented by limited modelling capacity. When dealing with complex real-world problems this could drive to over-simplification and thus reduced reliability in optimization outcomes. On the one hand, a solution to over-simplification could be the use of more sophisticated algorithms able to deal with a higher number of objectives, as many-objective optimization algorithms are able to deal with up to 15 objectives (Chand and Wagner, 2015), though this would inevitably lead to increase in needed computational effort. On the other hand, consideration of the more appropriate approach (i.e. robust or evolutionary) based on the temporal horizon of the problem (e.g. infrastructure scheduling, management planning) could reduce the overall uncertainty as it would account for the level of decision making incorporation (Grossmann et al., 2016). Lastly, improving the flexibility in optimization problem structure (e.g. by finding a benchmark model structure) to be applicable for different scales (e.g. Shiau and Wu, 2013) could help discover nested trade-offs within the same study system or similar systems thus by fostering comparison.

5. Outlook and recommendations: Using optimization procedures in water management

The need for stating clearer reference boundaries in study descriptions has already been identified by Gleeson and Paszkowski (2014). We consider this even more significant for optimization problems, particularly concerning decision-making transparency throughout model development around the final assessment scales. Clear definition of targeted and modelled spatial and temporal scales within optimization procedures for environmental water allocation could support the identification of potential minimum thresholds (i.e. scale) at which e-flow management should be implemented. However, this process requires an increased understanding of how modelling limitations relate to option selection. We believe that unravelling the relationship between existing options between the problem formulation phase and the modelling phase provides a useful pathway for improving the take-up of results at the right management level and increasing our ability to model across scales. The first step in this process would be clear communication of the optimization problem statement throughout the two phases (see Section 5.1). This may also include discussion of how the problem design can be altered to increase understandability, which can also improve the understanding of system trade-offs (Seppelt, Lautenbach, and Volk, 2013).

5.1. *Towards increased transparency: Recommendations for optimization problem development*

The framework provided in Section 3 mapped the crucial decisions and options related to each phase of model development (the problem perception phase and the problem formulation phase) and the implications for the temporal and spatial scales of each stage. In this section, by building on the aforementioned framework, we propose recommendations for model development under the form of essential questions that need to be addressed. This questionnaire, presented in Table 8, assists system conceptualization and serves to check information availability. By doing so, it supports clarity in problem translation from the problem formulation to the modelling phase.

We believe that making the role of information availability explicit throughout model development will support system understanding and further foster transparency around the trade-off process in model development and system scale representation when defining an optimization model for water management problems.

Table 8
Series of key questions that need to be addressed during optimization model development for water management. The table presents questions for each optimization phase.

Problem perception phase
Physical system
How many flow-altering infrastructures are involved? What is the nature of the flow alteration? What types of operations are performed?
What is the timeframe of the operational scheme?
How frequently does the infrastructure management plan need to be updated?
What is the scale of effect of the flow altering infrastructure operations?
What are the targeted environmental assets? What are the ecological endpoints for the targeted environmental asset? What is the location of the environmental asset and ecological endpoint?
At what scale are the ecological outcomes manifested?
Management objectives & Limiting conditions
What are the management objectives for the considered management horizon?
How are management objectives defined?
What is the temporal scale of the considered objectives?
What are the limiting conditions that characterize my objectives?
What are the bounding conditions that characterize the problem setting (e.g. structural, hydrological)?
What is the temporal dependence of the limiting conditions?
Problem formulation phase
Hydrological state and indicators
What is the source of hydrological information?
What is the temporal resolution of the hydrological information?
What is the location of the gauging stations?
What assessment approach is used to represent the requirements?
What instrument/tool/source of information is used to define the environmental water requirements for the targeted environmental asset? What is its spatial/temporal resolution?
Objective functions, decision variables, and constraint functions
What hydrological metrics are representative of the selected ecological endpoints?
Do the hydrological metrics match the planning horizon?
What and how many decision variables are needed to represent the problem objectives?
How many and what functions are needed to represent the problem objectives and constraints?
What is the nature of the considered decision variables (discrete, continuous)?
Solution methods
What computational/modelling resources are available to handle the selected functions?
What approaches are implemented to reduce computational/modelling effort?
Optimization scenario
How is uncertainty in optimization outcomes addressed?
What is the uncertainty in climatic conditions?
What is the uncertainty in hydrological information used?
What is the uncertainty in the operational horizon?

