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ORIGINAL ARTICLE

Integrated energy-water-land nexus planning in the Colorado River Basin (Argentina)

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Abstract

Integrated energy-water-land (EWL) planning promotes synergies and avoids conflicts in ways that sector-specific planning approaches cannot. Many important decisions that influence emerging EWL nexus issues are implemented at regional (e.g., large river basin, electricity grid) and sub-regional (e.g., small river basin, irrigation district) scales. However, actual implementation of integrated planning at these scales has been limited. Simply collecting and visualizing data and interconnections across multiple sectors and sub-regions in a single modeling platform is a unique endeavor in many regions. This study introduces and applies a novel approach to linking together multiple sub-regions in a single platform to characterize and visualize EWL resource use, EWL system linkages within and among sub-regions, and the EWL nexus implications of future policies and investments. This integrated planning methodology is applied in the water-stressed Colorado River Basin in Argentina, which is facing increasing demands for agricultural and fossil fuel commodities. Guided by stakeholders, this study seeks to inform basin planning activities by characterizing and visualizing (1) the basin's current state of EWL resources, (2) the linkages between sectors within and among basin sub-regions, and (3) the EWL nexus implications of planned future agricultural development activities. Results show that water scarcity, driven in part by human demands that have historically reached 60% of total surface water supply, poses a substantial constraint to economic development in the basin. The Colorado basin has the potential to serve as a testbed for crafting novel and generalizable sub-regional EWL planning approaches capable of informing the EWL planning dialogue globally.

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Introduction

Many regions of the world have developed effective institutional and infrastructural mechanisms for managing resources within individual sectors. For example, river basin commissions have long existed to serve roles such as enforcing legally binding water compacts, developing drought contingency plans, facilitating coordination among multiple actors with conflicting water objectives and rights, and synthesizing and summarizing state-of-the-art knowledge about the physical functioning of the riverine system (Loucks et al. 1981; Gopalakrishnan 2005; Hooper 2010; Kauffman 2015). However, the traditional sectoral planning paradigm is becoming decreasingly effective because energy, water, and land (EWL) systems are becoming increasingly interconnected and strained (Bazilian et al. 2011; Ringler et al. 2013; Scanlon et al. 2017; D'Odorico et al. 2018; Liu et al. 2018). For example, pumping and treating water can have steep electricity requirements (Sanders and Webber 2012), while the electricity system may in turn demand significant quantities of cooling water (Feeley et al. 2008). Meanwhile, the electricity system may increasingly rely on agricultural products (e.g., biomass) to meet demands for a decarbonized electricity system to mitigate climate change (Azar et al. 2010), which in turn increases agricultural water demand (Gerbens-Leenes et al. 2009). Characterizing EWL system linkages creates opportunities to discover synergistic options (e.g., infrastructure investment plans), as well as to avoid plans that give rise to unnecessarily sharp conflicts across EWL systems. Ultimately, the success of ambitious efforts currently underway at national and global scales, such as the Sustainable Development Goals (SDGs) and mid-century strategies to mitigate climate change, will require more integrated planning at the regional (e.g., river basin) and sub-regional (e.g., sub-basin) scales at which many important EWL decisions are made.

Extensive research in the past two decades has enhanced EWL nexus modeling at the scale of river basins and sub-basins (Johnson et al. 2019). However, most studies have focused on representing particular sectors (e.g., water) in more detail (Endo et al. 2017; Miralles-Wilhelm 2016), rather than focusing explicitly and holistically on the linkages among multiple sectors. Most experts have sector-specific training that gives them an appreciation for sectoral complexities but may cause an over-reliance on familiar tools or problem formulations favoring their expertise (Kaplan 1964; Wild et al. 2021). However, we argue that for studies seeking to explore interconnectivity across multiple sectors, there is value in holistically representing all sectors with a similar level of detail. This philosophy has been used effectively by the Integrated Assessment Modeling (IAM) community in studies of regional, national, and global human-earth system interactions (Calvin and Bond-Lamberty 2018; Weyant 2017; Fisher-Vanden and Weyant 2020). A pillar of the IAM approach is to constrain the level of detail with which particular systems are modeled in order to allow for greater focus on the interactions between systems and to maintain computational and data tractability. Because of this tractability, IAMs have proven valuable for stakeholder-driven research (Salter et al. 2010) on long-term, coarse scale (regional-to-global) challenges (Fisher-Vanden and Weyant 2020). However, holistic multi-sector analysis poses a challenge in smaller regions (e.g., within river basins) or sectors, particularly when data are scarce. This paper introduces an option for addressing the data scarcity challenge in a multi-sector sub-regional planning context, by fusing together local data sets with globally available data sets that are commonly used by the IAM community. The methodology we introduce contributes to the emerging field of MultiSector Dynamics, which seeks to develop tools that improve our understanding of the co-evolution of human and natural systems over time by building tools that bridge across sectors (energy, water, land, economy) and scales (spatial, temporal) (US DOE (United States Department of Energy) 2020; Fisher-Vanden and Weyant 2020).

