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Adaptation Challenges in Complex Rivers Around the World: The Guadiana and the Colorado Basins

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Abstract Integrated water resources management provides an often-recommended governance framework to manage water resources in a sustainable way. The application of this framework on Transboundary Rivers brings additional challenges, which can be exacerbated due to climate changes and extremes (such as droughts). These changes affect the operation of water infrastructures and will affect water management practices. Thus, the understanding and development of adaptation measures (across socio-economic, environmental and administrative systems) are critical, mainly on drought prone transboundary river basins. The paper draws on research conducted to 1) assess climatic risks in those watersheds, 2) describe the challenges in water resources management in the context of climate change, and 3) draw lessons for improving the use of research-based information. Two case studies were selected, the Colorado River Basin (North America) and the Guadiana River (Iberian Peninsula), the latter of which in the context of the five river basins shared between Portugal and Spain. Research and experience in these Basins show that several paradoxes in multistate water management and governance across borders militate against the accurate assessment of socio-economic impacts and the effective use of scientific information for meeting short-term needs in reducing longer-term vulnerabilities. Lessons drawn from both studies, but not always learned in practice, abound. These lessons include an expanded use of incentives for improving collaboration, water-use efficiency, demand management and for the development of climate services to inform water-related management as new threats arise. Recommendations are established for more effectively linking risk assessment approaches with resilience strategies that are applicable in practice and available to decision makers in a changing climate.

Keywords Adaptation · Climate · Drought · Transboundary river basins · Colorado basin · Guadiana basin

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1 Introduction

The Convention on the Protection and Use of Transboundary Watercourses and International Lakes (UNECE 1992) defines "transboundary waters" as referring to "any surface or ground waters which mark, cross or are located on the boundaries between two or more states". Rivers have served as natural boundaries long before the rise of the modern concept of the nation state. Transboundary fluctuations and changes in river flow can be attributed to: (1) climate variations and change, (2) physical transformations of basin hydrology including increased storage, diversions, and landscape changes. In transboundary river basins, historical, legal, and cultural differences add to the complexity of the water resource management process (Raadgever et al. 2008). The "watershed scale" has long been advocated as a useful organizational unit on which to coordinate and evaluate socially relevant research in the context of geophysical, cultural, and jurisdictional boundaries (Krysanova et al. 2010). The European Union (EU) Water Framework Directive (WFD), in force since 2000, recognizes the river basin as a main natural unit for the protection of water bodies status, and as the appropriate scale to implement the principles of integrated water resources management (IWRM). Accordingly with the Directive, the EU Member states are obliged to define river basin districts, which may encompass one or more adjacent river basins (Directive 2000/60/EC, UNECE 2009). Yet, it has been argued that attempts at managing consistent regional units of analysis, such as the watershed, have not met expectations, since a greater cooperation across jurisdictional boundaries is essential (Cosens 2012). Adverse effects of climate change on freshwater systems aggravate the impacts of other stresses, such as population growth, changing economic activity, land-use change and urbanization (Iglesias et al. 2007). Increasing demands and aging infrastructure introduce additional concerns. Adaptive measures which have been recommended and employed to date include both demand and supply side approaches such as water recycling, reduction on irrigation demand, water markets, water metering, water pricing, optimized combined surface-groundwater use, increase storage capacity, and desalination. Critical for effective adaptation is the development and management of the information needed for coordinated data collection and quality control, which allows for the transformation of data and forecasts into accessible, credible, and usable information for early warning, risk reduction and adaptation practices in the water resources sector.

We examine, in detail, two cases from semi-arid areas, namely one from western North America (Colorado River) and another from the Iberian Peninsula (Guadiana River), the latter of which in the context of the five river basins shared between Portugal and Spain. The regions encompassing these basins are projected to become increasingly drier in the 21st Century (IPCC 2008, 2012, 2014). Therefore, these two basins offer unique opportunities for (1) identifying lessons for strategic learning on the evolution of cross-scale environmental risks over time, (2) the development of a collaborative framework between research and water resources management and (3) guidance on the development of information services in support of climate change adaptation at the watershed scale.

2 Methodological Approach

Wescoat (2009) notes that the early 21st century was characterized by increased efforts towards learning from water experiences and experiments in distant places and times. These are increasingly linked through the processes of globalization that drives the international diffusion of water technologies, policies, and water use patterns, and global climate change. In this context, the historical background provides insights into the viability of recommended strategies, namely regarding the reason for why much of the research-based analysis are not applied in practical situations. In addition, climate adaptation is inherently a cross-scale problem. Different approaches taken to address annual or multi-year droughts (whether or not exacerbated by higher temperatures), can reduce or increase future risks depending on the given changing climate scenario. The paper links anticipatory risk-based approaches (event likelihood forecasts, projections) with resilience-based approaches that do not rely on precise future projections. The paper synthesizes much of the work done by the authors and colleagues in assessing climate scenarios (in terms of extremes, variability and change) in the Colorado and Guadiana Basins. Comparative approaches have usually focused on climate projections, usually downscaled to regions and localities, along guidelines which are expected to follow a characterization of the climatic risks (Riebsame et al. 1995; Droogers and Aerts 2005). Much of the research on transboundary systems (whether developed intra or transnationally) focuses on formal legal instruments and conflict resolution mechanisms (Zeitoun and Warner 2006) with little emphasis on strategies and methods in relevant situations such as droughts or related risks that shape the evolution of practice (Do Ó 2010; Cooley et al. 2009; Krysanova et al. 2010). Since the paper attempts to draw lessons from droughts risk management in order to inform adaptation, we analysed the responses to past events and how these have been informing plans for addressing future conditions. We developed an analytic framework for conducting comparisons that includes, but moves beyond, technical considerations in the allocation structure required for the collaborative mechanisms needed in the face of the barriers and uncertainties inherent to decision-making. The analytical framework employed follows that of Lasswell's (1970) problem orientation in assessing goals, trends, conditioning factors, projections and alternatives. It also builds on the identification of critical "focusing events" and historical antecedents that have led to management changes, critical water problems, local political economy and leadership, and the role of mechanisms and actions that link research and management. The approach emphasizes the role of experiences and procedure, as key factors in informing future actions.

3 Basins Background

3.1 Colorado River Basin

The past and present alterations of the hydrology of the south-western United States and north-western Mexico reflect its complex history regarding human settlement, large-scale water diversions, the development and evolution of water policy and law and the expansion of water resources management framework. The Treaty of Guadalupe Hidalgo (1848) allotted to the United States, the Rio Grande boundary for Texas, the area comprising California, New Mexico, Arizona, Nevada, Utah, and parts of Wyoming and Colorado. About 86 % of the Colorado River's annual runoff originates within only 15 % of the area, in the high mountains of Colorado and Wyoming (Fig. 1).