6. Conclusions

This review paper analysed the implications of decisions and related options throughout the optimization model development stages for the final temporal and spatial scale of the assessment. We first explored the main decisions that have to be made by distinguishing two distinct phases in optimization problem development: problem perception and problem formulation. We found that most decisions have strong links with the spatial and temporal scales of the assessment that need to be accounted for. Successively, we mapped options related to each decision (i.e. related to the physical system, assessment objectives, the hydrological state and indicators, objective and constraint functions, solution methods and, optimization scenario) and provided scale-specific considerations for option selection.

Overall, given that water management problems involve a large number of factors to consider (e.g. operations schemes, supply competition, changing environmental conditions), the decision-making supported by optimization techniques is influenced by a series of challenges related to data availability and modelling capability. This consequently affects decision making about options, which resolves in tailoring the optimization model to the available data and modelling ability, retrieving additional data required or subdividing the problem. Further research focused on clarifying the underlying influences between options concerning scale would provide an enhanced insight into the relationship between options and improve the process of option selection. Besides, it would enable the integration of instruments that can improve reliability and comparability in optimization outcomes. Moreover, while exploring how trade-offs across scales are incorporated into the optimization process is more challenging for the application of optimization algorithms; it is also potentially most useful to an environmental water manager. As a foundation for these goals, we provided recommendations for model development by focusing on key questions related to each decision, with the intent of fostering transparency around decision making and options selection during both problem development phases.

Declaration of competing interest

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

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Annex.

Table A1

Summary of reviewed studies. Legend: / = no info, MP = mathematical programming, S = stochastic, MAG-d = magnitude of daily and sub-daily flows, MAG-m = magnitude of monthly and yearly flows, MAG/DUR-ext = magnitude and duration of extreme water conditions, FREQ/DUR-pulses = frequency and duration of high and low pulses, TIM = Timing of annual extreme water conditions, NH = non-hydrologic indicator, G = graph, T = table, DF = designer flows, PF=Pareto front. [Continuing on the next pages]

Reference	Study system location	Management purpose	Targeted scale		Planning period	Solution method	Hydrological indicators	Objectives		Constraints	Trade-offs	Scenarios
			Spatial	Temporal				≤3	≥4			
Arslan (2015)	Aksu River Basin (Turkey)	energy production, ecological health	River	Sub-daily	/	MP-based	MAG-m	•		physical-environmental, infrastructure-related, supply-related, ecological	/	x
Chen and Olden (2017)	San Juan River, (Colorado River tributary, US)	disturbance reduction, ecological health	River section	Seasonal	3-year plan	MP-based	MAG-d	•		physical-environmental, infrastructure-related, supply-related	G	x
Dai et al. (2017)	Three Gorges-Gezhouba reservoirs, Yangtze River (China)	energy production, ecological health	Multi-Reservoir	Seasonal	/	S	MAG-d	•		physical-environmental, infrastructure-related	G	x
Fallah-Mehdipour, Bozorg-Haddad and Loáiciga (2018)	Karoon IV dam on Karoon River (Iran)	energy production, ecological health	Reservoir	Daily	/	MP-based/S	/	•		physical-environmental, infrastructure-related	G	/
Fleifle et al. (2014)	El-Qalaa River, Nile River (Egypt)	functional purpose, ecological health	Sub-basin	Seasonal	/	S	NH	•		physical-environmental, supply-related, ecological	G	/
Torabi Haghighi and Kløve (2015)	Bakhtegan catchment (Iran)	disturbance reduction	River basin	Monthly	Intra-annual	MP-based	MAG-m	•		supply-related, ecological	G	x
Hassanjabbar, Saghafian and Jamali (2018)	Karkheh Basin (Iran, Iraq border)	energy production, disturbance reduction	Multi-reservoir	Monthly	Annual	S	MAG-d, MAG/DUR-ext, FREQ/DUR-pulses	•		physical-environmental, infrastructure-related, supply-related	/	x
Lewis and Randall (2017)	Murrumbidgee River Irrigation Area (Australia)	functional purpose, ecological health	River basin	Monthly	Annual	S	MAG-m	•		physical-environmental, infrastructure-related, supply-related, ecological	G	X
Martin et al. (2017)	Goulburn-Broken River catchment (Murray–Darling Basin, Australia)	functional purpose	Sub-basin	Daily	/	S	MAG-m			/	G	/
Mullick, Babel and Perret (2013)	Teesta River (Bangladesh)	functional purpose	River section	Monthly	Annual	MP-based	MAG-m		•	physical-environmental, ecological	T	x
Paredes-Arquiola et al. (2013)	Duero River basin (Spain)	consumptive use, ecological health	River Basin	Monthly	Annual	/	MAG-m		•	supply-related	G	/

(continued on next page)

Table A1 (*continued*)