Argentina provides a rich context for exploring the potential to holistically characterize sub-regional EWL system tradeoffs. Arid and semi-arid lands cover two thirds of the country (Calcagno et al. 2000). As a result, Argentina has the lowest mean annual rainfall depth total among all countries in the Latin America and Caribbean (LAC) region (Willaarts et al. 2014). Meanwhile, water-intensive agricultural production accounts for over 10% of Argentina's GDP, which is the highest share among the LAC region's larger economies (Central Intelligence Agency (CIA) 2019). Indeed, 54% of Argentina's total land area is used for agricultural purposes. As countries around the world seek to decarbonize their economies consistent with their pledges in the Paris Climate Agreement (Iyer et al. 2015), Argentina's land resources could undergo significant change to accommodate increased demands for crops (Dallemand et al. 2015; Scarlat et al. 2015; da Silva et al. 2019; Bataille et al. 2020; Mahlknecht et al. 2020). The resulting competition for land and water could have non-trivial implications for food security (Fujimori et al. 2019). Climate change could sharpen these tradeoffs by reducing water supplies and renewable energy potential (e.g., hydropower, wind, and solar) in some regions of Argentina, with concomitant implications for electricity sector investment needs (Turner et al. 2017; da Silva et al. 2021).

The Colorado River Basin in Argentina is a microcosm of the EWL system interactions discussed above. Fig. 1a shows the 48,000 km^2 Colorado basin, which meanders for over 1100 km from Argentina's western border with Chile in the Andes mountains to its eastern outlet into the Atlantic Ocean. Agriculture drives the basin's economy (COIRCO 2014), yet this economic model is exposed to water scarcity risk. The basin's land is semi-arid desert, with evapotranspiration potential that exceeds its limited precipitation. The basin has experienced frequent extreme drought conditions during the last 10 years. Additionally, the snowpack that feeds the basin's runoff could steeply decline as a result of global climate change impacts (Nogués-Bravo et al. 2007; Adam et al. 2009). Climate impacts on global crop yields could also induce shifts in global agricultural trade patterns that increase pressure to produce water consumptive crops in Argentina in a handful of hotspot basins, including the Colorado basin. In this sense, climate impacts could manifest most prominently in the Colorado basin through the human system—via agricultural trade—rather than through physical climate impacts (Baker et al. 2018). This is consistent with other studies demonstrating that human impacts on water systems can outpace physical climate impacts (Graham et al. 2019). Meanwhile, human water demands in the Colorado basin are increasing for irrigation, fossil fuel extraction, and municipal needs (COIRCO 2014). Population growth within and beyond the basin is increasing municipal water demands (Supplementary Fig. S1), as is occurring in other parts of the world (Garrick et al. 2019). Electricity demands within the basin are satisfied by a national grid. The electricity generated within the basin, which feeds into the national grid, is exposed to climate change risk given its heavy reliance on hydropower for 50% of total generation.

Clearly, the future will pose EWL system planning challenges for the Colorado basin, particularly given the relatively limited cross-sector coordination that currently takes place among the basin's five provinces. In this sense, the basin represents an ideal testbed for crafting novel and generalizable sub-regional EWL planning approaches capable of informing the regional EWL planning dialogue globally. Studies in the LAC region also present an important and unique perspective; because, despite the complex EWL linkages that characterize the LAC region, most integrated EWL studies has focused on Europe and North America (Khan et al. 2020b).

The five political provinces that share the basin's resources are collectively pursuing multiple conflicting objectives that require careful coordination to achieve more balanced and sustainable outcomes as resource demands increase and become more intertwined. For example, the La Pampa and Rio Negro provinces are considering plans to increase irrigated land use by 30% in total in the coming years (COIRCO 2014), which may affect water availability for downstream users. Water-intensive oil and gas extraction are expected to increase in different areas of the basin as well. Finally, new proposed infrastructure projects (e.g., large dams) could disrupt the spatiotemporal distribution of water within the basin. To establish the Colorado basin as a testbed for evaluating novel, integrated sub-regional planning approaches, we organized a multidisciplinary team in Argentina comprised of academic researchers, regional development experts, national government representatives, and river basin committee representatives. This paper addresses the following stakeholder-driven research questions in the Colorado basin:

(1) Resource accounting. What are the current energy, water, and land supplies and demands within the basin, and what interlinkages exist among these sectors?
(2) Policy. What will be the energy, water, and land implications of planned (and/or under construction) agricultural expansion projects in the basin?

In addressing these questions, our objective was to develop and apply an accounting framework to identify EWL system issues that warrant more detailed consideration. This insight can provide context to sectoral experts as they consider the EWL nexus implications of their sectoral plans. This study seeks to demonstrate that this more strategic planning approach has the potential to promote synergies and avoid tradeoffs in ways that current sector-specific planning approaches cannot. In this sense, our study and modeling approach seek to complement, rather than replace, existing sectoral planning approaches. The study's results can be fully reproduced by downloading the input files and software at https://github.com/FeralFlows/wild-etal_2021_ColoradoNexus.

