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# Managing hydroclimatic risks in federal rivers: a diagnostic assessment

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Hydroclimatic risks and adaptive capacity are not distributed evenly in large river basins of federal countries, where authority is divided across national and territorial governments. Transboundary river basins are a major test of federal systems of governance because key management roles exist at all levels. This paper examines the evolution and design of interstate water allocation institutions in semi-arid federal rivers prone to drought extremes, climatic variability and intensified competition for scarce water. We conceptualize, categorize and compare federal rivers as social–ecological systems to analyse the relationship between governance arrangements and hydroclimatic risks. A diagnostic approach is used to map over 300 federal rivers and classify the

hydroclimatic risks of three semi-arid federal rivers with a long history of interstate allocation tensions: the Colorado River (USA/Mexico), Ebro River (Spain) and Murray–Darling River (Australia). Case studies review the evolution and design of water allocation institutions. Three institutional design trends have emerged: adoption of proportional interstate allocation rules; emergence of multi-layered river basin governance arrangements for planning, conflict resolution and joint monitoring; and new flexibility to adjust historic allocation patterns. Proportional allocation rules apportion water between states based on a share of available water, not a fixed volume or priority. Interstate allocation reform efforts in the Colorado and Murray–Darling rivers indicate that proportional allocation rules are prevalent for upstream states, while downstream states seek reliable deliveries of fixed volumes to increase water security. River basin governance arrangements establish new venues for multilayered planning, monitoring and conflict resolution to balance self governance by users and states with basin-wide coordination. Flexibility to adjust historic allocation agreements, without risk of defection or costly court action, also provides adaptive capacity to manage climatic variability and shifting values. Future research should develop evidence about pathways to adaptive capacity in different classes of federal rivers, while acknowledging limits to transferability and the need for context-sensitive design.

# 1. Introduction

## (a) The importance of federal rivers

Major river basins in federal countries are a unique form of transboundary river with authority divided between national and territorial governments. Federal rivers are basins within or shared by one of the world's 28 federal countries,[1] which encompass over 40% of global population [1]. Transboundary river basins are a major test of federal systems of governance. Effective management is not the mandate of one level of governance: all levels of governance have key roles. As a consequence, federal rivers face constraints on risk sharing and conflict resolution despite constitutional provisions to coordinate power sharing and manage interjurisdictional disputes.

Federalism has increasing influence on river basin management across diverse geographical and political economic contexts, ranging from Australia and the USA to India and Iraq. However, prior research about global change in federal rivers has focused on individual basins and countries, or small *N* comparisons (with three or fewer case studies; [3,4] but see [5,6]). Federal rivers lie at the intersection of two traditions of research on collective action in the water commons—one focused on user self-organization and the other on the geopolitics of international rivers. The coordination of local and multi-level collective action in water management has become more important in a context of global change and intensified competition for water [7]. Local dilemmas are increasingly difficult to insulate from global change, and subnational water conflicts are an increasing share of water disputes [8]. Multi-level water governance dilemmas are particularly challenging in semi-arid regions vulnerable to climate variability and change; the distribution of benefits and risks for shared waters in such settings is already the source of tensions between upstream and downstream sub-national jurisdictions [5–7].

In this paper, we conceptualize federal rivers as social–ecological systems (SESs) and conduct a multi-level diagnostic assessment to address: what is the nature of climate risk in federal rivers, and which types of climate risks distinguish semi-arid federal rivers? How do these risks interact with other characteristics of the resource system and socio-political, economic and ecological settings? Under which conditions and contexts have interstate water allocation institutions enhanced robustness to climate variability and competition? The robustness of semi-arid federal

[1]Federal political systems are defined as 'self-rule plus shared-rule' with powers and functions distributed by constitutional provisions across multiple levels of governance at the state and national levels, which are formally autonomous [2] (see §3).

rivers to climate risks and allocation conflicts is expected to increase when benefits and risks of water allocation are distributed proportionally (i.e. as a share of the total, rather than a fixed amount). Robust interstate water allocation institutions balance self-governance and multi-jurisdictional coordination to ensure accountability to local and basin-wide interests [5,9,10].[2]

### (b) Problem statement and objectives

The core contribution of this paper is a multi-level diagnostic assessment that uses an SES framework to conceptualize, categorize and compare semi-arid federal rivers in terms of their climatic risks and institutional responses. The assessment is used to (i) conceptualize federal rivers as SESs, and (ii) diagnose the common climatic risks for semi-arid river basins with 'difficult hydrology'—a set of hydroclimatic risks defined by low runoff, high climate variability and exposure to extreme climate events [9]. A comparative analysis of three semi-arid federal rivers examines the evolution of interstate water allocation policy to manage past, current and projected climate risks. This analysis explores empirical evidence for a set of propositions about institutional design principles posited to enhance robustness to climate risks in large river basins. The goal is to deliver a reference document to motivate comparative research and lessons for theory and practice of large-scale collective action in the water commons.

### (c) Paper organization

Section 2 characterizes federal rivers as SESs and uses collective action theory to elaborate theoretical propositions about key subsystem attributes and the interactions and outcomes of climate risks and interstate allocation responses. Section 3 maps the global extent of federalism in major river basins to establish a typology of federal rivers using datasets on political and hydrological boundaries. Section 4 characterizes climate risks globally and plots three semi-arid river basins within this global distribution to define a common set of challenges associated with difficulty hydrology in semi-arid federal rivers. Case studies (§5) examine the design and evolution of multi-jurisdictional water allocation to share hydroclimatic risks tied to scarcity, competition and drought in the three semi-arid federal river basins: the Murray–Darling (Australia), Ebro (Spain) and Colorado rivers (USA and Mexico). The case studies emphasize the initial design and subsequent institutional changes to the (i) water rights systems, interstate allocation and drought risk sharing, and (ii) river basin organizations for planning, joint monitoring and conflict resolution. Section 6 provides concluding remarks and directions for future research.

## 2. Federal river basins as social–ecological systems

Complex contemporary environmental management challenges highlight the interdependency of humans and the environment. An SES framework has been developed to analyse and understand complex structures, patterns and outcomes of human–environment interactions across multiple disciplinary and theoretical traditions. An SES framework represents SESs as decomposable into four subsystems—resource system, resource units, governance system and resource users/actors—'in which *resource users* extract *resource units* from a *resource system*' and maintain that system 'according to rules and procedures determined by an overarching *governance system*, and in the context of related *ecological systems* and broader *social-political-economic* settings' (figure 1 [11, p. 7]).[3] Application of the SES framework to large rivers has been rare until the last

[2]Robustness and related resilience and vulnerability concepts are subject to a sprawling literature (e.g. [10]). We focus on robustness as the 'capacity of a system to continue to function given external shocks' [10, pg. 14]. Robustness is distinguished from resilience by its focus on relatively shorter time scales and designed systems [10, pg. 14] (the focus on designed systems applies to constitutionally designed political systems and many of the river basin institutions established in such systems).

[3]The italicized words refer to subsystems (resource system, resource units, users/actors and governance system), linkages (interactions and outcomes) and settings (social–political–economic and ecological settings). The users' subsystem has been updated to 'actors' to capture the broader range of participants in collective action dilemmas within SESs. See ref. [11].

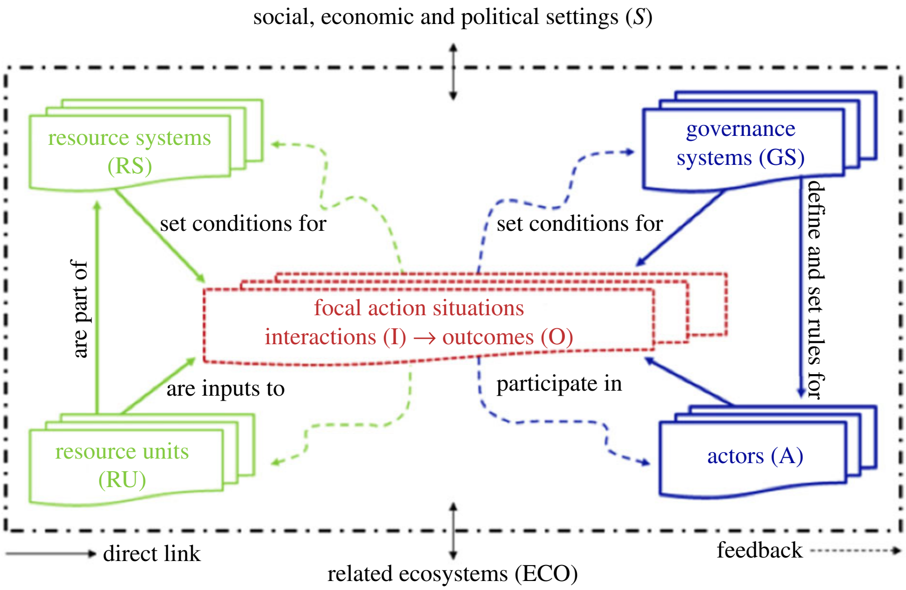


**Figure 1.** SES framework. (Adapted from [11].)

decade (e.g. [12]) and has never been applied to federal rivers despite the potential benefits of such a systematic and interdisciplinary approach. This research therefore conceptualizes federal rivers as SESs and diagnostically assesses the challenges of climate risk and interstate water allocation in semi-arid rivers.