The Colorado is a highly variable river with a coefficient of variation between precipitation and stream flow of about 0.5. The River is fully allocated (the ratio between demand and precipitation supply exceeds 1). The Colorado River now supplies much of the water needs for seven U.S. states, two Mexican states, and 34 Native American tribes. This represents a total population of 25 million inhabitants with projections indicating an increase up to almost 40 million by the year 2020, who, at least to some degree, receive water from the Colorado. In only 80 years, the population of the seven Colorado River Basin states has increased by 800 %,

Fig. 1 The Colorado river basin (https://coyotegulch.files.wordpress.com/2013/11/coloradoriverbasinviarandjusticeinfrastructureandenvironment.jpg)

adding 44 million people. Nevada, Arizona, and Colorado, all heavily dependent on the Colorado River's water for municipal and agricultural uses, both in and outside of the Basin, were among the fastest growing states in the nation over the past two decades. About 12 million residents live along the border, a number projected to as much as double (to 24 million) by 2020 (Bennett and Herzog 2000). These forces place a great strain on the different streams, aquifers, and on two major international river systems (the Colorado and the Rio Grande/Rio Bravo Rivers) shared by the two nations – especially given the current decade of drought which has occurred over much of the international border. In the case of the Colorado, two boundaries form the administrative basis for management to support geopolitical equity – the separation of the Lower and Upper Basin at Lee's Ferry in Arizona, and the international border between the US and Mexico.

Droughts have played a major role in the evolution of western water institutions. Most notably, the droughts of 1860s gave rise to the prior appropriation law. In the arid West, the true test of any water management regime is its ability to withstand drought. At present the

Colorado Basin is undergoing the second driest 15-year period on record. Recent tree-ring reconstructions show that more severe droughts have occurred in the past, some lasting multiple decades. Even in a normal year, most of the international border region receives less than 508 mm/year of precipitation, with some areas receiving less than 127 mm. There are increasingly greater reasons for believing that warmer and potentially dryer conditions will characterize the future climate of this border region, a trend which is likely to further disrupt water budgets, currently already overwhelmed by other demographic factors.

3.2 Guadiana River Basin (in the Context of Iberian Peninsula Transboundary Rivers)

Portugal and Spain share 5 river basins – Lima, Minho, Douro, Tejo and Guadiana – which represent about 45 % of the Iberian Peninsula, corresponding, respectively, to about 61 and 41 % of the Portuguese and Spanish territory (Fig. 2). For all those transboundary rivers except Guadiana, Spain is always the upstream country. The Guadiana River has a distinctive feature since the lower reach and estuarine area are common to both countries, what brings additional challenges for water resources management, (Maia 2003; Timmerman and Langaas 2004).

The riverine downstream position of Portugal makes the country highly dependent on Spain's water uses, flow regimes and sediment transport. Table 1 summarizes the main characteristics of the shared river basins.

In accordance with that data, although only 22 % of the shared river basin area belongs to Portugal, more than one third of those basins total natural water resources is accounted to the Portuguese part, the most of it (82 %) due to surface water. The average yearly precipitation of the shared river basins is 719 mm (925 mm for Portugal and 661 mm for Spain), with a wide temporal distribution, with about two thirds of the precipitation occurring during the wet semester (October to March). There is also a wide spatial variation in precipitation, decreasing from North to South and from the coastal region (Portugal) zone to the inner continental region

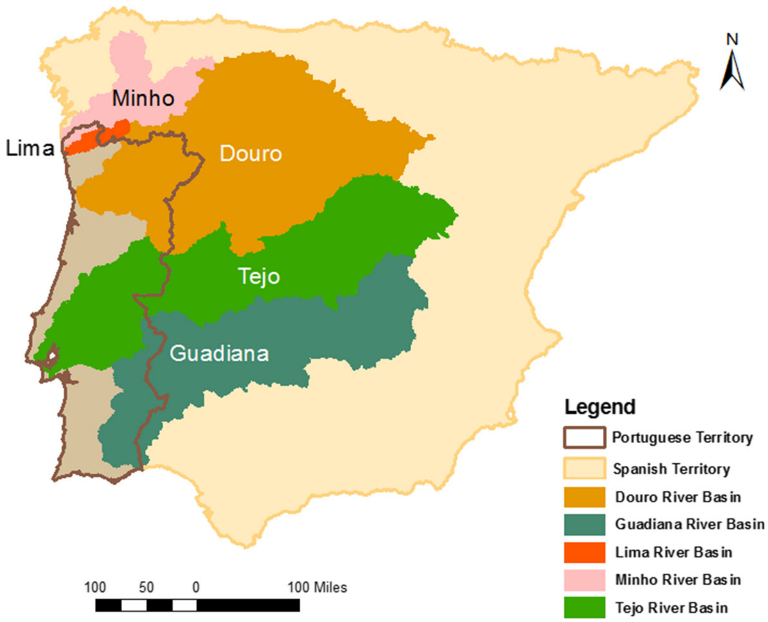

Fig. 2 The five shared river basins in the Iberian Peninsula

(Spain). The water intensity utilization ratio (defined as the ratio between water demands and the total internal natural water resources), as shown in Table 1, presents also a similar North to South overall trend – ranging from 3 % in Minho/Lima to 35 % in Guadiana –, with values also increasing from the Portuguese (western) to the Spanish (eastern) river basin parts of all three major shared rivers (Douro, Tejo, and Guadiana), the biggest difference occurring in Guadiana river basin, that mostly due to the large water demands in Spain (almost 50 % of the internal water resources).