Methodology

Study region

The Colorado basin is in the Northern (semi-arid) portion of Argentina's Patagonia region. Argentina's more temperate Cuyo and Dry Pampas regions lie to the north of Patagonia, so the basin is situated in a transition zone between semi-arid and temperate climatic regions. The basin's mean annual runoff of 4.6 km^3 is largely generated by snowmelt in the Andes mountains that flows downstream through the two large tributaries shown toward the basin's headwaters in Fig. 1a: the Grande River (to the north) and the Barrancas River (to the south). Approximately 70% of the basin's mean daily natural flow of 150 m^3/s (at the basin outlet) is contributed by the Grande River, while most of the remaining 30% is contributed by the Barrancas River. The basin's land downstream of the Barrancas and Grande tributaries is semi-arid desert with evapotranspiration potential that exceeds its limited

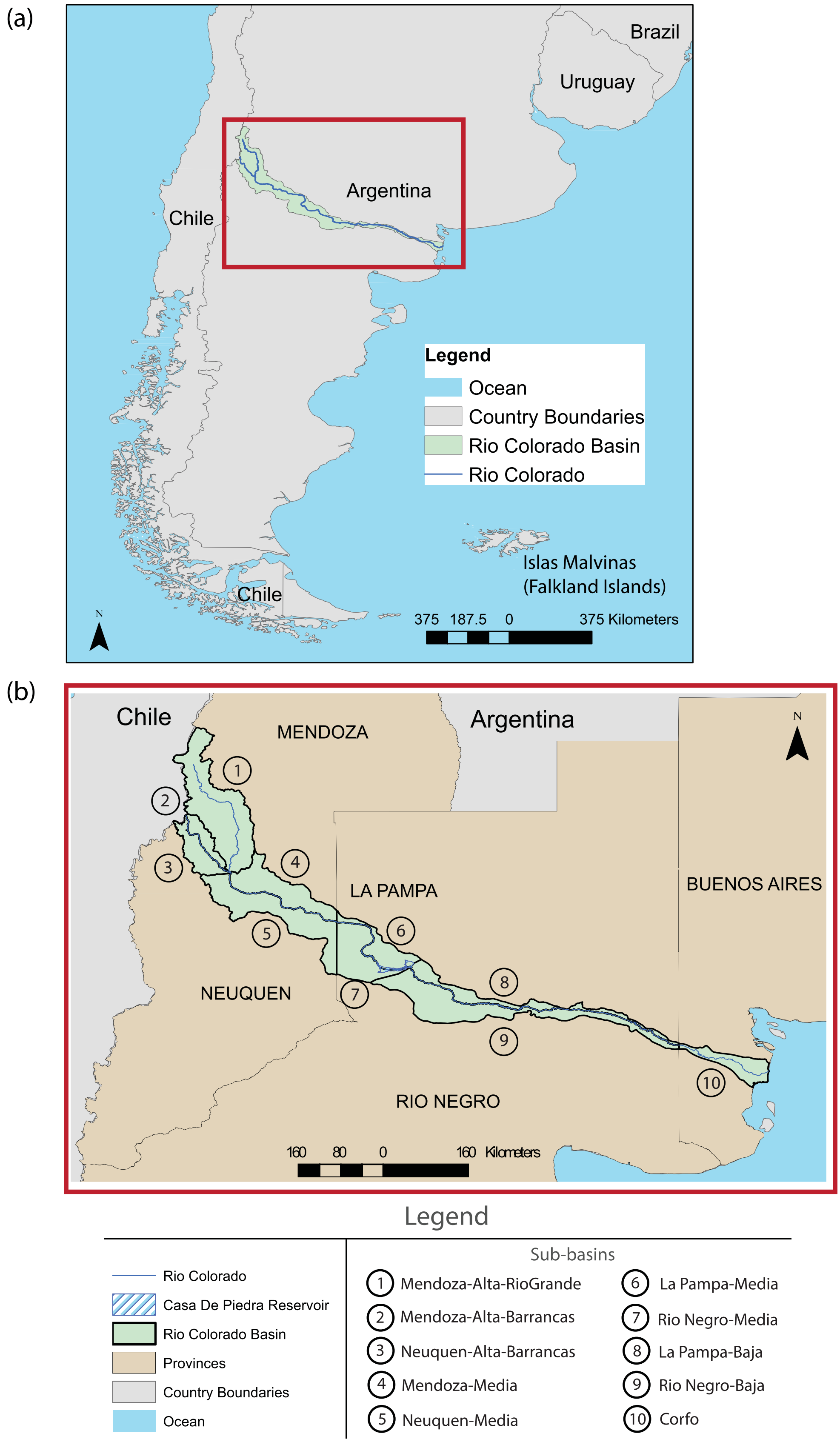

Fig. 1 **a** Colorado River Basin in Argentina. **b** Ten sub-regions within the Colorado basin considered in this study

precipitation. The basin has a single reservoir, Casa de Piedra, which has 2.6 km^3 of total storage capacity.