## (a) Managing contested water commons in the twenty-first century

Water allocation in federal rivers is an example of a collective action dilemma to share risks and benefits from large-scale common pool resources (CPRs): resources defined by costly exclusion and risk of collapse due to overextraction. A large body of interdisciplinary research advanced by Elinor Ostrom and colleagues has investigated characteristics of actors, institutions and the environment contributing to sustainable self-governance of CPRs (see [13]). Efforts to cope with complex human–environment interactions in the water commons initially triggered simplified institutional prescriptions of public, private or common property rights to manage shared water resources (following [14–17]). Empirical studies focused on small-scale CPRs before addressing more complex and large-scale CPRs, such as river basins. Some of the institutional design principles and explanatory factors associated with effective collective action for small-scale commons may be scalable for larger systems. However, Ostrom *et al.* [18] identify several new challenges for large-scale commons, several of which apply to large multi-jurisdictional river basins, including:

- scaling up problem. Higher numbers of participants raise the costs of organization, rule development and enforcement;
- interlinked CPRs. Interactions between systems (e.g. climate and water in this instance) are complex and therefore more difficult to manage; and
- unanimity requirements. Decision-rules requiring unanimity (which are prevalent in transboundary and interstate river sharing agreements) empower governments to behave opportunistically by holding out to seek rents that undermine performance and sustainability of the SES.

To define federal rivers as an SES involves multiple layers of detail. The *first* level of the SES defines the subsystems: resource, resource units, governance and actors (figure 1). Each

**Table 1.** Second-level attributes of SES (adapted from [11,19]). This identifies selected second-level attributes of each subsystem of the SES. The theoretical propositions from literatures on water security (§2*c*(i)) and institutional fit (§2*c*(ii)) were used to identify focal attributes for this study. Examples of selected attributes are defined in additional detail (italicized) to illustrate variables or characteristics related to climate risk and interstate water allocation, although this list is meant as illustrative and not exhaustive. This illustration follows the example from [14].

| | | | |
|---|---|---|---|
| social, economic, and political settings (S) | | | |
| S1, economic development; S2, demographic trends; S3, political stability; | | | |
| S4, government resource policies; S5, market incentives; S6, media organization | | | |
| resource systems | | governance systems | |
| RS1 | sector: *water* | GS1 | policy area: *interstate water allocation* |
| RS2 | clarity of system boundaries: *river basin; alignment of political and basin boundaries* | GS2 | geographical scale of governance system: *nested* (*river basin*) *arrangements* |
| RS3 | size of resource system: *discharge area* | GS3 | population |
| RS4 | human-constructed facilities: *dams, canals and distribution* | GS4 | regime type: *federal versus unitary* |
| RS5 | productivity of system: *runoff* | GS5 | rule-making organizations: *users associations, state and federal agencies, river basin authorities* |
| RS6 | equilibrium properties: *coefficient of variation for mean annual runoff* | GS6 | rules-in-use: *allocation and monitoring* |
| RS7 | predictability of system dynamics: *uncertainty of future runoff and climate variability* | GS7 | property rights systems: *fixed versus proportional* |
| RS8 | storage characteristics: *reservoir capacity* | GS8 | repertoire of norms and strategies |
| RS9 | location | GS9 | network structure |
| | | GS10 | historical continuity: *adaptive capacity of interstate water agreements* |
| resource units | | actors | |
| RU1 | resource unit mobility | A1 | number of relevant actors: *state governments and water-related agencies* |
| RU2 | growth or replacement rate | A2 | socioeconomic attributes of actors |
| RU3 | interaction among resource units | A3 | history of use |
| RU4 | economic value: *productivity of water, including scarcity value* | A4 | location: *upstream versus downstream* |

(*Continued*.)

**Table 1.** (*Continued.*)

| resource units | | actors | |
|---|---|---|---|
| RU5 | number of units | A5 | leadership/entrepreneurship |
| RU6 | distinctive markings | A6 | norms (trust-reciprocity)/social capital |
| RU7 | spatial and temporal distribution: *upstream–downstream asymmetries* | A7 | knowledge of SES/mental models |
| | | A8 | importance of resource (dependence): *irrigation activity* |
| | | A9 | technology used |
| **action situations: interactions (I) and outcomes (O)** | | | |
| I1 | harvesting levels: *appropriation; river basin closure* | O1 | social performance measures: *e.g. robustness* |
| I2 | information sharing: *environmental assessments* | O2 | ecological performance measures: *e.g. outflows to the sea* |
| I3 | deliberation processes: *river basin planning* | O3 | externalities to other SESs |
| I4 | conflicts: *allocation disputes* | | |
| I5 | investment activities: *federal–state spending* | | |
| I6 | lobbying activities | | |
| I7 | self-organizing activities | | |
| I8 | networking activities | | |
| I9 | monitoring activities: *joint monitoring* | | |
| **related ecosystems** | | | |
| ECO1, climate patterns; ECO2, pollution patterns; ECO3, flows into and out of focal SES. | | | |

subsystem has multiple second-level attributes (table 1). Some second-level attributes can be specified across additional layers of detail. Theory is needed to elaborate the relevant attributes and associated empirical measures in any given context. Attributes can be measured empirically through quantitative, qualitative and/or geospatial techniques at varying levels of measurement (e.g. nominal to ratio).

## (b) Diagnostic analysis of federal rivers as social–ecological systems

The development of frameworks to analyse SESs has coincided with diagnosis of governance dilemmas to identify solutions well matched to the nature of the problem. Diagnostic assessment of climate risks in federal rivers requires progressively more specific questions to understand the nature of interstate water allocation challenges. Cox [17] identifies three objectives of diagnosis: (i) to clarify causal factors explaining outcomes in a given case, (ii) to compare the specific case to others to support theory-building or cross-case generalizations, and (iii) to articulate propositions and predictions based on the accumulated knowledge and evidence to structure future research. Diagnosis is therefore a reference point to structure comparative analysis for systems, such as federal rivers, characterized by complexity and diversity [20]. Diagnostic assessment must be grounded in theory and empirical evidence to avoid a 'checklist' approach that strips away complexity and creates 'blind spots' [20].[4]

Federalism affects major river basins across diverse contexts in which the climate risks, environmental conditions and political economic challenges vary greatly. The SES framework allows for diagnostic assessment of causal dynamics and patterns of interactions between allocation institutions (governance systems) and hydroclimatic regimes (resource system) in large river basins (following [17,19,21–23]). This classification process can be used to better understand the interstate water allocation institutions appropriate for different combinations of climatic and non-climate risk factors. The diagnostic assessment is used to investigate the interaction between difficult hydrology and jurisdictional complexity in a subset of the world's federal rivers, namely semi-arid regions of federal countries with high levels of infrastructure and institutional investment to manage climatic risks and competition between sub-national jurisdictions.

## (c) Theory and evidence: propositions, focal attributes and interactions

A river basin SES is too large and complex to assess system-wide patterns and behaviour comprehensively across all subsystems and their major attributes (table 1). Theory and evidence can be used to generate propositions about the relevant attributes of the resource system, actors, governance arrangements and their interactions in a river basin SES in relation to a particular outcome (e.g. the adaptive capacity or robustness of the interstate allocation institutions to hydroclimatic risks). In her 2009 illustration of the SES framework, for example, Ostrom [19] identifies 10 second-level attributes linked to the likelihood of user self-organization to manage commons dilemmas. She marked these focal attributes and interactions with asterisks in a system-wide mapping of potential second-level attributes. Meinzen-Dick [14] used the framework to investigate irrigation institutions and provided one of the first empirical applications of the diagnostic approach to water resources.