Similarly to the Colorado, the inter-annual variability of the flow regimes in the southern regions is large. The Guadiana – the fourth longest river in the Iberian Peninsula, but ranking only as the 10th in terms of average yearly flow volume – is characterized by an inter-annual variability coefficient of 10.5, on top of the marked flow seasonality. This flow irregularity justifies Portugal interest – made public in the 1960's –, on building the Alqueva dam, which was completed in 2002. The Alqueva reservoir, the largest artificial reservoir in Europe, enabled the Portuguese Guadiana basin storage capacity to increase eightfold. Overall, more than three quarters of the total existing storage capacity of the shared river basins is located in the Spanish territory, where more than 80 % of total water use occurs. Droughts are a factor of

Table 1 Iberian Peninsula's shared river basins: main characteristics (data sources: ARH Alentejo 2012; ARH Norte, 2012a, b; ARH Tejo 2012; Confederación Hidrográfica del Duero 2012; Confederación Hidrográfica del Guadiana 2013; Confederación Hidrográfica del Miño-Sil 2012; Confederación Hidrográfica del Tajo 2013; INAG 2001)

		Minho/Lima	Douro	Tejo	Gaudiana
Population (10^6 inhab)	Spain	0,86 (76 %)	2,20 (53 %)	7,2 (67 %)	1,44 (88 %)
	Portugal	0,28 (24 %)	1,94 (47 %)	3,49 (33 %)	0,2 (12 %)
	Total (Iberian)	1,14	4,17	10,69	1,64
Basin area (10^3 km^2)	Spain	17,52 (88 %)	78,89 (80 %)	55,65 (68 %)	55,53 (83 %)
	Portugal	2,4 (12 %)	19,21 (20 %)	25,67 (32 %)	11,62 (17 %)
	Total (Iberian)	19,92	98,10	81,32	67,15
Mean Percipitation (mm)	Spain	1 941	638	633	547
	Portugal	1 215	1047	819	572
	Total (Iberian)	1 854	718	692	551
Total internal natural water resource, (1) (Mm^3/year) (SW[a)]/GW[b)])	Spain	11 810 / 3 190 (77 % / 94 %)	12 390 / 3 740 (61 %/ 79 %)	7 980 / 1 070 (56 % / 28 %)	4 190 / 570 (70 % / 58 %)
	Portugal	3 440 / 220 (23 % / 6 %)	8 020 / 980 (39 % / 21 %)	6 200 / 2 700 (44 % / 72 %)	1 770 / 410 (30 % / 42 %)
	Total (Iberian)	15 250 / 3 410	20 410 / 4 720	14 180 / 3 770	5 960 / 980
Water Demands, (2) (Mm^3/year)	Spain	440 (77 %)	4 800 (86 %)	2 890 (68 %)	2 220 (92 %)
	Portugal	130 (23 %)	790 (14 %)	1 350 (32 %)	190 (8 %)
	Total (Iberian)	570	5 590	4 240	2 410
Water intensity utilisation ratio (2)/(1) (%)	Spain	3 %	30 %	32 %	47 %
	Portugal	4 %	9 %	15 %	9 %
	Total (Iberian)	3 %	22 %	24 %	35 %
Storage capacity (Mm^3)	Spain	3 100 (89 %)	7 870 (88 %)	11 100 (80 %)	9 200 (67 %)
	Portugal	400 (11 %)	1 080 (12 %)	2 800 (20 %)	4 610 (33 %)
	Total (Iberian)	3 500	8 950	13 900	13 810

[a] Surface water, [b] Groundwater

great concern in the Iberian Peninsula, as they may trigger major imbalances between available water resources and the demands of both countries. In Portugal, the drought period of 2004/2005 was ranked as the worst drought event in the last 60 years (based on PDSI classification in terms of area affected). Spain was also affected by this extreme drought, which lasted there through 2007.

In accordance with a recent research project involving the authors of this paper (Maia et al. 2014) to assess the impacts of climate change in the Portuguese Guadiana basin, this region is expected to become warmer and drier, during the 21st century. This situation is expected to become more extreme in the last decades of this century. All the climate change scenarios defined in the project describe a drier and hotter future when in comparison with the historical period (Ramos et al. 2014; Valverde et al. 2014).

4 Conditioning Factors and Drivers of Change

4.1 Colorado River Basin

As has been well documented, the most important management agreement in this basin (the Colorado River Compact of 1922) was based on an overestimation of the reliable average annual supply of water due to it being based on a short observational record. Briefly, the period 1905–1925 was the wettest 20-year period in 400 years of records, with a 20.200 Mm^3 reconstructed annual average flow at Lees Ferry. The 1922 Compact signatories used this average number as the base minimum for fixed allocation between the Upper and Lower Basins. As a nod to inter-annual variability in water supply, the Compact signatories assumed that flow would average out over 10 years and defined the downstream requirements to be 92.500 Mm^3 over the referred 10-year period. The water needs for endangered species, recreation and Indian water rights were largely neglected. Colorado River stream flow exhibits strong decadal (and longer) variations. Since the signing of the Compact, the estimated annual virgin flow has been of about 17.600 Mm^3, with an historic low flow of 6.900 Mm^3 in 1934. The flow of the river is apportioned among the seven basin states and Mexico based on an elaborate set of legal compromises known simply as the “Law of the River,” originating with the Colorado River Compact of 1922 (Pulwarty et al. 2005). Because of the scale of the impoundments and withdrawals in comparison with its flow, the Colorado has been called the most legislated and managed river in the world. This complex set of multiple objectives results in management demands that cross several timescales and that are climate dependent (Table 2). The overall intent of the Law of the River is to equally divide the river’s flow amongst the states of the Upper Basin (Colorado, Wyoming, New Mexico and Utah) and the Lower Basin (Nevada, Arizona and California).

The burden of a potential shortage, as stipulated by the Law of the River, technically falls on the upper basin. The risk of shortage to the upper basin lies in the fixed obligation of delivering the referred 92.500 Mm^3 every 10 years. Theoretically, the upper basin should curtail its water uses in order to ensure the deliveries when there is not enough water in the system. The risk of variability in the system, however, falls on the lower basin. The lower basin is more vulnerable to shortage situations as it has developed water uses that depend on water deliveries above those which it is entitled to, requiring more than 9.250 Mm^3 in years of high flow. Additionally, the 1944 Treaty promises a total of 1.900 Mm^3 (minimum) per year to be delivered to Mexico, resulting in the apportionment of 21.500 Mm^3 of water total (20.300 Mm^3 of which are considered “firm”) – a value significantly beyond that which the river can consistently provide. The treaty authorized the International Boundary and Water

Table 2 Cross-scale issues in the integrated water management of the Colorado river basin (Pulwarty and Melis 2001)

Temporal scale	Issue
Indeterminate	Flow necessary to protect endangered species
Long-term	Inter-basin allocation and allocation among basin states
Decade	Upper basin delivery obligation
Year	Lake Powell fill obligations to achieve equalization with Lake Mead storage
Seasonal	Peak heating and cooling months
Daily-monthly	Flood control operations
Hourly	Western area power administration's power generation
Spatial scale	
Global	Climate influences, Grand Canyon National Park
Regional	Prior appropriation (e.g. Upper Colorado River Commission)
State	Different agreements on water marketing within and out of state water district
Municipal and communities	Watering schedules, treatment, domestic use

Commission (IBWC) to resolve disputes. Colorado River water quality was not considered at the time.