The Colorado basin has three climate-land zones characterized by distinct differences in climate, land cover, and land use: Alta (i.e., "Upper"), Media (i.e., "Middle"), and Baja (i.e., "Lower"). The Alta region to the northwest includes part of the Andes mountains and produces much of the basin's precipitation (mostly via snowfall) and runoff (mostly via snowmelt). Sub-regions downstream of Alta are defined by semi-arid desert land with significant evapotranspiration potential. On its way to the Atlantic Ocean, water flows downstream from the Alta region into the Media region, which extends southeast to the Casa de Piedra dam and reservoir. Water then flows through the Baja region, which includes the Bonaerense Valley Development Corporation of the Colorado River (i.e., CORFO) sub-region. The economic activity of the entire basin is strongly shaped by the industrial agricultural output in the CORFO sub-region. As shown in Fig. 1b, the basin's three climate-land zones intersect five different political provinces: Mendoza, Neuquén, La Pampa, Río Negro, and Buenos Aires. The ten distinct sub-regions we explore in this study generally form the intersection between the three climate-land zones and five political provinces. The sub-region names are a combination of the province and climate-land zone names. For example, "La Pampa-Media" is the portion of the Colorado River Basin that lies in both the La Pampa province and the Media climate-land zone. For sub-regions situated within the Media and Baja zones, the river itself demarcates the sub-regions, as provinces are situated on opposite sides of the river. The Alta region is an exception to this sub-regional naming nomenclature. The Alta region is divided into two river sub-basins: the Grande River to the north and the Barrancas River to the south. Thus, sub-regions within the Alta zone are subdivided not just by province, but also by sub-basin. Finally, the CORFO sub-region is separated out from the Baja region due to its unique agricultural and economic character.

Scenarios

To address the two study questions posed in the "Introduction" section, we co-developed two decision-relevant scenarios with stakeholders, including academic researchers, regional development experts, national government representatives, and members of the Colorado River Basin planning committee. Our intention here is not to predict the likelihood of any particular future; rather, it is to demonstrate an approach for identifying potential EWL challenges and opportunities that may arise in the Colorado basin. Toward this goal, we explore the following two scenarios in this study:

1. **Reference scenario**. This scenario uses representative historical EWL data in the Colorado River Basin to establish a holistic spatial accounting of historical EWL resources and an evaluation of the interrelationships among sectors. No major forces (e.g., climate change) are imposed on the basin. However, given we account here for historical resource usage patterns (e.g., human water demands), EWL policies that were in place in the historical period (e.g., environmental flow requirements) are indirectly accounted for in the Reference scenario if they affected historical EWL resource usage. Conducting a holistic accounting of EWL resources and interconnectivity, as is conducted in the Reference scenario, is a unique endeavor in many river basins, with few examples appearing in the literature (Wada et al. 2019; Vinca et al. 2020).
2. **Agricultural policy scenario**. This scenario builds on the historical data and sectoral interconnectivity developed in the Reference scenario by superimposing on it a planned policy that increases basin-wide irrigated cropland by 30% (from 1570 to 2044 km^2), with expansion confined to the La Pampa-Baja and Río Negro-Baja sub-regions (COIRCO 2014). Supplementary Fig. S2 provides a schematic of the greater Colorado River Basin's 27 independent irrigation systems (COIRCO 2014), including the planned expansions that constitute the policy scenario. Irrigation districts in the Colorado basin are currently irrigating only 30% of total irrigable land (COIRCO 2014). Thus, there remains significant potential to generate economic growth in the basin by irrigating additional land to increase agricultural output. In some cases, this can be accomplished by using or expanding existing irrigation systems, whereas in other cases new irrigation systems would need to be constructed.

Modeling framework and data

To facilitate evaluation of sub-regional EWL resources, sectoral connectivity, and futures under alternative development strategies, we developed and applied the Metis model. Metis' software design and features are described in the corresponding publication for Metis v.1.0.0 (Khan et al. 2020a). Metis integrates multiple sectors within a single framework to facilitate analysis across sectors, including electricity, water, and land, at any user-defined spatial and temporal scale of interest (e.g., small or large river basins, electricity grid regions, or political boundaries). Metis is designed specifically to assemble, harmonize, and visualize multi-sector data sets characterized by variable spatial resolution, by aggregating or disaggregating these data to a common spatial resolution of interest for a given analysis (e.g., the 10 sub-regions in this study). The harmonized data are used to infer relationships between the sectors (e.g., the quantity of water used in the energy sector). These relationships, defined through an input-output matrix analysis approach (Miller and Blair 2009), can then be used to explore the cross-sector implications (i.e., nexus impacts) of alternative future policies or investments, such as hydropower or irrigation expansion. In a similar fashion to integrated assessment models (e.g., Calvin et al. 2019), Metis is capable of representing all sectors with comparable detail and resolution, rather than focusing attention on representing particular sectors in more detail. There are few examples in the literature of sub-regional nexus models capable of flexibly addressing multiple sectors equally, while also interacting with large-scale national or global integrated assessment models (e.g., Vinca et al. 2019).