In federal rivers, we examine the role of *cross-scale institutional linkages* in interstate water allocation institutions used to manage hydroclimate risks (resource system) in a context of jurisdictional complexity (governance system). Cross-scale institutional linkages refer to connections between 'two or more actors or collective bodies established through institutions that create functional interdependencies between them' [6, p. 122]. We posit that institutional linkages in interstate allocation must share benefits and risks proportionally to achieve better social and ecological outcomes, although a full treatment of SES performance outcomes is beyond the scope of this study. Instead, we diagnose the common challenges facing

[4]For example, the politics and political economy of interstate allocation are important influences on conflict and cooperation in the management of climate risks that may be underemphasized in SES analysis.

**Table 2.** Proposition and second-level attributes: water security.

| | water security and climate adaptation (difficult hydrology) | |
|---|---|---|
| | proposition | second-level attributes |
| 1 | highly variable, large semi-arid federal rivers require (comparably) high levels of infrastructure and institutional development to create and share benefits and to achieve tolerable levels of hydroclimatic risk [9] | RS3 (size)<br>RS4/8 (human-constructed facilities/ storage characteristics)<br>RS5 (productivity)<br>RS6 (equilibrium properties)<br>RS7 (predictability of system dynamics)<br>RU7 (spatial/temporal distribution)<br>A8 (resource dependence)<br>I1 (harvesting levels) |

semi-arid federal rivers to identify potential institutional design attributes contributing to SES robustness.

Theoretical propositions are derived from two bodies of literature compatible with a coupled SES framework: (i) water security and climate adaptation (coping with 'difficult hydrology') and (ii) institutional fit in large-scale CPR governance (jurisdictional complexity in federal political systems). These two streams of literature identify relevant second-level attributes and interactions between difficulty hydrology and jurisdictional complexity. These propositions identify the subsystems, key attributes, interactions and relevant outcomes of interstate water allocation to share climate risks.

### (i) Water security: difficult hydrology and hydroclimatic risk

*Water security* is defined as sufficient availability of water for productive uses coupled with sufficient protection against water-related risks [9]. Grey *et al.* [24] refine this definition and refer to water security as a tolerable level of water-related risk to society, noting that water security risks have expanded from local risks experienced by users and communities to include river basin and global level challenges. Grey & Sadoff [9] argue that water security becomes more difficult to achieve for 'difficult hydrology': high levels of intra-annual and interannual variability mark the most difficult hydrology, and therefore necessitate the highest 'level of institutional refinement and infrastructure investment' (p. 549). Polycentric, multi-layered governance arrangements are posited to contribute such institutional capacity and enhance robustness to climate risks under certain conditions, particularly by ensuring rules are matched to local conditions and reducing vulnerability to the spread of local failures throughout the river basin [25,26]. Owing to the challenges of scaling up collective action noted above, the management of climate risk in larger multi-scale systems may require nested enterprises to allow for the decomposition of problems into smaller scale dilemmas [27,28]. In such settings, cross-scale institutional linkages are needed to supplement self-organization to build capacity, address spillovers and coordinate across levels [6].

As shown in table 2, managing water security risks in a context of difficult hydrology requires attention to a set of *resource system* attributes to define hydroclimatic risk in large river basins based on the area (RS3), reservoir storage (RS4/8), runoff (RS5), climatic variability and extremes (RS6–7). In the *resource unit* subsystem, the spatial and temporal distribution (RU7) of streamflows and storage is the primary focus to characterize potential upstream/downstream asymmetries underpinning tensions over interstate water allocation and harvesting levels (I1) in regions with high water resource dependence (A8).

**Table 3.** Propositions and second-level attributes: institutional fit in large-scale CPRs (federalism and jurisdictional complexity).

| institutional fit in large-scale CPRs | | |
|---|---|---|
| | proposition | second-level attributes |
| 2 | jurisdictional complexity elevates the risk that constituent governments will behave opportunistically based on narrow upstream and downstream positions | RS2 (clarity of system boundaries)<br>GS2 (geographical scale of governance)<br>GS4 (regime type)<br>A1 (number of relevant actors) |
| 3 | interstate allocation rules that divide water rights in terms of shares of available supplies share risks better than allocation rules assigning a fixed volume or priority [4,33] | GS1 (policy area)<br>GS6 (rules-in-use)<br>GS7 (property rights system)<br>I4 (conflicts) |
| 4 | outcomes of interstate allocation improve with multi-level decision-making venues, monitoring, planning and conflict management to address extended droughts and overallocation | GS5 (rule-making organizations)<br>GS6 (rules-in-use)<br>GS7 (property rights system)<br>GS10 (historical continuity)<br>I3 (deliberation processes)<br>I4 (conflicts)<br>O1 (social performance)<br>O2 (ecological performance) |

### (ii) Federalism and jurisdictional complexity: the importance of institutional fit and cross-scale linkages

Federal rivers are defined by their *jurisdictional complexity* [5] (see §3 below). Jurisdictional boundaries have been devised for a range of purposes, including democratic legitimacy, accountability and the provision of other public services, and therefore are often poorly aligned with the dimensions of environmental management challenges. These mismatches create challenges of institutional fit [12,29,30]. The performance of interstate water allocation institutions therefore 'depends on how well the rules are matched to the biophysical and social setting' [5, p. 462]. Resource boundaries and political jurisdictions diverge in federal political systems due the separation of powers and functions across levels of government; multi-jurisdictional issues become classic tests for power sharing and coordination between jurisdictions and actors within (horizontally) and across levels of government (vertically).

In this context, interstate water allocation rules are expected to perform best when hydroclimatic risks are shared proportionally by jurisdictions and perceived as fair. The national government plays a complementary role to users associations, states and interstate bodies to ensure the alignment of rules, monitoring and conflict resolution across levels of governance [5]. Ostrom [16] identified the need for 'governance activities to be organized in multiple layers of nested enterprises' (nesting principle, cf. [31]). This presents an example of the problem of institutional fit between governance and resource systems [21,22,32]. Young [21,22] has addressed the problem of fit and used diagnostic analysis to identify sources of and responses to misfits, leading to recent efforts to formalize theories of fit [30].

The interplay of hydroclimate risk and jurisdictional complexity elevates the importance of cross-scale institutional linkages that strengthen institutional fit and limit the consequences (e.g. conflict, overharvesting) stemming from misfits. Heikkila *et al.* [6] advance theoretical and empirical understanding of *cross-scale institutional linkages* for interstate water (allocation) compacts of the Western USA. In this context, Schlager & Heikkila [5] operationalize Ostrom's

**Table 4.** Multilevel characterization of federal rivers: second-level attributes of subsystems. Second-level attributes use the attribute numbering scheme updated in McGinnis & Ostrom [11]. MacPDM, global hydrology model, following [34]; GRanD, global reservoir and dam database [35]; GADM, global administrative areas database; CIESIN, Centre for International Earth Science Information Network; FAO, global map of irrigated areas [36]. Global Runoff Data Centre (GRDC) [37]; Transboundary Freshwater Dispute Database (TFDD); Forum of Federations, list of federal countries. Unlicensed data and metadata are accessible online at the Federal Rivers research hub website, contact corresponding author for access. References provided for all data sources contain metadata and technical guidance describing data coverage, quality and uncertainty.

| subsystem (paper section) | attribute | characteristic or variable | data source (units) |
|---|---|---|---|
| (*a*) multi-level characterization of federal rivers: selected attributes of the resource and resource unit subsystem | | | |
| resource system (§§3 and 4) | clarity of system boundaries (RS2) | alignment of political and river basin boundaries | TFDD; GRDC; GADM (basins and basin-country units) |
| | Size (RS3) | area of basins and basin-country units | MacPDM ($km^2$) |
| | human-constructed facilities/storage characteristics (RS4/8) | reservoir storage, representative maximum capacity | GRanD (million $m^3$) |
| | productivity of the system (RS5) | mean annual runoff | MacPDM (mm) |
| | equilibrium properties (RS6) | coefficient of variation, mean annual runoff | MacPDM (n.a) |
| | predictability of system dynamics (RS7) | projected percentage change in mean annual runoff, 2050 | MacPDM (%) |
| | | uncertainty about projected change in mean annual runoff, range between 10th and 90th percentile projection, 2050 | |
| resource units (§4) | spatial and temporal distribution (RU7) | basin-state mean annual runoff | MacPDM (mm) |
| (*b*) multi-level characterization of federal rivers: selected attributes of the governance subsystem | | | |
| governance system (§5) | policy area (GS1) | interstate water allocation | n.a |
| | geographical scale of governance system (GS2) | nested river basin arrangements | n.a |
| | regime type (GS4) | federal versus unitary | forum of federations |
| | rule-making organizations (GS5) | interstate organization and/or river basin organization | case study discussion |
| | rules-in-use (GS6) | allocation rules | case study discussion |
| | property rights systems (GS7) | drought sharing rule | |
| | | decision-making rules for interstate conflict resolution, planning and monitoring | |

(*Continued*.)