A subsequent Compact (in 1948) apportions the flow amongst the four Upper Basin states, while the Boulder Canyon Project Act of 1928, and a subsequent lawsuit (Arizona v. California 1963), defined the three-state apportionment in the Lower Basin. In a critical omission, however, the Compact did not anticipate shortages, nor did it specify how water would be shared between the states within the basins. The Law of the River includes some guidelines on sharing shortages between the basins and between states within each basin. However, these provisions are, typically, either not explicit or have not been evaluated in comparison with stakeholder needs, which were not considered at the time of the Compact. In the 1950s, development in the southwest United States resulted in rapidly growing demands and diversions for irrigation. Mexico lodged a formal protest in 1961, stating that the quality of the water received from the U.S. was not appropriate for agriculture and that agricultural production in the Mexicali Valley was being negatively impacted. In 1972 the U.S. agreed that, in addition to providing Mexico with the 1944 Treaty obligation, it would meet the required standards for average water quality. The United States then built a desalination plant in Arizona to process the water for return to the Colorado from the Wellton-Mohawk diversion.

Paleoclimate evidence suggests that, over the last two millennia, several droughts occurred in this region that were of substantially greater severity and longer duration than any observed in the modern observational record, including the 1930's and the 1950's (Meko et al. 2007). This scenario was explored in great detail in the Severe Sustained Drought study in the Southwestern United States project (hereafter the "SSD study"). The SSD, completed in 1994, used dendrochronology and water modelling to track the potential impacts that a severe, sustained drought could have on the modern water delivery system (Powell Consortium 1995).

The historical SSD emerging from the paleo record which would most stress the system was the event from 1579 to 1600, which featured an estimated streamflow mean of 14.100 Mm^3. This drought – estimated as having a return interval of 400 to 700 years – was clearly severe and would stress the system significantly, but for the purposes of analysis, researchers decided that an even more catastrophic scenario was merited. Under SSD, Lake Powell rapidly drops below minimum power pool by year 17 of the drought, and proceeding to dead storage by year 18 (where it remained until year 25). Even under this scenario, both reservoirs (Lakes Mead and Powell) recover significantly, as anticipated, in the second half of the SSD scenario.

In reality, by 2004, the severe drought in the Colorado Basin began to remind researchers and water managers of the extreme SSD scenario, but with one notable and disturbing exception: the onset of recent real-world drought impacts was much quicker than shown in the presumably unrealistic SSD research scenario, with sharp declines in Lakes Powell and Mead storage providing the most striking visual evidence of this crisis (Kenney et al. 2010). Subsequent analyses revealed that even the SSD study was too optimistic. The identified SSD was considered unlikely but, in the present drought, the rates of decline were faster than that for the SSD. The over-apportionment of the river has, historically, not been problematic because the Upper Basin does not use its full apportionment. In addition, the structure of the Compact calls upon the Upper Basin states to allow the Lower Basin apportionment to flow downstream (past the inter-basin dividing point at Lee's Ferry), which has the effect of creating a de facto delivery obligation on the Upper Basin.

4.2 Guadiana River Basin (in the Context of Iberian Peninsula Transboundary Rivers)

Portugal has been independent from Spain since 1640. Rivalry has characterized the two countries' relationship up to the 19th century, with the corresponding 1000 km border (two thirds of it demarcated by rivers) being established by the 1864 "Tratado de Limites" (Treaty of Limits), and completed by the 1926 Convention. The Treaty can also be considered a landmark for cooperation on water resources by establishing (in the corresponding Annex I) the common use of the bordering river stretches, with a complimentary agreement declaring that both Nations have the same rights on the bordering river stretches and that they are entitled to using half of the corresponding streamflows at any time (Maia 2000).

In the following period, up to the end of the last century, the shared water resources management can be characterized by (1) distrust, with both parties withholding or making strategic management of information disclosure timing (Garrido et al. 2010), (2) being applied almost exclusively to the bordering stretches (Maia 2011), mostly aiming for economic benefits from water use, particularly from hydroelectric exploitation. In fact:

- The "Convention on Regulation of the Hydroelectric Utilisation of the International Parts of the River Douro", signed in 1927, was the first joint agreement between the two countries, aiming to coordinate hydroelectric production in the Douro River Basin;
- The 1968 "Convention on the Regulation of the Hydraulic Utilisation of the International Parts of the Rivers Minho, Lima, Tejo and Guadiana, Chança and their tributaries", signed in 1968, enlarged the goal of the partition of the hydroelectric potential to the other shared basins. Apart from hydroelectric production, other uses for water are also considered, together with some basic environmental measures (Álvares Ribeiro and Maia 1996).

Under the 1968 Convention, a water transfer, for a volume up to 1.000 Mm^3/year, from the Spanish part of the Tejo basin to the Spanish Segura River Basin (waterway Tejo-Segura), was accepted by Portugal. This remains the only effective water transfer agreed between the two countries. This agreement served also as a basis for the later development and construction, by Portugal, in the Guadiana River, of the Alqueva dam and associated infrastructural plan.

A new cooperation phase began with the "Convention on co-operation for protection and sustainable use of Portuguese-Spanish river basins", commonly referred to as Albufeira Convention, agreed by the two countries in 1998, and which came into effect in 2000. This agreement was triggered by the presentation, by Spain, of the Project of the National

Hydrologic Plan, in 1993, in which an inter-basin transfer of water, from the Douro to the Tejo, was planned. Portugal reacted and a common work leading to a new Convention followed (Maia 1997). The negotiation of the Albufeira Convention took advantage of the fact that, since 1986, both countries became members of the European Union (EU) (with common regional benefits in terms of cohesion funds) and also from the involvement of both States in the negotiation process of the Water Framework Directive (WFD), approved in 2000. The Albufeira Convention was framed aiming at freshwater and groundwater protection and also at the sustainable use of shared water resources. Two institutional boards were defined under the Convention: (i) the Parts Conference, a high deliberative instance of political co-ordination and (ii) the Commission for Convention Development and Appliance (known as CADC), with deliberative, consultative and supervisory functions (Maia 2008, 2009; Garrido et al. 2010; Ardá et al. 2010). The CADC is the main board for the Iberian water management cooperation, but has a somewhat limited power because of its dependence on both governments. The CADC is poised to play an increasing role in the WFD's implementation with the creation of different Work Groups, namely regarding: (1) flow regimes, droughts and emergency situations; (2) information exchange; (3) hydraulic structures' security and floods; and (4) water quality.