Data scarcity can be a significant constraint in regional and sub-regional planning studies seeking to evaluate multi-sector dynamics. Metis seeks to overcome this barrier by providing users with default data sets describing EWL supplies and demands for their specific region of interest. Metis' default data set is built using inputs and outputs of the open-source Global Change Analysis Model (GCAM) (Calvin et al. 2019). GCAM is a global integrated assessment model used to capture long-term regional and global EWL dynamics in response to drivers such as socioeconomic change, technological change, and policy decisions. The version of GCAM we use in this study, GCAM-LAC, represents the global energy-economy system by disaggregating the world into 33 geopolitical regions, including Argentina. Within GCAM, Argentina's water and land systems operate at the level of 12 large river basins, including the Colorado basin. Metis leverages GCAM's strength in collecting and organizing consistent, historical, EWL data sets with global coverage, including not just resources but also technology costs and sectoral relationships. A suite of downscaling EWL models designed specifically to interact with GCAM then project GCAM data onto a grid, thus enabling finer resolution evaluation of EWL interactions. The broader GCAM suite of tools produces a globally consistent, downscaled set of gridded EWL data that Metis uses by default, at variable resolutions between 0.25 and 0.5°. The downscaling tools enable sub-regional planning issues to be linked to broader national and international dynamics, although these broader linkages are not a focus of this initial Metis application in the Colorado basin. Metis aggregates the downscaled, gridded data to any spatial boundary.

Users can overwrite Metis' default data sets at any time as local data (e.g., supplied by stakeholders) become available. Additionally, users may wish to overwrite default data using outputs from fine-scale sectoral modeling tools, such as a water management model (e.g., HYDROBID, WEAP) or electricity planning models (e.g., PLEXOS) (WEAP 2017; Moreda et al. 2016; PLEXOS 2017). In this study, the local data (Supplementary Table S4) consist of a mix of point and distributed data sources, such as power plant locations and corresponding electricity generation values, electricity demand by end-use sectors, populations of individual cities, land areas used for particular crops, water demand and consumption for irrigation systems, and surface and groundwater supply.

In general, using a mix of global and local data sets can introduce challenges in maintaining compatibility among assumptions across the different data sets. In this study, the wide sectoral coverage and quality of the data set available in the Colorado basin significantly limited the extent to which we ultimately used global data sets (COIRCO 2014). We use three core data sets from GCAM that were not available locally for each sub-region: (1) electricity sector water withdrawal intensity (Macknick et al. 2012); (2) livestock water withdrawal intensity (Mekonnen and Hoekstra 2012); and (3) the proportion of water withdrawals in each irrigation system/sub-region allocated to individual crop types. These data are summarized in detail in Section I of the Supplementary materials. The fused data set serves as the basis for the resource accounting and sectoral interconnectivity calibration and analysis in the reference scenario.

After aggregating data to relevant spatial and temporal scales, Metis identifies the relationships among sectors using linear input/output methods to establish correlation matrices. The input-output structure tracks physical commodity flows, rather than economic flows, between sectors in each sub-region. Correlation matrices are calibrated to reproduce historical (2010-2015) inter-sectoral linkages by calculating intensity coefficients that describe the commodity flows from one sector (e.g., electricity) that are required to produce one unit of output in another sector (e.g., water). Imports and exports are assumed to occur to ensure that commodity flows balance, in the sense that all demands are met by a supply source. An abstracted representation of a Metis sectoral connectivity table for a given sub-region is shown in Supplementary Figs. S3 and S4. The mathematical relationships that describe inter-sectoral flows in Metis are given in Supplementary Eqs. S1a–S1e.

Currently, Metis allows users to represent both supplies and demands in three main sectors: land use and/or agricultural production, water, and electricity. Within these main sectors, users can also establish sub-sectors (e.g., natural gas, solar PV) or technologies (e.g., combined cycle natural gas with once-through cooling, or distributed rooftop PV versus centralized PV generation). The sectors and their interlinkages that exist in any given Metis application will depend upon the data used to populate the model. Section I of the Supplementary materials discusses the sectoral and sub-sectoral data used in this study to populate the connectivity table for the Colorado basin. The two key sectoral linkages established in this study (see Supplementary Table S4) were (1) water for agricultural production and (2) water for energy production. The data sets employed in this study did not support other linkages. For example, in this basin, no strong linkage currently exists between irrigation and electricity because the majority of the basin's irrigation districts are supplied by gravity-fed distribution systems rather than pumped water.

The calibration process described above is performed for every sub-region. Imports (e.g., water transfers) are assumed to occur if inadequate sub-regional supply exists to satisfy demands, and exports are assumed to occur if excess supply (e.g., surface water runoff) exists. However, the model does not specifically track the external sub-regional source or destination of imports or exports, except for water. Water naturally flows from upstream sub-regions to downstream sub-regions, so Metis includes basic flow routing procedures that pass water between sub-regions, guided by a user-defined network flow connectivity matrix. Any water that is consumed (e.g., through evaporation or losses to deep aquifers) is removed from the water balance as the water passes to downstream sub-regions.