**Table 4.** (*Continued*.)

| subsystem (paper section) | attribute | characteristic or variable | data source (units) |
|---|---|---|---|
| | historical continuity (GS10) | adaptive capacity of interstate water agreements, including flexibility to adjust historic apportionment decisions | case study discussion |
| (*c*) multi-level characterization of federal rivers: selected attributes of the actors subsystem | | | |
| actors (§§3 and 5) | number of actors (A1) | number of states | GADM |
| | | number of regulatory agencies with jurisdiction over water | see case study |
| | socio-economic attributes of users (A2) | GDP *per capita* (national) | World Bank (2011 USD/person) |
| | location (A4) | upstream–downstream states | GADM |
| | resource dependence (A8) | irrigation acreage as a percentage of basin area | FAO |
| | resource dependence (A8) | population density (2010) | CIESIN (persons per $km^2$) |
| (*d*) multi-level characterization of federal rivers: selected attributes of the interactions and outcomes | | | |
| interactions (§5) | harvesting levels (I1) | river basin closure (downstream deliveries)<br>overallocation | case study discussion |
| | information sharing (I2) | environmental impact assessments<br>joint monitoring | case study discussion |
| | deliberation processes (I3) | river basin planning activities | case study discussion |
| | conflicts (I4) | administrative hearings<br>court cases | case study discussion |
| outcomes (§5) | social performance measures (O1) | robustness (economic productivity over time)<br>equitable trade-offs (perceived fairness of cross-sectoral and interstate allocation decisions) | case study discussion |
| | ecological performance measures (O2) | outflows to the delta/mouth | case study discussion |
| | externalities to other SESs (O3) | effects on land use and biodiversity | case study discussion |

nesting principle about the design of layered, multi-level CPR institutions and property rights in three categories: (i) allocation rules, (ii) scope rules, and (iii) aggregation rules (decision venue). Allocation rules affect access, use, withdrawal and decision-making. Scope rules refer to the functional scope and range of outcomes affected by the rule (e.g. whether drought contingencies have been addressed), and aggregation rules determine how the interests of multiple, diverse stakeholders are coordinated and translated into a decision (e.g. voting, unanimity, consensus, multi-level consultation, etc.). They elaborate propositions about the type and quality of cross-scale institutional linkages to govern climatic variability in the Western USA, which we extended here for other large semi-arid federal rivers.

As shown in table 3, institutional fit in large-scale common pool water resources requires attention to the design and evolution of the governance system. The *governance system* is therefore defined in relation to interstate water allocation as the focal policy domain (GS1). The design attributes of interstate water allocation institutions include the geographical scale(s) of nested river basin governance arrangements (GS2), federal versus unitary type of governance regime (GS4), rule-making organizations, including the design and functions of river basin organizations (GS5), rules-in-use for multi-level river basin planning (GS6), property rights systems for interstate allocation (GS7) and historic continuity, or path dependency, of prior interstate water allocation decisions (GS10). The *actors* within this subsystem include a range of stakeholders; however, state jurisdictions (A1) are the primary focus for interstate water allocation, their upstream versus downstream location (A4) and, in semi-arid environments, their irrigation dependence (A8). The interactions of social and ecological subsystems include water diversions (I1), information sharing (I2), deliberation in river basin planning (I3) and allocation conflicts (I4) that affect the robustness to historic, current and future climate risks (O1) and downstream consequences of overallocation (O2).

#### (iii) Characterization of second-level attributes

Table 4 presents the subsystems, second-level attributes and selected metrics used to characterize and assess hydroclimatic risk and institutional response in federal rivers SES based on the propositions presented in the sections above.

## 3. Categorizing federal rivers as social–ecological systems

### (a) Extent and types of federal river basins

*What are the global extent and major types of federal river basins?* Federal rivers are defined as major river basins within or shared by a federal country. Mapping federal rivers requires the coupling of social and hydrological dimensions: federal regime types (GS4) and 'major' river basins (RS2–3). The starting point is a list of federal countries. Elazer [2] identifies three defining elements of federal systems: a written constitution, non-centralization and a territorial division of power (p. 157). Even unitary regimes have elements of decentralization and devolution, which makes the distinction between federalism and unitary systems a continuum. Bednar [38] defines federalism in terms of a geopolitical division of jurisdictional boundaries, distribution of authority between independent state and national governments, and capacity of each government to make binding laws for citizens falling within its jurisdiction. Beyond these defining elements, federal countries vary along a range of attributes, such as the degree of decentralization, fiscal policy and age of the first federal constitution (and hence evolution of state–federal relationships), along with other geographical and economic characteristics. The *Forum of Federations* identifies 25 federal countries and two countries (Sudan and Iraq) in transition to federalism. South Sudan became the 28th federal country in July 2011.

The spatial boundaries of major river basins are derived from two partially overlapping global datasets. The Global Runoff Data Centre (GRDC) [37] mapped the major river basin boundaries of the world, yielding 405 river basin polygons of which 278 are contained wholly within a single

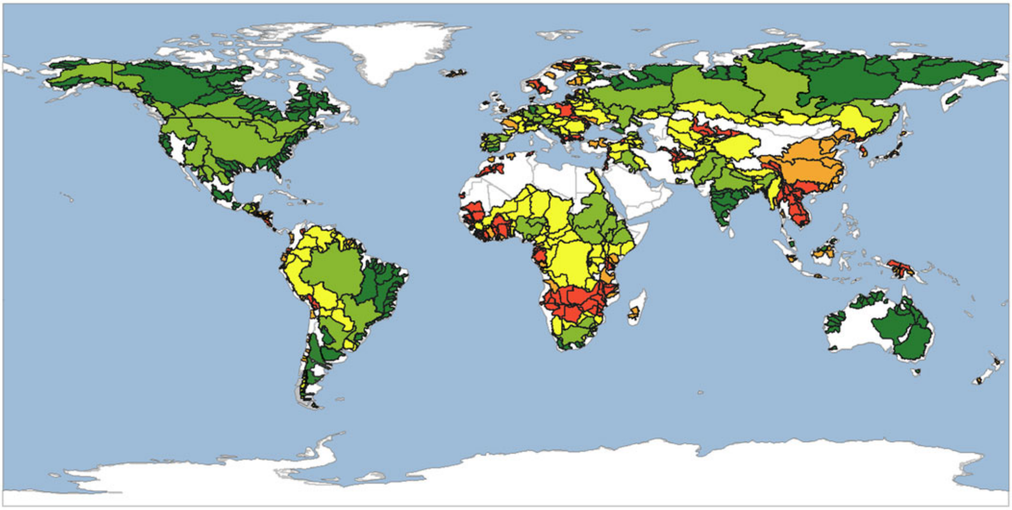

**Figure 2.** Federal rivers. Dark green refers to domestic rivers falling within a single federal country (*domestic federal rivers*). Light green refers to the federal portion (basin-country unit) of a river shared by two or more countries that include at least one federal country (*international federal rivers*). Yellow refers to non-federal (unitary) basin-country units of international federal rivers (e.g. Egypt portion of the Nile). Light orange refers to domestic rivers in unitary countries. Finally, dark orange refers to international rivers without federal basin-country units. This demonstrates the global reach of federal rivers across more than 300 of the world's major river basins, including over half of the world's international rivers.

country.[5] The transboundary freshwater dispute database (TFDD)[6] headquartered at Oregon State University has delineated the world's international rivers and identified 276 rivers divided into 751 basin-country units. De Stefano *et al.* [39] define the 'basin-country unit as the spatial portion of a basin that is within a single country' (p. 198). The focus on federal rivers must include domestic rivers (which fall wholly within a single country) and international rivers (shared by two or more countries). Our global dataset combines domestic rivers from the GRDC dataset ($n = 278$) and basin-country units of international rivers from the TFDD dataset ($n = 751$) for a total of 1029 spatial units.[7]

A typology (figure 2 and table 5) of major rivers characterizes a gradient of federal influence on river basins. First, *domestic* federal rivers refer to basins wholly within a single federal country.[8] Large domestic federal rivers are shared by two or more states or provinces within a single country (e.g. Murray–Darling of Australia). Like basin-country units (see above), *basin-state* units are the spatial portion of a federal river basin within a single state or province (e.g. the Victoria portion of the Murray–Darling). *International* federal rivers are the second type of federal river and refer to international rivers (two or more countries) shared by one or more federal countries; international federal rivers have at least one federal basin-country unit (e.g. Mexican and US portions of the Colorado River). Finally, federalism has an indirect effect on the unitary basin-country units (e.g. Egypt in the Nile) in international rivers with at least one federal country (e.g. Ethiopia and Sudan in the Nile).[9]

[5]This includes river basins that touch only the border of a second country, i.e. when the basin boundary, but not the river itself, serves also as the national boundary.