One of the most relevant demonstrations of the progress, and a driver of change in the recent years (and into the future), concerns the definition of ecological flow regimes and the corresponding minimum guaranteed allocated flow regimes. The Albufeira Convention states that the necessary flow regime should be defined and guaranteed separately for each shared river basin, with environmental goals in mind. Initially, the Convention only set values for the minimum guaranteed annual flow volumes (although non-applicable to "exceptional years") and, for Guadiana river a minimum instantaneous flow (2 m^3/s) to be equally verified in two different sections of the river (one at the upstream border river entrance in Portugal; the second, at the downstream section of the Portuguese part, at the beginning of the common and estuarine river stretch). This regime has been revised in 2008, and, since then, in addition to the annual volumes, a minimum guaranteed trimestral flow volumes for all shared rivers (except Minho) was established. However, the referred values continue to be not guaranteed in exceptional situations, as defined in terms of precipitation (in pre-selected monitoring stations) and also, for the Guadiana, on the existing storage (in pre-selected reservoirs). Maia (2008) describes the flow regime definition for the shared river basins in detail.

The "double dependency" (precipitation and reservoirs storage) for the definition of exceptional situations on the Guadiana basin reflects the higher priority of the flow regime definition for guaranteeing supply to southern water scarce regions, and also reflects the Spain's concern with the lower and common bordering and estuarine river stretch.

To date, under the 1998 Convention provisions, no exceptional situation has been declared for the Guadiana, although some periods of droughts have occurred in the Iberian Peninsula. Also, only once (2005/2006, period of severe drought in both countries) did Spain not comply with the flow discharge obligations in this basin. Garrido et al. (2010) concluded that the revised flow was used to solve an historical litigation issue. It should be noted that, although foreseen by the Albufeira Convention, (1) no criteria for the definition of a minimum flow to be guaranteed under exceptional situations, (2) nor any sets of measures to be adopted in those situations, have been defined so far.

Finally, it should be stressed that the adopted minimum flow regime discharges guaranteed by the Albufeira Convention should also comply with the potential downstream water needs, including the ecological flow regimes established under the River Basin Management Plans (RBMP), elaborated and approved under the WFD, separately (as at present) or jointly (as is envisaged in the near future) by the Portuguese and Spanish authorities.

5 Drought Risk Management: Strategies for Shortages

5.1 Colorado River Basin

Few rivers offer the drought protection provided by the Colorado River, where reservoirs can roughly store 4 years' volume of the average annual flows. However, even this level of protection can be challenged by a severe drought. The driest 5-year period on record occurred from 2000 to 2004. In 2006, as a result of the ongoing drought, the basin states successfully responded to a directive from the Secretary of the Interior by producing a proposal for a shortage sharing plan for the Lower Basin, necessarily implicating the Upper Basin by clarifying and modifying the rules for reservoir operations at lakes Powell and Mead. Three important considerations were identified. The first was to encourage conservation of water, particularly during times of drought. The second was to contemplate reservoir operations at all operational levels, not just when reservoirs are low. The last consideration was to establish operational guidelines for an interim period, in order to gain valuable operational experience for informing future management decisions (Jerla et al. 2011).

The Preferred Alternative (PA), based on the Basin States consensus alternative and on an alternative submitted by the environmental NGOs called "Conservation Before Shortage," was comprised of four key operational elements emerging from the three considerations identified during the scoping phase. The PA proposed (1) a fully coordinated operation of the reservoirs (Powell and Mead) to minimize shortages in the Lower Basin and to avoid risk of curtailments of water use in the Upper Basin, (2) the Intentionally Created Surplus (ICS) mechanism to provide for the creation, accounting, and delivery of conserved system and non-system water, thereby promoting water conservation in the Lower Basin, (3) modifying and extending elements of the existing Interim Surplus Guidelines (ISG), which determines the conditions under which surplus water is made available for use within the Lower Division states and (4) extending the term of the ISG and modifying those guidelines by eliminating the most liberal surplus conditions, thereby leaving more water in storage for reducing the severity of future shortages.

The Interim Guidelines are in place through 2026 and include a provision that "Beginning no later than December 31, 2020, the Secretary shall initiate a formal review for purposes of evaluating the effectiveness of these Guidelines". Further knowledge of the impacts of a changing climate, both realized and projected, will be critical when such a review is initiated. In a recent assessment the US Bureau of Reclamation (BoR 2012) found that water supply in the basin is likely to fall by at least 9 % over the next 50 years (current water supply averages about 17.900 Mm^3). Shortfalls between supply and demand will range between 3.700 and 9.900 Mm^3 by 2060 (the current water use volume in the basin is of about 18.500 Mm^3) with the potential for more critical imbalances as early as 2025. The US Bureau of Reclamation attempted to quantify the environmental needs (wildlife and riparian habitats). The amount of water allocated for environmental flows varied between scenarios, acknowledging the shortcomings in the studies.

Most recently (November 2012), Minute 319, now in its second year, entitled the "Interim International Cooperative Measures in the Colorado River Basin," was signed by the U.S. and Mexican commissioners of the International Boundary Water Commission, the bi-national agency that manages water crossing the border (IBWC 2012). This interim (5-year agreement) is a major milestone in U.S.-Mexico relations on the River. As part of the 5-year restoration pilot program, the United States, Mexico and non-governmental groups (NGOs) will jointly provide a total of 65 Mm^3 of water as base flows to keep water in the channels and Delta year-round for riparian vegetation. The base flows will come from the NGOs, which secure water via the trust acquired from Mexico's treaty delivery. In addition, a pulse flow – 130 Mm^3 – will mimic a spring runoff that scientists believe will ultimately help replenish the Delta. How the Law of the River performs in an extended shortage situation is being tested at present, with the Basin undergoing, since 1999, the driest 15 year period on record. In the 2014 Water Year, deliveries are being curtailed (by almost 10 %) for the first time since the Glen Canyon Dam Lake Powell was built.

5.1.1 Potential Changes due to Climate

Some estimates indicate that the Colorado River Compact may only be met 60–75 % of the time by 2025, and that, by 2050, the average moisture conditions in the south-western USA could equal the conditions observed in the 1950s, when drought extended for 10 years (BoR 2012). A shortfall of 20 % is projected by the year 2060 due to increasing population demands, energy diversions and environmental streamflow requirements.