Having established sectoral intensity coefficients in the reference scenario, the policy scenario is executed by increasing agricultural land use and commodity demands in certain sub-regions. Those sectors (e.g., water) that are linked to agricultural demands through intensity coefficients then experience increased demands. In this sense, Metis v.1.0.0 is not a traditional process-based simulation model that evaluates the implications of policies by proceeding forward in time at incremental time steps to evaluate the dynamic interaction among sectors. Rather, Metis v1.0.0 focuses on assembling, harmonizing, and visualizing multi-sector data, and on discovering sectoral connectivity, in order to explore the multi-sector implications of sectoral changes, much like comparative static analysis. Metis enables a first-order analysis to be conducted to identify broad issues worth further exploring with more detailed modeling tools.

Results and discussion

Reference scenario

Resource accounting

Figure 2 presents a visual multi-sector assessment of the current state of EWL supplies and demands in the Colorado basin. Figure 2a shows that agricultural production drives the basin's economy and was responsible for a total revenue of approximately 12 million USD in 2010. Most of this production is concentrated in the southeastern portion of the basin, particularly in the CORFO sub-region, which is also responsible for most of the basin's industrial agricultural and livestock output. Some the basin's most populous sub-regions (e.g., Neuquén-Media) have limited agricultural production, while the most agriculturally productive region, CORFO, has a relatively small population. Supplementary Fig. S1 shows the basin's population distribution. In 2010, about 75,000 people lived within the basin's physical boundaries, most of whom live in the Neuquén-Media, Río Negro-Media, and Río Negro-Baja sub-regions. Another approximately 650,000 people draw on the basin's water resources from outside the basin's physical watershed boundary). Of the basin's 50,000 km^2 surface area, only about 1600 km^2 is actively used agricultural land. Supplementary Fig. S5 shows the spatial distribution of this 1600 km^2 of land by crop type and sub-region for the following aggregate categories: cereals (wheat, corn, sunflower seeds), specialty (olives, walnuts, and wine), fruit trees (pears and apples), pasture (alfalfa, fescue, and fodder), and vegetables (onion and squash). The largest land allocation by crop is pasture (1110 km^2), followed by cereals (558 km^2). Combined pasture and cereals account for 75% of land allocation for crops. Despite its relatively smaller share of land, vegetables (240 km^2) are responsible for well over 50% of the basin's agricultural revenue, largely from onion production.

Given the importance of agricultural production for the region's economic growth, it is important to identify factors that could (or already do) limit the sector's productivity. Water (Fig. 2b) is a key issue in this regard because (1) the basin's mean annual runoff of 4.6 km^3 is largely generated by snowmelt in the Andes mountains, far upstream of where agricultural production takes place; and (2) much of the basin's agricultural production takes place in a semi-arid desert environment, which gives rise to water losses through evapotranspiration and groundwater infiltration that exceed the magnitude of runoff in many areas (COIRCO 2014). For this reason, rainfed irrigation is essentially non-existent in the basin. Figure 2b provides a visual summary of sub-regional water supply and demand. Some level of supply (i.e., runoff) occurs in most parts of the basin, but nearly all of the basin's total runoff is produced in the Alta sub-region. Data suggest that groundwater is not a significant source of supply throughout the basin. Likewise, the majority of water demands take place in a small subset of sub-regions: CORFO, La Pampa-Baja, and Río Negro-Baja.

Importantly, Fig. 2b shows that the agriculturally productive CORFO sub-region is already experiencing severe water scarcity. As detailed in Section IV of the Supplementary materials, water scarcity is defined here as the quotient of the magnitude of water demands relative to available water supply (Raskin et al. 1997; Rijsberman 2006; Savenije 2000). Likewise, La Pampa-Media and Río Negro-Baja are beginning to experience low levels of water scarcity. The presence of water scarcity is a result of both supply-side and demand-side factors. On the demand side, Supplementary Fig. S6 shows that irrigation water withdrawals are significant in the regions experiencing some level of scarcity, largely as a result of cereals and pasture operations. Figure S6 puts the scale of irrigation withdrawals into context in the water sector by visualizing irrigation demands alongside municipal water demands, livestock water demands, and electricity water