[6]Product of the Transboundary Freshwater Dispute Database, Department of Geosciences, Oregon State University. Additional information about the TFDD can be found at: http://www.transboundarywaters.orst.edu.

[7]The TFDD was chosen for international rivers because it includes many smaller international rivers (e.g. in North Africa and South America) which are not included among the international rivers of the GRDC dataset.

[8]Domestic rivers within federal countries are further categorized into intrastate and interstate rivers. For example, national water law in Brazil and Spain distinguishes between the two types. Intrastate rivers are the responsibility of states or autonomous regions, whereas interstate rivers have a federal character.

[9]For example, in the Nile river basin, South Sudan, Sudan and Ethiopia are federal countries whose internal (domestic) multi-level governance arrangements influence basin-wide agreements with other riparian countries that are not federal, such as Egypt.

**Table 5.** Types of federal rivers. Percentage of total (column 3) refers to the percentage of domestic and international rivers that are federal in character. For example, 182 of 278 (65%) domestic rivers and 137 of 276 (just under 50%) international rivers are federal.

| type | description | no. (% total of type) | example |
|---|---|---|---|
| domestic | river basin within a single federal country | 182 of 278 (65%) | Murray–Darling River (Australia) |
| international | international river shared by at least one federal basin-country unit | 137 of 276 (50%) | Colorado River (USA and Mexico) |

This geospatial analysis yields a global map of federal river basins. There are 319 federal rivers. Of these, 182 are domestic federal rivers (of 278 total domestic rivers). The other 137 federal rivers are international rivers with at least one federal basin-country unit. International federal rivers ($n = 137$) therefore encompass almost half of the world's 276 international rivers. The 137 international federal rivers also include basin-country units that are not federal (e.g. Egypt's portion of the Nile shared with federal countries of Sudan and Ethiopia). The other 139 international rivers and 96 domestic rivers are governed by unitary regimes and therefore lack a direct federal nexus. This analysis clearly demonstrates the global extent and diversity of federal rivers as well as the corresponding need for a systematic and diagnostic approach for comparative analysis.

# 4. Defining hydroclimate risks in federal rivers

## (a) Hydroclimatic risk and metrics

### (i) What is the nature of hydroclimatic risk across the world's federal rivers?

Hydroclimatic risks are a function of exposure to variability (RS5, RS7) and extremes (RS6) and the level of vulnerability, which is influenced by the dependence on water (A8), storage capacity (RS4) and economic development (S1). These metrics are analysed within the 1029 spatial units delineated in §3 for both historic and projected hydroclimatic trends. Hydroclimatic risk metrics include the following.

### (ii) Historic runoff (RS5) and variability (RS6/7)

Metrics include historic simulated mean annual runoff and the coefficient of variation of mean annual runoff. The analysis uses outputs of the MacPDM global hydrological model (following [34]), which includes historic data (1961–1990) with a spatial resolution of 1 degree, as well as future time slices from 2020 to 2080 for the CMIP3 set of climate models for SRES A2 and SRES A1B emissions scenarios [40].[10]

### (iii) Future runoff and uncertainty (RS6/7)

Metrics include the projected percentage change in runoff in 2050 for the median value (50th percentile) from the ensemble of results generated by the CMIP3 set of climate models. A metric of uncertainty is computed as the difference (in percentage change) between the 10th percentile (dry) and 90th percentile (wet) projected changes in mean annual runoff in 2050 from the same ensemble of results.

### (iv) Reservoir storage (RS4/8)

Reservoir storage capacity in millions of cubic metres (GRanD database) is used to assess infrastructure available to mitigate hydroclimate risks associated with low productivity, high

[10]Knutti & Sedlacek [40] note that the CMIP 5 model intercomparison developed for the IPCC fifth assessment generates 'remarkably similar' results to those of the IPCC fourth assessment (based on the CMIP 3), when accounting for the underlying scenarios.

variability and/or extreme events (e.g. [41]). This metric may exclude many small-scale structures and coping strategies used for such purposes.

Metrics of exposure to extreme drought events are a topic for future research based on hydrological (e.g. Palmer Drought Severity Index) and social–ecological data (event coding based on archival reports, administrative drought declarations, water shortages, etc.). Future research should also address the role of floods and the interstate management of flood risks in federal rivers. The World Resources Institute Aqueduct 2.0 project (released in 2013) has made progress incorporating droughts and floods into water risk analysis.

## (b) Categorizing semi-arid federal rivers with difficult hydrology

### (i) Which hydroclimatic risks distinguish semi-arid federal rivers with 'difficult hydrology'?

Semi-arid federal rivers are expected to have comparably low mean annual runoff and high interannual variability, as well as comparably high levels of storage and irrigation dependence associated with seasonal and interannual variability.

### (ii) Difficult hydrology in the Colorado, Ebro and Murray–Darling

The hydroclimate risk analysis confirms that rivers in three regions—Southeast Australia, Spain and the Western USA—are a distinct subtype of large, semi-arid federal river, although other rivers are also members of this subset.[11] Figure 3 presents a series of box plots of hydroclimate risk factors to assess the position of three study basins within a global context. The three basins are in the top quartile for size (RS3) and per capita reservoir storage (RS4). The Colorado and Murray–Darling are in the lowest quartile for annual runoff (RS5) and the highest quartile for the coefficient of variation for mean annual runoff (RS6/7), demonstrating semi-arid, highly variable conditions consistent with the difficult hydrology thesis. Although relatively wet, the Ebro is shared by nine autonomous regions and has been the focus for interbasin transfer proposals to more arid regions of Spain; it has also experienced declining trends in historic runoff and faces the highest projected reductions in mean annual runoff of the three basins. Therefore, it is likely to confront a difficult future hydrology.

Projected changes in runoff can be used to gauge uncertainty about equilibrium properties (RS6); all three basins are projected to experience reductions in runoff in 2050 for the 50th percentile values of the modelling results generated for the CMIP3 climate model ensemble. Of the three, the Ebro faces the largest reduction (up to 27% decrease) in annual runoff. The Murray–Darling faces the highest uncertainty in projected future changes based on the range between the 10th and 90th percentile values generated by the CMIP3 ensemble, with over a 40% range between high- and low-projected changes in runoff, including a difference in the projected direction of change (the projections range from a minor increase to a decrease in runoff). All three basins manage this low mean annual runoff, high interannual variability and future uncertainty through relatively high storage capacity in both aggregate terms and *per capita* (RS4/8). Therefore, the Colorado and Murray–Darling have attributes associated with difficult hydrology: relatively low runoff, high variability and high uncertainty. The Ebro is not a clear case of a semi-arid river with difficult hydrology but has a high degree of irrigation dependence (in terms of the percentage of basin area being irrigated) which magnifies the effects of projected reductions in future runoff.

### (iii) Jurisdictional complexity and upstream–downstream asymmetries

Figure 4 depicts the spatial variability of mean annual runoff for basin-state units to demonstrate upstream–downstream asymmetries in mean annual runoff (RU7). For example, the upstream state of Colorado (in the Colorado River basin) contributes higher mean annual runoff than the

[11] The Rio Grande of the USA/Mexico and most rivers of Southern Spain all share these attributes. However, economic development further distinguishes these basins. While South Africa's federal rivers confront similar hydroclimatic risks, for example, the country differs in terms of its social, political and economic setting.