These numbers have high degrees of uncertainties associated with them, but the general direction of change is clear. Vano et al. (2014) state that major sources of disparities arise from both methodological and model differences that produce uncertainties. These differences could be explained (in rising order of relevance) by the: (1) Global Climate Models (GCMs) and emission scenarios used; (2) ability of land surface and atmospheric models to properly simulate the high elevation runoff source areas; (3) sensitivities of land surface hydrology models to precipitation and temperature changes; and (4) methods used to statistically downscale GCM scenarios.

Water managers in the Colorado Basin's states are explicitly considering how to incorporate the potential effects of climate change into specific designs and multi-stakeholder settings. Most decision makers engaged in cooperative strategies addressing water scarcity have repeatedly stated the need for integrated management of existing supplies and infrastructure (Pulwarty et al. 2005).

5.2 Guadiana River Basin (in the Context of Iberian Peninsula Transboundary Rivers)

Drought conditions in Portugal are traditionally managed on a reactive response approach. Drought events are monitored by the Agência Portuguesa do Ambiente, I.P. (Portuguese Environmental Agency) based on cumulative precipitation values along the hydrological year and in the evolution of water storage levels on reservoirs and aquifer systems. The verification of drought events is conducted during the 8th month of the hydrological year (May).

During the severe drought period of 2004/05, a special Drought Commission was created to monitor and implement appropriate mitigation measures for minimization of drought impacts. In 2004/05, this Commission stated the need for new and systematic procedures regarding drought management, including: (1) the creation of an integrated drought early warning and management system; (2) the establishment of a reliable monitoring system of the (surface and ground) water source's availabilities, as well as the estimation of main water uses for different sectors (in terms of volume and monthly distribution); (3) the wider promotion of efficient water use.

The Portuguese EU Presidency (on the 2nd semester of 2007) dedicated special attention to water scarcity and droughts, leading to the development by Portugal of a pilot "Drought Alert and Management System" (Sistema de Prevenção e Gestão de Secas, SPGS for short). This project envisaged an integrated system for socioeconomic evaluation of the potential drought impacts on several water use sectors (Maia et al. 2013). This system, however, is still not implemented and, during the 2012 drought, the management of the situation was still mainly based on the evolution of the PDSI values and of the hydrological situation (available/stored water volumes), thereby not taking into consideration drought risk analysis or the quantification of potential socioeconomic impacts.

In contrast, for Spain, the last, most severe drought period (2004 to 2007) spurred intense activities, resulting in the development of the Special Plans for Drought Situations for all river basin districts and a supporting system of hydrological indicators and Emergency Plans for settlements with populations larger than 20 000 inhabitants.

The Spanish drought indicator system is based on operational variables (hydro-meteorological variables, e.g. stored volumes on reservoirs; groundwater tables for aquifers; river flow levels; reservoir's discharges; cumulated precipitation in significant meteorological stations; snowpack, where significant), with a drought's severity final evaluation being performed via a standardization of the different types of variables through a special index (called "Índice de Estado"). The methodology adopted includes: (1) the identification of existing water sources for representative units of demand; (2) the selection of the most suitable indicators for representing water availability evolution for each demand unit; (3) the weighting of indicators, in order to achieve representative numerical results of different drought levels in a river basin's water systems; and (4) the validation of the selected indicators. These indicators are supposed to enable the detection and early warning, with sufficient time for the application of informed responses, of different drought severity levels in order to adopt adequate mitigation measures and actions and are the basis for the implementation of the corresponding Drought Plans at the river basin level. In 2012, the Spanish River basin authorities, by following the evolution of the hydrological indicator system's results, ensured the adoption of appropriate measures, according to triggers defined in the Special Plans for Drought Situations for each river basin (MAGRAMA 2012).

However, as described in Maia (2009), the Albufeira Convention specifies that both Portugal and Spain shall "coordinate actions to prevent and control drought and water scarcity situations, setting the exceptional mechanisms to mitigate consequent effects and define the nature of exceptionality to the general regime established in the present Convention…" and also that both parties should "undertake joint studies of drought and water scarcity situations to define measures to be applied and define the criteria and indicators of the exceptional regime". In fact, in 2003, the CADC (by then) specific Work Group (WG) on Droughts agreed on a two-phase work plan aiming at the establishment of an indicator system and corresponding trigger values and at the identification of the main uses to be guaranteed under special circumstances. The 2007–2008 plan of action (CADC 2007) of the (broader) WG on Flow regime, Droughts and Emergency Situations still included, as its goals, the: (1) selection of the hydro-meteorological variables and definition of monitoring points to assess drought situations; (2) definition of indicators and alert trigger values; and (3) definition of exceptionality and management for drought situations. In reality, still at present (mid 2014), no common and homogeneous indicator system has been created and such a necessity does not seem to have been taken into account by the two countries which are currently at different stages in terms of addressing drought management and planning issues.

5.2.1 Potential Changes due to Climate

The projected climate changes in the Guadiana region are likely to increase the frequency and severity of drought events and, consequently, may disrupt the water budget, which in turn may already be in a delicate situation due to the expected development of the irrigated areas in that region. According to the above referred research project for the Portuguese region involving the authors (Maia et al 2014), these areas are expected to have a decisive role in the future of water availability in the region, particularly during the dry periods (when the evapotranspiration is higher). The water availability (in terms of runoff values) in the Guadiana region is expected to decrease, during the 21st century, namely due to the projected rise in temperatures (as well as evapotranspiration) and decrease in precipitation mean values in that region (Ramos et al. 2014; Valverde et al. 2014).

The European Union is very much concerned with the adaptation to climate change (CC), being mainly focused on increasing the resilience of biodiversity, ecosystems and water (COM 2009), for which WFD is relevant. The current (first) set of RBMPs developed under WFD were due to include an initial check on the corresponding programmes for adaptation measures regarding CC. The next generation of plans (due in 2015) should fully take into account the CC effects and impacts and integrate them in the implementation of the Floods Directive, as well as on measures for addressing water scarcity and droughts (Maia 2009).

At the Iberian Peninsula level, both countries have already prepared specific National Strategies for Adaptation to CC (Spain in 2006 and Portugal in 2010), including initial evaluations on the expected Climate Change Impacts – a general increase of the average temperature and a reduction in precipitation levels is foreseen for the two countries – and the corresponding objectives for CC adaptation strategies on water resources. These objectives are, mainly, and similarly for both countries: (1) to reduce the hydrological pressures on water bodies, (2) to improve the safety and reliability of water systems, (3) to foment risk management and (4) to promote the deepening of knowledge through research and development and also by increasing public awareness and appropriate technical training (PNACC 2006; ENAAC 2010).