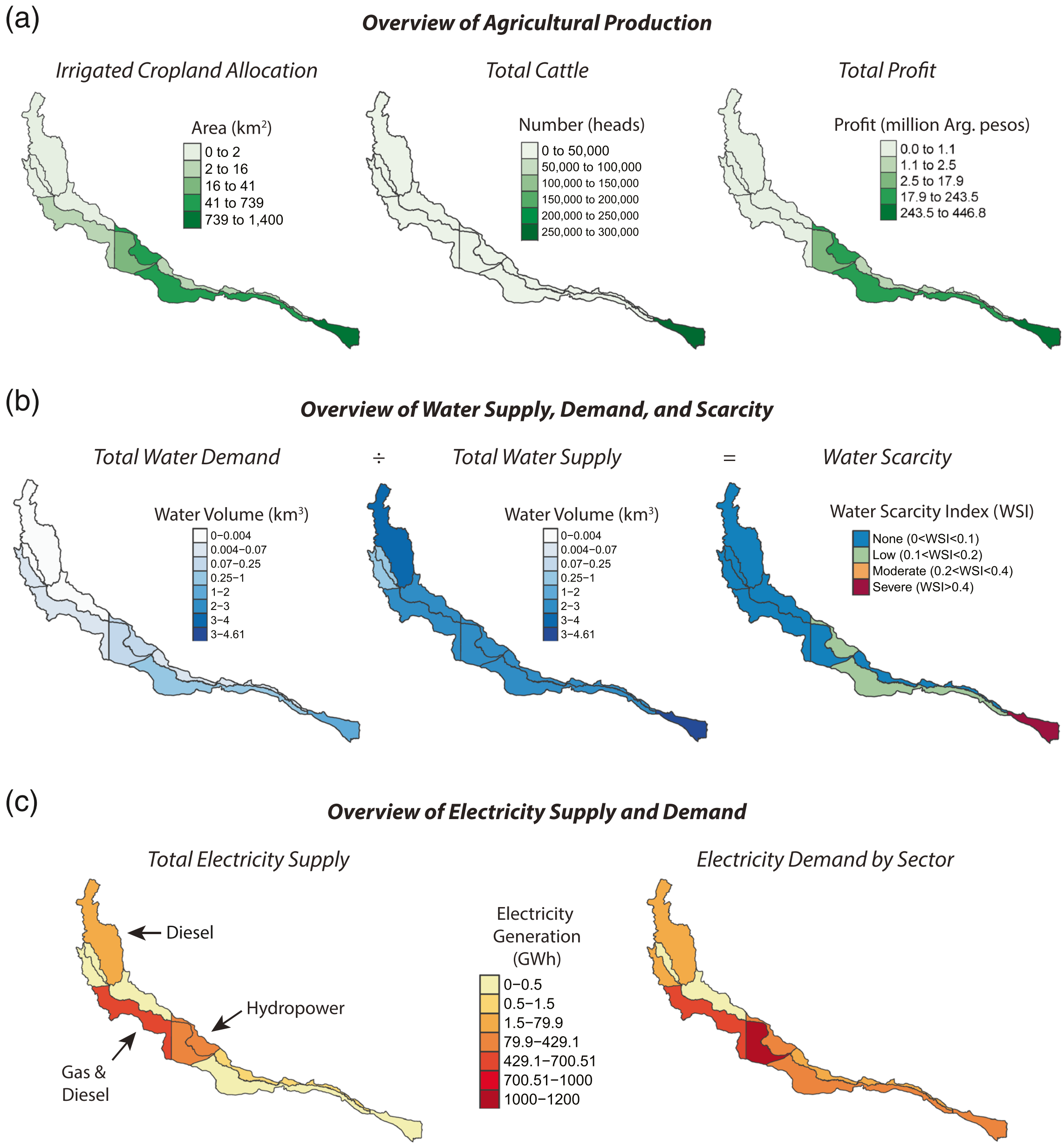

Fig. 2 Reference scenario (i.e., historical) spatial visualization of the Colorado Basin's **a** cropland allocation, livestock production, and agricultural profit; **b** water supply, demand, and scarcity; and **c** electricity supply and demand

demands (for cooling). While irrigation water demands are indeed the largest by sub-sector, the other sub-sectors still contribute to the reduction in water availability in CORFO, La Pampa-Media, and Río Negro-Baja. This is because water usage in many sub-regions is highly consumptive (i.e., resulting in significant losses of water from the system), which reduces the flow of water into the downstream sub-regions experiencing scarcity.

Power plants within the basin generate 1000 GWh of electricity to feed into the national grid. This supply comes from hydropower (the Casa de Piedra dam), as well as several thermal plants supplied by diesel and gas. Currently, electricity generation within the basin is about 50% hydropower and 50% thermal generation (see Fig. 2c). Because electricity is supplied by the national grid, which is in turn supplied by a variety of generation technologies, the electricity mix that supplies demands within the basin is different than the mix of generation within the basin. Supplementary Fig. S7 shows that end-use demands from commercial, residential, building, and other sub-sectors total about 2000 GWh/year, making the basin a "net importer" of electricity from the grid.

Currently, there is no strong linkage between the electricity and agricultural systems. The electricity system does not rely on inputs from the local agricultural system to generate power (e.g., biomass generation), and Metis v1.0.0 does not represent energy usage in the agriculture sector (e.g., fuel usage to operate machinery) due to its relatively limited magnitude. The electricity system may become more interconnected with the agricultural and water systems as Argentina increases efforts to mitigate greenhouse gas emissions via bioenergy production.