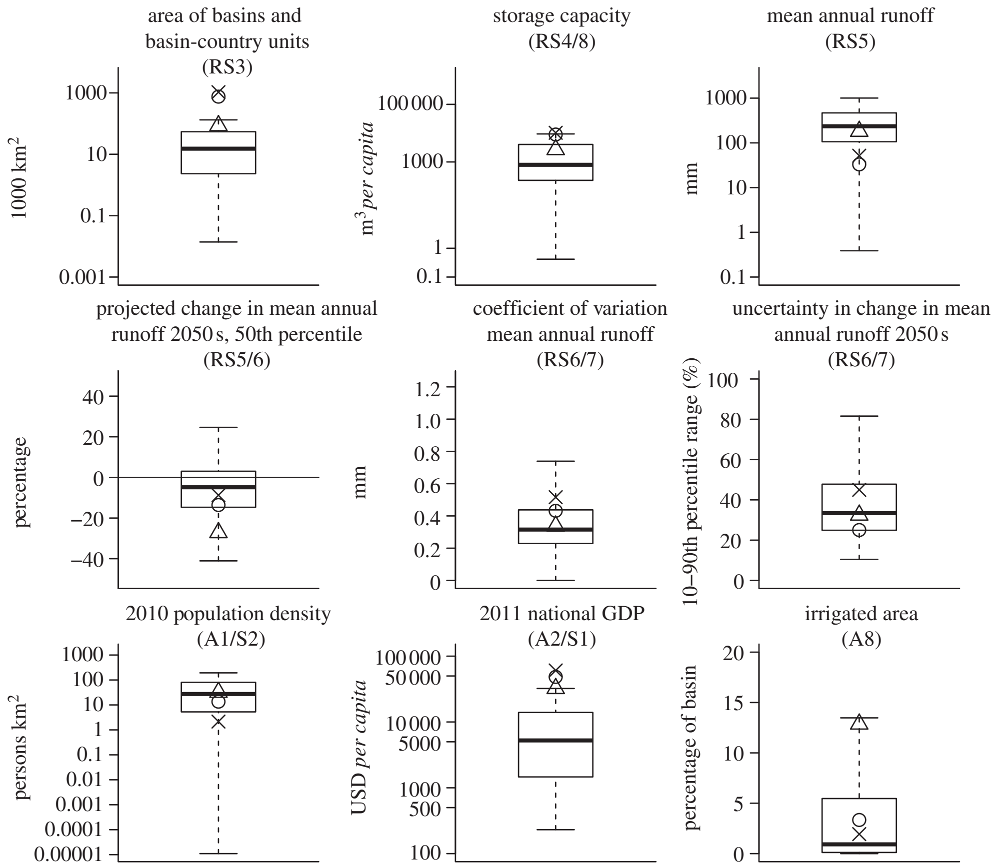


**Figure 3.** Box plot (1.5 interquartile range) for resource system and setting characteristics. Crosses, Murray–Darling; circles, Colorado River (US portion); triangles, Ebro river. Figure 3 presents a series of box plots of hydroclimate risk factors to assess the position of three study basins within a global context, concluding that the Colorado and Murray–Darling have characteristics associated with difficulty hydrology (high interannual variability, low mean annual runoff, high storage), whereas the Ebro has signs that it faces a difficult future (projected reductions in mean annual runoff). Basin area, storage capacity, mean annual runoff and population density are on log scale. Population density refers to the basin or basin-country unit and does not account for population outside of the basin served by inter-basin transfers. See tables 1 and 4 and also §4 for more a detailed definition of variables and units. See McGinnis & Ostrom [11] for variable codes, following table 1.

downstream state of Arizona as part of a snowmelt-driven hydrograph; California, on the other hand, contributes a negligible proportion of the runoff yet holds an entitlement to almost a third of the average annual runoff. The spatial variability in mean annual runoff underpins interstate allocation tensions and is often invoked in disputes between upstream states and downstream states. The three basins exhibit high jurisdictional complexity, which distributes the hydroclimatic risks unevenly over space and time. This diagnostic assessment defines attributes of a specific class of semi-arid federal rivers to examine the design of interstate water allocation institutions robust to difficult hydrology and jurisdictional complexity.

## 5. Interstate water allocation to manage hydroclimatic risk

*How have large, semi-arid federal rivers managed hydroclimatic risks and allocation disputes between multiple jurisdictions?* The propositions (§2) highlight the importance of allocation rules that share risks proportionally and nested river basin organizations with capacity for multi-layered planning, conflict resolution and joint monitoring. The robustness of interstate water allocation

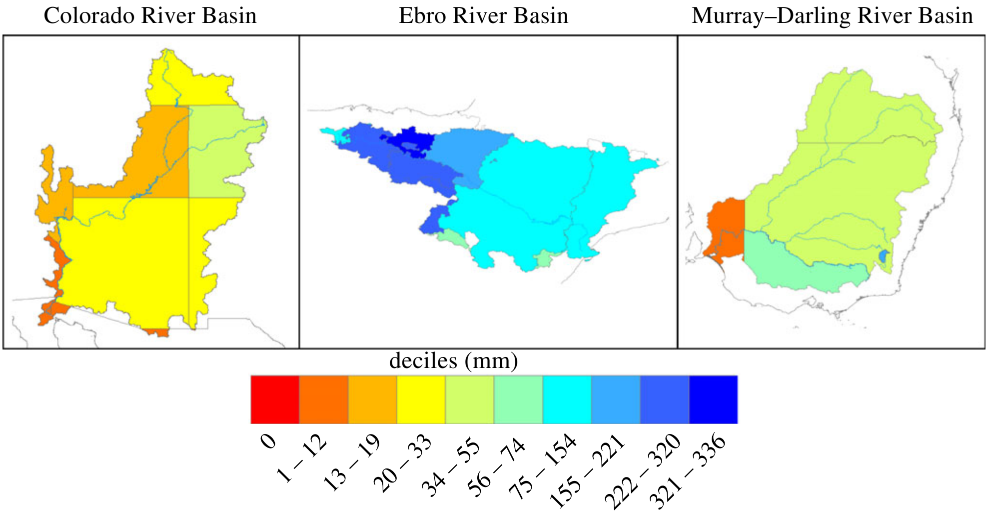


**Figure 4.** Spatial variability of mean annual runoff (mm) for basin-state units, 1961–1990 period. It depicts the spatial variability of mean annual runoff for basin-state units to demonstrate upstream–downstream asymmetries in mean annual runoff (RU7).

institutions to climate risks, and particularly droughts, is expected to require at least three common features in addition to context-specific elements tailored to circumstances in each basin. The common design features include proportional allocation rules, institutional flexibility to update historic agreements and river basin organizations to balance self-governance with basin-wide coordination. Proportional interstate allocation rules (based on a share of the available water rather than fixed volumes) have perceived advantages for managing climatic variability, which mirrors findings for international waters [33]. The basins require flexibility to adjust historic allocation agreements without risk of defection by individual states or costly court action. The fundamental design challenge of interstate water allocation institutions is to balance self-governance and basin-wide coordination through river basin governance arrangements that ensure effective local, state and federal involvement. This section briefly introduces the three river basins and then considers design trends in response to historic, current and projected hydroclimatic risks.

## (a) Colorado River

The Colorado River straddles seven states in the USA and two in Mexico (629 100 km$^2$). According to the 2012 Colorado River Basin Water Supply and Demand Study [42], the basin supports almost 5.5 million acres of irrigated agriculture, water supply for approximately 40 million people and over 4200 megawatts of hydropower generating capacity. Long-term average annual flows (naturalized flows at Lees Ferry, AZ) are approximately 18.5 billion m$^3$ with an extreme annual low and high in 1977 and 1984, respectively. Upstream reservoirs store up to 4 years of the basin's mean annual runoff to buffer against climate variability and sustained drought conditions, which are a prominent feature of the instrumented and palaeoclimate hydrologic records [43]. The once-vast delta ecosystem has declined owing to the combination of upstream reservoirs and diversions [7]. Projected climate change impacts include decreases in runoff, earlier snowmelt and severe droughts [43].

## (b) Ebro river

The Ebro River (85 362 km$^2$ or 17% of Spain) crosses nine autonomous regions and has a small portion of its territory in France and Andorra. It is managed by the Spanish government through the Ebro River Basin Authority (RBA). Average natural runoff is 14.62 billion m$^3$ yr$^{-1}$, with a

decrease of 11% during the past two decades. Climate change projections point to a significant decrease in average runoff [44] and suggest a hotter climate, with increases in prolonged droughts [45]. The Ebro's water resources support the irrigation of about 800 000 hectares, livestock breeding, energy production and water supplies for a sparsely populated territory (32.3 inhabitants per km$^2$). Most users withdraw water from 187 reservoirs having a total capacity of 7.49 billion m$^3$. The Ebro delta hosts a high-value ecosystem that is heavily affected by the decrease in water and sediment flows due to upstream water development and is threatened by projected climate change impacts on coastal dynamics [46]. Persistent pollutants from historical mining and industrial activity, and organic pollution from agricultural and urban areas are also sources of concern.