These adaptation strategies were nonetheless developed individually for each country. In fact, at present, there is no tangible coordinated effort for performing a specific joint assessment for the shared river basins, nor to include the fundamental problematic on the transboundary management of water resources. This behaviour is in line with the status quo in the EU, where, according to a 2012 review on WS&D policy (EC 2012), only 5 % of the screened international RBMPs include co-ordinated measures for the entire international RBD to deal with WS&D.

6 Learning from Comparative Assessments to Support Adaptation: The Colorado and Guadiana River Basins (in the Context of Iberian Peninsula Transboundary Rivers)

Climate and weather events form a variable background on which transboundary agreements and conflicts are played out. On Colorado River, major issues in responding to climate change on water supply relate to the questions: “why is there such a wide range of impact projections on future climate change (especially precipitation) in the river streamflow, and how should this uncertainty be interpreted?” (Vano et al. 2014). There is substantial evidence that both the future Guadiana and Colorado River streamflows will be reduced under anthropogenic warming scenarios, due to a combination of strong temperature-induced runoff curtailment and the reduced annual precipitation (Mariotti 2010; Hoerling et al. 2012; Vano et al. 2014).

As illustrated in the context of both the Guadiana and the Colorado rivers, institutional conditions that limit management flexibility tend to exacerbate the underlying resource availability issues, even when technical knowledge is available.

Events such as droughts, which may span from seasonal to decadal and longer timescales, expose critically vulnerable conditions and, despite providing warning on potential crisis, are also opportunities for innovation. Transboundary cooperation has been evolving in the last decades, and seems to have strengthened, but much more will be necessary in the face of a changing climate. The development experience in the Colorado and the Guadiana clearly illustrate that impacts and interventions can reverberate through systems in ways that can only be partially traced or predicted. The discussion here is based on the premise that, in order to understand how effectively society might identify common goals, for the best use of climatic and other information, and also how to prepare for the consequences of future variability and unexpected events, it is necessary to identify and evaluate the present systematic efforts (i.e. field-tested alternatives) to experiment, characterize uncertainties, make decisions, and to cope with environmental variability across temporal and spatial scales. Given this backdrop, three questions may be posed:

- What are the early signs and likely locations of water-related stresses and conflicts?
- Are the assumptions about planning borne out by what is known from the climate record and climate projections?
- What can governments, organizations, communities and individuals do to reduce and manage risks?

Historically, in the Colorado River Basin, reservoirs and inter-basin transfers have been used to mitigate the effects of short-term drought. The lessons and impacts of these adjustment strategies, and more recent settlement agreements, are still being assessed. The system's ability to maintain reliable supply during periods of severe long-term droughts more than 10–15 years long (the timescales of development, project implementation, and ecosystem management efforts), known to have occurred in the Western US over the past 1000 years, is not yet fully tested. While opportunities for "win-win" situations and rule changes exist, such changes are extremely difficult to implement in practice, especially when winners already exist.

The fact that the stark projections of the SSD were not embraced until relatively recently, illustrates a major problem with the role of such studies in informing decision making in the absence of a strong focusing event. While better information can result in better policy, and better information can confer political and economic advantage, policy is frequently made, not by a single discrete decision, or by a unitary decision-maker, but by a multi-stage process and it is well acknowledged that policy processes have prodigious appetites for information (Ascher and Healy 1995).

The Interim Guidelines, which extend only through 2026, provide an opportunity for gaining valuable operating experience regarding the management of Lake Powell and Lake Mead and to improve the basis for additional future operational decisions to be made, whether during the interim period or thereafter. Most critically, the Basin States have agreed to address future controversies on the Colorado River through consultation and negotiation before resorting to litigation, up until 2026. It is critical to note that each drought event is unique in terms of drought intensity, impact on the economy, and ability of individuals and the society to respond. Therefore, a drought assessment framework, no matter how consistent it may be, can only be applied as a guide, and not as an exact model. To guide progress:

- It is necessary to harmonise different conceptualisations of losses. The existing guidance documents and agreements apply different, ill-matched loss classifications.
- Drought loss data collection should be standardised and institutionalised; the current available data are inappropriate in spatial, temporal, and sectorial resolution.
- Any assessment of drought-related losses should be subjected to uncertainty analysis. The consequences of (1) methodological choices and (2) the implicit uncertainty in the loss data should be explored and commented on.

On the other hand, in the case of the Iberian Peninsula's shared river basins, despite their spatial proximity, Portugal and Spain have not always suffered on the same level and at the same time from extreme events. For example, the higher water storage capacity existing in Spain has been an important advantage during droughts, especially in the Guadiana Basin. Meanwhile, the water storage capacity introduced by the Alqueva multipurpose plant has counterbalanced this reality for Portugal. Also, the increasing cooperation between both countries, through the development and implementation of bilateral agreements on water resources planning and management, has contributed for improved relations between Portugal and Spain in terms of sharing water resources in regular years.

However, it is recognized (Maia 2009; Maia 2011) that there is still a critical need for the development of a fully cooperative management of shared water resources for the definition of: (1) the minimum volumes needed to guarantee downstream flow during drought situations; (2) the procedures and measures to be adopted by both countries for preventing and/or mitigating drought effects; (3) the "exceptional situations", using long-term natural flow series (obtained through tree-ring reconstructions) and climate change scenarios; and (4) the necessary reserves for water uses including the ecological needs of both countries. It is expected that the further implementation of the European Union WFD program, that both Portugal and Spain must comply with, contributes to an effective reinforcement of the bilateral cooperation between the two countries, namely because both are expected to progress from the current situation of developing each a River Basin Management Plan (RBMP) for its territory basin, although in cooperation, to producing a single and joint RBMP for each of the international river basins in 2015. In order of that, a more dynamic approach to transboundary issues is required, in order to address and solve detected coordination gaps affecting water governance for the case of Portugal and Spain shared rivers, in accordance with Brito et al. (2013).

In the case of the Iberian Peninsula, when compared to the Colorado Basin (sections 4. and 5.), there is a further gap to be emphasized, in terms of sustaining a collaborative framework between research and water resources management that could provide a better support and guidance for decision-making.

In both the cases in the present paper, the major stumbling blocks, exacerbated by shifts in climate, or in the frequency of climate extremes, relate to the adversarial relationship that usually develops between upstream and downstream users of water. The definition of when a particular use is equitable and reasonable requires the definition of broad concepts such as "no harm," and "optimal utilization". Problems are further compounded by the lack of agreement on event definitions, such as what constitutes an "extraordinary or exceptional" (i.e., severe and persistent) drought in different places. The spatial extention and persistence of droughts may produce shortages, not only in the locale considered, but also in neighboring regions that are otherwise supposed to make surplus water available for interbasin transfers. These concepts seem clear from the standpoint of water measures, but difficulties emerge in (1) the practical and equitable sharing of quality water, or (2) how an upstream country or state should share water with downstream countries, especially during periods of water stress.