Reference	Study system location	Management purpose	Targeted scale		Planning period	Solution method	Hydrological indicators	Objectives		Constraints	Trade-offs	Scenarios
			Spatial	Temporal				≤3	≥4			
Porse, Sandoval-Solis and Lane (2015)	Luis L. Leon reservoir, Big Bend region of the Rio Grande/Bravo (Mexico-US)	ecological health	Reservoir	Monthly	/	MP-based	MAG-d, MAG-m, FREQ/DUR-pulses		•	physical-environmental, infrastructure-related, supply-related	DF	/
Schlüter et al. (2005)	Amudarya River Basin (Central Asia)	consumptive use, disturbance reduction	Multi-reach	Monthly	Annual	MP-based	MAG-m			physical-environmental, infrastructure-related, supply-related, ecological	/	x
Shang (2015)	Ertix River/Ebinur Lake (Xinjiang, China)	consumptive use, ecological health	River section/ Lake	Monthly	/	MP-based	MAG-m		•	infrastructure-related	G	/
Shiau and Chou (2016)	Hsintien Creek (Taiwan)	consumptive use, energy production, safety, disturbance reduction	River basin	Daily	/	S	MAG-m, MAG/DUR-ext, NH			physical-environmental, infrastructure-related	T	x
Shiau and Wu (2013)	Feitsui Reservoir (Taiwan)	consumptive use, energy production, safety, disturbance reduction	Multi-reach/ Multi-reservoir	Sub-daily	Annual/ Multi-annual	S	MAG-d, MAG/DUR-ext, RAT/FREQ-change			physical-environmental, infrastructure-related	G	x
Szemis et al. (2012)	Murray-Darling River (Australia)	/	Reservoir	Monthly	Multi-annual	S	MAG-d, FREQ/DUR-pulses		•	physical-environmental, infrastructure-related	DF	x
Szemis et al. (2013)	Murray-Darling River (Australia)	/	Reservoir	Monthly	Multi-annual	S	MAG-d, FREQ/DUR-pulses		•	physical-environmental, infrastructure-related	DF	x
Szemis et al. (2014)	Murray-Darling River (Australia)	/	Reservoir	Monthly	Multi-annual	S	MAG-d, FREQ/DUR-pulses		•	physical-environmental, infrastructure-related	DF	x
Steinschneider et al. (2014)	Connecticut River (New England, US)	disturbance reduction	River basin	Daily	Annual	MP-based	MAG-d, MAG-m		•	physical-environmental, infrastructure-related, supply-related, ecological	PF	x
Suen and Eheart (2006)	Dahan River Basin (Taiwan)	consumptive use, energy production, ecological health	River basin	Monthly	/	S	FREQ/DUR-pulses, TIM-ext		•	physical-environmental, infrastructure-related	PF	/
Wang et al. (2015)	Philpott dam on Smith River (US)	consumptive use, energy production, disturbance reduction	Reservoir	Daily	Monthly	MP-based	MAG-m, MAG/DUR-ext		•	physical-environmental, infrastructure-related, supply-related, process-based	G	x
Xevi and Khan (2005)	Berembed Weir, Murrumbidgee River (Australia)	consumptive use	Multi-reach	Monthly	Seasonal	MP-based	MAG-m		•	physical-environmental, infrastructure-related, ecological	T	x
Xu et al. (2017)	Han River, Yangtze River tributary (China)	consumptive use, energy production, disturbance reduction, ecological health	River	Daily	/	S	NH			physical-environmental, infrastructure-related, supply-related, ecological	DF	/
Yin, Yang and Petts (2012)	Tanghe Reservoir on the Tang River (China)	disturbance reduction	Reservoir	Daily	Annual	S	MAG-d, FREQ/DUR-pulses,		•	physical-environmental, supply-related	DF	/

(*continued on next page*)

Table A1 (*continued*)

Reference	Study system location	Management purpose	Targeted scale		Planning period	Solution method	Hydrological indicators	Objectives		Constraints	Trade-offs	Scenarios
			Spatial	Temporal				≤3	≥4			
							RAT/FREQ-change					
Yin, Yang and Liu (2014)	Wangkuai Reservoir (Hai River basin, China)	disturbance reduction	Reservoir	Monthly	Annual	S	MAG-d, FREQ/DUR-pulses		•	physical-environmental, infrastructure-related, supply-related, process-based	DF	x
Yin et al. (2015)	Wangkuai Reservoir, Hai River basin (China)	energy production	Reservoir	Monthly	Annual	S	MAG-d		•	infrastructure-related, supply-related, ecological	G, T	/

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