## (c) Murray–Darling river

The Murray–Darling Basin (MDB) lies within the jurisdictions of four states, a territory and the federal government and totals over a million square kilometres. The average annual outflows to the sea at the Murray Mouth have declined from 12.23 billion m$^3$ per year (prior to water resource development) to 4.73 billion m$^3$ per year (after upstream development) [47]. It is the country's most productive agricultural region generating 65% of irrigated agriculture and a gross value of $15 billion in 2005–2006. Decadal-scale droughts are a recurrent feature, to which Australia has responded by constructing reservoirs that can store the equivalent of an average year's runoff. Overallocation to irrigation and the impact of infrastructure have resulted in extensive environmental degradation, including flood plain forest death, salinization, thermal pollution, acidification, invasion of exotic species, barriers to species' migration and loss of biodiversity [48]. Confronted by climate change predictions of more extreme floods and droughts and in anticipation of intensified competition, policy-makers are struggling to develop effective institutions to manage uncertainties and overcome interstate tensions [49].

## (d) Institutional design and change in interstate water allocation

Section 4 showed that these three basins share similar characteristics in terms of difficult hydrology, particularly low mean annual runoff (RS5), high interannual variability (RS7); dependence on the resource for irrigation (A8) and significant storage capacity (RS4/8) to buffer against seasonal and interannual variability (RS6/7). These risks strain already contested interstate water allocation agreements when combined with overallocation or intensified competition for water (principally for irrigation, hydropower, and more recently emerging, urban and environmental needs). Efforts in improving water-use efficiency, especially in irrigation, are also a feature common to the three basins. In this context, three design trends have emerged: a transition to proportional allocation rules; emergence of multi-layered river basin arrangements for planning, conflict resolution and joint monitoring; and new flexibility to adjust historic allocation patterns.

### (i) Property rights systems for interstate water allocation (GS7): towards proportional rules

Historically, interstate water apportionment agreements featured fixed volumetric allocations for downstream states, which underpinned asymmetries in water supply and use across state jurisdictions. Many of these rules were devised under assumptions of stationarity, even as infrastructure was planned to buffer seasonal and some interannual variability. These allocation rules have not proved robust to climate extremes and prolonged droughts, which exposed an uneven distribution of risk across (and within) jurisdictions, particularly when combined with mounting competition among water users and stakeholders. Fixed allocations to deliver water for downstream states have provided security but limit flexibility to adjust allocation rules to share risks during extended droughts, imposing residual risk on upstream states. However, the Murray–Darling and Colorado confirm the trend towards proportional allocation rules as

climate risks and competition intensify, particularly among upstream states and during extended droughts.

*Colorado River*. The Colorado River Basin is governed by a complex mix of more than 100 laws, court decisions, operational guidelines and technical rules known as the Law of the River [50]. The 1922 Colorado River Compact and the 1928 Boulder Canyon Project Act established a fixed allocation for downstream states. The legal framework required 'upper division' states (Wyoming, Colorado, Utah and New Mexico) to deliver 92.51 billion $m^3$ to the 'lower division' states (Arizona, California and Nevada) over a rolling 10-year period. It formally allocated an equivalent volume to the upper division states, as well as 1.85 billion $m^3$ annually for Mexico under a subsequent 1944 international treaty. The 10-year accounting period acknowledged interannual climate variability. However, the fixed allocation left the upper basin states with residual flows and disproportionate exposure to hydroclimate risks (see proposition 4 above). Each of the lower division states received fixed volumetric allocations, which have contributed to comparatively higher levels of interstate conflicts, particularly between California and Arizona. The legal framework was updated by the 1948 Upper Colorado River Basin Compact to divide the upper division entitlement on a proportional basis among the upper division states of Wyoming, Colorado, Utah and New Mexico; this proportional allocation rule has limited conflict among these states. Water rights within states are established under a priority system of prior appropriation where the first to establish and maintain a beneficial use is the last to lose access during shortages (fixed allocation). This intrastate water allocation system contributes to water allocation disputes between users within states most vulnerable to shortages (particularly Arizona which faces a junior priority among the lower division states).

*Ebro River*. In 1926, the Spanish government created the Ebro RBA to manage the basin with the participation of irrigators. During Franco's dictatorship (1939–1975), the powerful central government determined water allocation to users (individual or collective water rights) and executed it through the construction of large water infrastructure. With the 1978 democratic Constitution, Spain became a quasi-federal country, with 17 regions having broad powers and their own parliament (autonomous regions are roughly equivalent to 'states' in the US and Australian contexts). The Constitution established that interregional rivers like the Ebro would be managed by the central government through its RBAs. The 1985 Water Act for the first time admitted representatives of regions into some of the RBA boards and committees, with participation quotas proportional to the regions' territory and population shares in the basin. According to the 1985 water act, water uses should be regulated through River Basin Management Plans (RBMPs), which allocate water volumes to basin subsystems sharing regulation and distribution networks ('exploitation systems') and to specific user groups (irrigators, industries, etc.) within each subsystem. Individual or collective water rights are nested in these subsystems, where annual allocation quotas to rights holders are defined in user-based RBA bodies based on annual precipitation and available water volumes.

*Murray–Darling*. Evolving state–federal water management institutions have created a mixed legacy. The initial agreement in 1915 included only the three southern basin states and the federal government, codified a minimum annual volume (fixed allocation) of water for South Australia as the most downstream state and was focused on enabling use of water for irrigation and transport [51].

The extreme variability of flows was recognized in the initial River Murray Waters Agreement that was incorporated in identical legislation adopted by the three southern MDB states and the Commonwealth in 1914/1915. Although complex, the basic formula developed at that time has been included in all subsequent agreements [51]. In non-drought periods, New South Wales and Victoria are required to provide a designated volume to South Australia. The two upriver states, New South Wales and Victoria, then share equally whatever is left in the storages (proportional allocation). In addition, they are entitled to all water in their tributaries flowing into the Murray.

The water allocation system between states and to individual irrigators is based on the principle of proportions of the water actually available each season. During serious drought, 'special accounting' rules are implemented, and the three southern states are each entitled to

an equal share of two upriver storages. A countervailing pressure comes through a great variety of administrative arrangements that stem from the understandable desire of irrigators (and the subsequent political pressure to achieve it) to lock in supplies when water is scarce. To the degree that this pressure is successful, the forced reduction is concentrated in that portion of the flow left for the environment [51].

### (ii) River basin governance arrangements: multi-layered planning, monitoring and conflict resolution (GS5–6)

Recent interstate water allocation responses to hydroclimate risks, overallocation or intensive river regulation have involved a mixture of hard (binding) and soft (deliberative) decision-making forums to govern multi-jurisdictional trade-offs—exemplified by the MDB Plan, the Colorado River Basin study and the Ebro River Basin planning (most recently under the EU water framework directive). The federal government plays the role of catalyst of cooperation among states, using federal funds or the commitment to build new water infrastructure to foster that cooperation. These initiatives include new interstate cooperation to monitor water supply and use, and to manage conflicts through multi-stakeholder forums at nested user association, state and interjurisdictional levels. This marks a departure from the high cost, zero-sum conflict resolution processes in early periods of the Colorado River, or the recent protests of the proposed Ebro River interbasin transfer from northeast to southern Spain.

*Colorado River*. Since the early 2000s, an unprecedented dry period has prompted a range of basin planning and shortage sharing reforms. The 2007 shortage sharing agreement was the result of an environmental impact assessment undertaken through a multi-level river basin planning process coordinated by the states and federal government [50]. The assessment evaluated management alternatives negotiated by the seven US basin states to establish operational reservoir management criteria for triggering shortage conditions and sharing the associated risks. The resulting agreement included supply augmentation (re-regulating reservoirs), demand management (conservation programmes) and interstate water storage agreements, including the 'intentionally created surplus' programme for states to store unused water allocations to buffer against future droughts. These mechanisms relied on new institutional linkages in information gathering and basin planning. The Lower Colorado River states agreed to divide shortage risks between Arizona and Nevada while California is legally protected from reductions. Mexico's allocation was unaffected until the November 2012 passage of Minute 319 (an amendment) of the international water treaty between the USA and Mexico. The agreement reduces deliveries to Mexico only when the US experiences operational shortages under the 2007 agreement described above.