7 Conclusions

Integrated water resources management (IWRM) provides an important and often recommended governance framework for building adaptation measures across socio-economic, environmental and administrative systems. IWRM has come under criticism in recent years due to a poor record of implementation and a strong emphasis on technocratic "solutions" (Mukhtarov and Gerlak 2014). The practical range of choice is set by the culture and institutions and not simply by the theoretical range (supply) defined from the physical environment (White 1988; Hooper 2003). The river basins, described above, exhibit characteristics of "closed or closing" water systems, where demands exceed supply, and where the development of mechanisms for engaging in negotiations and binding agreements becomes necessary. These problems are further complicated by the unique context imposed by the transboundary resources at the borders themselves. On Colorado Basin the inclusion of stakeholders in water management policy has become the norm (Varady and Morehouse 2003). However, regardless of how robust civil-society institutions may be, severe drought (or flooding) can expose underlying institutional barriers to effective cooperation (Pulwarty 2003). The advantage of integrated watershed approaches lies in its mechanisms for engaging stakeholders on critical issues of multi-criteria allocation, data-sharing, experimentation and sustainability in the face of a changing climate (Raadgever et al. 2008; Mukhtarov and Gerlak 2014). Although stakeholder involvement is a requirement for European Union WFD implementation, that does not translate into participation in decision making. Concerning the Portuguese-Spanish shared rivers reality, some public information and discussion of the corresponding RBMPs (currently being implemented and to be revised in 2015, according to WFD implementation schedule) have occurred, promoted – some few sessions jointly – by the Portuguese and the Spanish River Basin Districts Administrations. However, the Stakeholder participation is considered insufficient, with river councils ineffective since 2011, in Portugal, and consultation with downstream transboundary impacts insufficient, in Spain (Brito et al. 2013).

Several paradoxes in multistate water management and governance across borders militate against the assessment of socio-economic impacts, the development of communities of practice, and the effective use of scientific information for meeting short term needs in the context of reducing longer-term vulnerabilities. Much of the work and experience produced has shown that long-term environmental problems can seldom be dealt with by single discrete actions or policies but tend to respond only to continued, sustained efforts towards learning, supported by steady public attention and visibility. At the same time, there is an increasing number of calls for greater decentralization, along with calls for better coordination.

The scale at which reliable climate change information is produced (i.e. global, regional) does not always match that which is needed for adaptation decisions (i.e. watershed and local scales). Relatively short records also limit the application of purely technical "solutions". There are also significant gaps in the knowledge regarding adaptation, as well as impediments to flows of knowledge and information relevant for decision makers. The cases show that changes in the management of climate-related risks (in this case "drought") may be most readily accomplished when: (1) a focusing event (climatic, legal, or social) occurs, creating widespread public awareness and opportunities for action; (2) leadership and the public, the so-called "policy entrepreneurs", are engaged; and (3) a basis for integrating research and management is established. This latter dimension should provide the basis for developing the capacity to apply knowledge and to evaluate the consequences of actions amongst partners, to ensure the reliability and credibility of the projections of changes in the system outputs and to enable acceptable revisions on management practices in light of new information.

If lessons learned are to be actually applied, then a significant part of the scientific goal should be dedicated to inform processes that can decrease impediments to the flow of information and innovations. Developing such an integrated basis for managing water resources in both Basins requires a mixed portfolio of approaches, including mechanisms for anticipatory coordination within development plans (e.g. adaptive management within integrated watershed and coastal zone plans) that considers the consequences of short-term adjustments in the context of longer-term risks enablement or restraint. One such innovation, in the Colorado Basin, is the National Integrated Drought Information System (NIDIS) that provides coordination of diverse state, local data and information for supporting planning and preparedness (Pulwarty and Verdin 2013). The NIDIS:

- Develops usable climate risk management triggers for early warning of potential impacts in agriculture, water, energy, health, environment, and coastal zones;
- Conducts studies to understand and characterize environmental consumptive use trade-offs and environmental management-"best bets", given thresholds and irreversibility, and inflow scenarios;
- Actively engages communities and states in mainstreaming climate information into practice though participatory mechanisms, such as the co-development of scenarios that link climate and management goals.

Most major programs for complex utilization of rivers assume that average conditions for hydrologic records available at the time of project planning phase will remain stable into the future. Relatively short records have resulted in overestimations of supply or underestimations of demand in long-term analysis. The complications resulting from changes in the spatial and temporal distributions of rainfall, soil moisture, runoff, frequency and magnitudes of droughts and floods have not been explicitly included in response planning, even though some initial steps are being taken (Gleick 1993; Pulwarty and Melis 2001; IPCC 2008). The end result is that, in the absence of an explicit discussion of conflicts, the policy process is pushed toward the "technological fix" and time and resources are therefore allocated towards achieving near-term tangible results, rather than long-term solutions. Practice thus becomes largely issue-specific and incremental, with a focus on "winners" and "losers" rather than on the development of a consensual vision of the preferred future. There is, in addition, limited experience regarding the managing impacts of severe events, such as persistent drought, in the context of projected rates of development or in the context of closed international water systems.

Management, in the context of a changing climate, must emphasize the dynamic nature of climate (in terms of extremes, variability and change), of choices of lessons and innovations, and system robustness for potential sensitivity to surprises, given changing baselines. In the process of meeting the new challenges and tradeoffs brought on by a changing and variable environment and societal changes, decision makers and researchers simply do not know how precisely we must plan. Expectations about the future tend to be better understood by people within organizations if there is a clear parallel with the past. Incentives for conservation and opportunities for reallocating supplies as conditions change do not require long lead times, large financial commitments or accurate information about the future. There is, however, a clear need for exchange of experiences and learning among different basins, especially on how awareness of slow onset problems, in the context of decadal-scale variability, is developed and the ways in which societies and leadership have adjusted to them. A conspicuous aspect of water management across the basins has been the lack of careful post-audits (systematic and iterative evaluations) of the social and economic consequences of previous programs and ongoing projects (White 1988). One of the most important benefits that may be realized through a comparative study is an understanding of why some policies can be chosen over others, how these are related to particular climatic events, which ones rise to prominence, how the lessons become socialized into perception and practice, and which are allowed to persist. The identification of the barriers to implementation and evaluation in one setting may shed light on the likelihood of success of similar actions in another setting.

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