*Ebro River*. Although autonomous regions since 1985 are represented in the RBA boards, allocation decisions are still largely controlled by a rather close community of users and developers [52]. In 1992, Aragon was the first region to make explicit its claims over water through the Aragon Water Pact (AWP), a list of more than 20 new hydraulic works that would allow for doubling Aragon's irrigated surface. In 1998, the RBMPs of all the Spanish basins—including the Ebro—were approved. In 2001, the central government approved the National Hydrological Plan (NHP), which deals with interbasin issues. Both the Ebro RBMP and the NHP incorporate the AWP water works. The NHP also proposed the transfer of 1 billion $m^3\,yr^{-1}$ from the Ebro to other basins. This project triggered fierce opposition, mainly in Aragon and Catalonia. Even though it was cancelled in 2004, it marked a tipping point in the evolution of the power balance between regions and the central government.

*Murray–Darling*. Recognition of environmental degradation and limits to water resources led to a new MDB Agreement in 1992. A consensus-based commission was established by the governments to administer jointly agreed programmes. Water allocations were capped, and a market was established to enable seasonal or permanent trade in entitlements between water users and across state borders [51]. The limitations of the lowest-common-denominator commission governance structure resulted in the federal government using indirect constitutional

powers to centralize governance with the 2007 Water Act and the subsidiary Basin Plan and Authority.

### (iii) Historical continuity (GS10): moving beyond stationarity in interstate water allocations

Interstate water allocation tensions have been strongly influenced by path dependency of past property rights systems (fixed allocations) and associated infrastructure. However, hydroclimatic risks and drought events have combined with other driving forces of global and regional change to trigger interstate allocation reforms to achieve the proportional sharing mechanisms and expanding multi-layered decision venues, as outlined above. For example, international agreements and emerging recognition of downstream and basin-wide environmental needs have spurred basin-wide negotiations in the Murray–Darling (Ramsar wetlands), Ebro (European Union Water Framework Directive, WFD) and Colorado (Minute 319).

*Colorado River*. The 2009 Secure Water Act established a national basin study programme to assess supply–demand imbalances under projected scenarios of climate change. In 2010, the Colorado River Basin became a pilot area for this study programme with a cost-share between the federal and state governments to assess supply and demand, system reliability metrics and options for balancing supply and demand through 2060. The information-sharing mechanisms and modelling efforts have demonstrated the reliance on system-wide basin planning. The shortage sharing agreement has led to bilateral negotiations with Mexico to address previously intractable international shortage sharing, as well as restoration of the delta ecosystem through interstate and international allocation agreements. Minute 319 authorized incipient efforts to reconnect the river with its delta through a range of restoration projects and reallocation agreements.

*Ebro River*. The 2000 European Union Water Framework Directive set new challenges that the Spanish government began facing only in 2004, after the Ebro transfer repeal. In terms of water allocation, the WFD entails opening a new 6-year planning cycle and adds a new layer of complexity to allocation, as water uses should be compatible with the achievement of good status of all waters. In May 2012, the new Ebro RBMP was issued for public consultation, after strenuous negotiations over the in-stream flows in the Ebro delta (in Catalonia), whose maintenance is at odds with the current and planned upstream regulation. The new RBMP includes Aragon's water claims and 'water reserves' for other regions in the Ebro, to be executed through new hydraulic works. The new RBMP acknowledges projected climate change impact on runoff but fails to formulate adaptation strategies or to reconsider the planned water projects. Users seek water supply security mainly through increased water-use efficiency and through lobbying for new dams. In 2007, the RBA approved a Special Drought Plan that established drought measures by 'exploitation system', while leaving basin-wide issues to *ad hoc* negotiations.

*Murray–Darling*. Backed by a funding package of AUD $14.7 billion[12] over 17 years, which includes AUD $3.1 billion to purchase water entitlements for the environment, the Basin Plan adopted in late 2012 is meant to take account of all current and emerging issues [49]. The plan shifts responsibility for high-level policy to the national government, leaving the MDB state governments responsible for implementation. These institutional changes are being widely resisted by the states. In Australia, financial power rests overwhelmingly with the federal government, which has been repeatedly frustrated by state governments determined to use their greater water knowledge and administrative capacity to promote their own goals [51]. In preparation of the first Basin Plan, conflicts arose between state governments, with the upstream states resisting loss of water for their farmers. By contrast, South Australia threatened to take the Plan to the High Court, if there were insufficient environmental water allocations. Policies for adaptation to climatic variability and change are focused on water markets, environmental flows and iterative planning. A broader range of complementary adaptation measures would spread risks [53].

[12] AUD $1 = USD $1.0413 as of 3 December 2012.

**Table 6.** Institutional evolution and design for interstate water allocation: a three-basin comparison.

| | interstate apportionment | | drought provisions | | river basin decision venues | |
|---|---|---|---|---|---|---|
| | lower states | upper states | lower states | upper states | historic | current |
| Colorado River, USA and Mexico | fixed | proportional | fixed priority[a] | proportional | interstate compact; courts | basin planning; environmental assessments |
| Ebro river, Spain | fixed[b] | | priority by use | | centralized decision, or unilateral claims | RBMPs; courts |
| | allocation by water exploitation systems | | ad hoc negotiations when needed | | | |
| Murray–Darling river, Australia | fixed | proportional | proportional (special accounting) | | inter-governmental agreements | federal authority; basin plan |

[a] Arizona bears the brunt of shortage risk due to its junior priority under the 1968 Colorado River Basin Project Act; Nevada and Mexico share relatively small proportions of lower division shortages.
[b] Established by river management plans. Aragon and Catalonia have asserted unilateral claims for irrigation use and downstream deliveries for the Ebro Delta, respectively.

Table 6 summarizes key features of institutional arrangements and trends in the three case studies.

The use of proportional interstate allocation rules, adoption of drought management provisions through expanding multi-layered river basin management institutions and new flexibility to adjust historic diversions reflect a transition from zero-sum approaches to a portfolio combining binding and deliberative mechanisms. The polycentric governance arrangements in semi-arid federal rivers are not static and instead have adapted by renegotiating the balance of devolved decision-making and federal coordination.

## 6. Concluding remarks and future research

This diagnostic study demonstrates that federalism is an important influence on multi-level water management in a range of geographical and environmental contexts. The diversity and complexity of federal rivers require an SES perspective to understand dominant risks, interactions and outcomes relevant for semi-arid rivers with difficult hydrology and jurisdictional complexity. We developed a diagnostic assessment to examine semi-arid federal rivers with common climate and governance risks in interstate water allocation. Interstate water allocation reforms have evolved to establish proportional sharing, drought provisions that provide security for downstream states and flexibility for upstream states, and a portfolio of hard (binding) and soft (deliberative) river basin decision-making forums to balance self-governance and basin-wide coordination. Drought and environmental demands have been catalysts for interstate water allocation reforms, unlocking historic path dependencies and upstream–downstream asymmetries in risk sharing. The case studies illustrate that federal–state relationships are not static, but evolve as risks and institutions interact and change; therefore, the right balance between levels will shift and is increasingly impacted by policy changes at international and supranational levels, e.g. the EU Water Framework Directive.

This diagnostic study is an initial step to organize comparative analysis within and across regions with shared challenges. Future research should develop evidence about pathways to adaptive capacity in different classes of federal rivers, while acknowledging limits to transferability and the need for context-sensitive design, by

- developing a common coding form to assess institutional options for risk sharing in interstate water allocation;
- coding qualitative and quantitative data for institutional design and performance variables;
- assessing evidence about the factors contributing to effective multi-level governance of regional and global change risks in federal rivers, as well as the levers of policy reform to improve outcomes in contested river systems; and
- linking institutional design and performance with social and ecological outcomes, such as ecological status and productivity, economic development and social equity.

The link between governance effectiveness and on-the-ground ecological outcomes will require further conceptualization of the ecological setting and associated interactions between hydrology (including groundwater), climatology and land surface–atmospheric interactions. As one example, emerging demands to meet environmental flows in overallocated (closed) river basins requires greater attention to the political–ecological dimensions of environmental flow requirements, as experienced in the federal rivers of Australia and South Africa. Theory and metrics can be advanced and tested in specific river basins before undertaking further comparative assessment and meta-analysis for domestic and international federal rivers. In this future work, it will become increasingly important to critically engage with issues of scale in larger systems to identify opportunities and limits of scaling up collective action based on lessons from smaller scale SESs.

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