Sectoral interconnectivity

The spatial visualization in Fig. 2 (and Supplementary Fig. S5–Fig. S7), while valuable, does not explicitly quantify the interlinkages among sectors. Figure 3 uses a Sankey diagram to explicitly visualize the relationships among sectors in a single diagram, in this case for the entire Colorado basin, as well as for two selected sub-regions, CORFO and Rio Negro-Baja. The left-hand side of each diagram represents supply, while the right-hand side represents the end-use demand sectors receiving that supply. Each sector, represented by a different color, has a supply bar of equal width; thus, supply bars should not be compared across sectors (i.e., water vs. electricity). Each sector's identically sized supply bar is then subdivided by demand destination. To facilitate visualization, Fig. 3a aggregates supply sub-sectors into single aggregate supply categories (e.g., "Agriculture_all"). Figure 3b and c divides supply into its full constituent supply sub-sector categories for the selected two sub-regions.

Figure 3 shows that most of the basin's production of crops and livestock is to satisfy demands that are external to the basin (i.e., exports), as the basin's production is far in excess of demand within the basin. With respect to electricity supply and demand, the basin's more than 2000 GWh/yr supply from the national grid is largely serving industrial demand, followed by smaller categories such as residential, other, and commercial uses. The basin's 4.6 km^3 water supply is almost entirely sourced from surface water runoff, some of which is then stored and supplied by the Casa de Piedra reservoir. About 60% of the surface water supply has historically been used for purposes of agricultural production. Given the basin's high rate of consumption associated with irrigation (i.e., about 80% on average across the basin's irrigation systems), much of the irrigation water is lost to the system. This is why nearly 50% of the basin's surface water is lost in the system to evaporation or groundwater infiltration prior to reaching the basin's outlet. The remaining 50% is ultimately discharged into the ocean.

While it is valuable to conduct a basin-wide multi-sector assessment, it can also be valuable to evaluate individual sub-regions and sub-sectors in more detail with respect to EWL nexus flows. Figure 3 displays Sankey diagrams for two sub-regions that face water scarcity concerns: CORFO and Río Negro-Baja. In CORFO, pasture and cows dominate crop and livestock production activity, respectively. Meanwhile, in the electricity system, CORO demand constitutes a very small fraction of total basin demand. In Fig. 3a (i.e., the entire Colorado basin), 4.6 km^3 of water is suppled in total. However, note that in the CORFO Sankey diagram in Fig. 3, only 4.1 km^3 of the original 4.6 km^3 of surface water remains to be supplied due to inefficiency losses occurring in upstream sub-regions.

The scale of agricultural production in Río Negro-Baja is much smaller than in CORFO, so water consumption in Río Negro-Baja is less than water consumption in CORFO, as a result of evapotranspiration and infiltration from irrigation system operation. As shown in Fig. 1b, the Colorado River itself serves as the boundary between some sub-regions. In these cases, we allocate half of water flowing from upstream to both of the sub-regions on either side of the river. Rather than seeking to accurately represent the basin's complex water rights structure, we capture a coarse representation of legal constraints on water usage by equally partitioning water supply between the two opposite sub-regions, which are managed by different provinces. This is why the Sankey diagram in Fig. 3 shows only 2.2 km^3 of water supply in Río Negro-Baja versus 3.2 km^3 in the downstream CORFO region, despite no new surface water runoff. That is, Río Negro-Baja is assumed to have rights to only half of the 4.4 km^3 of water flowing from upstream, while CORFO is assumed to have rights to all of the water flowing from upstream since it shares the river with no neighboring sub-regions.

Agricultural expansion (policy) scenario

Figure 4 summarizes the land allocation by crop in the reference scenario versus the policy scenario. Expansion in the policy scenario is confined to the La Pampa-Baja (Fig. 4a) and Río Negro-Baja (Fig. 4b) sub-regions. Figure 4b shows that the La Pampa-Baja sub-region currently has very limited irrigated cropland, so it experiences an increase in land allocation by several orders of magnitude.

Implementing the agricultural land use expansion practices shown in Fig. 4 would increase agricultural revenue by 6 million USD per year. This represents a 50% increase in the basin's agricultural revenue. However, Fig. 5 shows that the agricultural sector is highly interconnected with the water sector. Thus, compared to the reference scenario (Fig. 5a), the policy scenario (Fig. 5b) results in significantly more of the basin's 4.6 km^3 surface water supply being used for highly consumptive agricultural purposes. This result is apparent when reviewing the difference in how water supply is partitioned to end-use demands in Fig. 5a versus Fig. 5b.

Figure 6 shows that this extensive agricultural expansion also has the potential to introduce moderate water scarcity in the La Pampa-Baja and Río Negro-Baja sub-regions. While severe water scarcity already exists in CORFO, the increased withdrawal and consumption of water in La Pampa-Baja and Río Negro-Baja sub-regions in the policy scenario would also worsen scarcity downstream in CORFO. Importantly, to

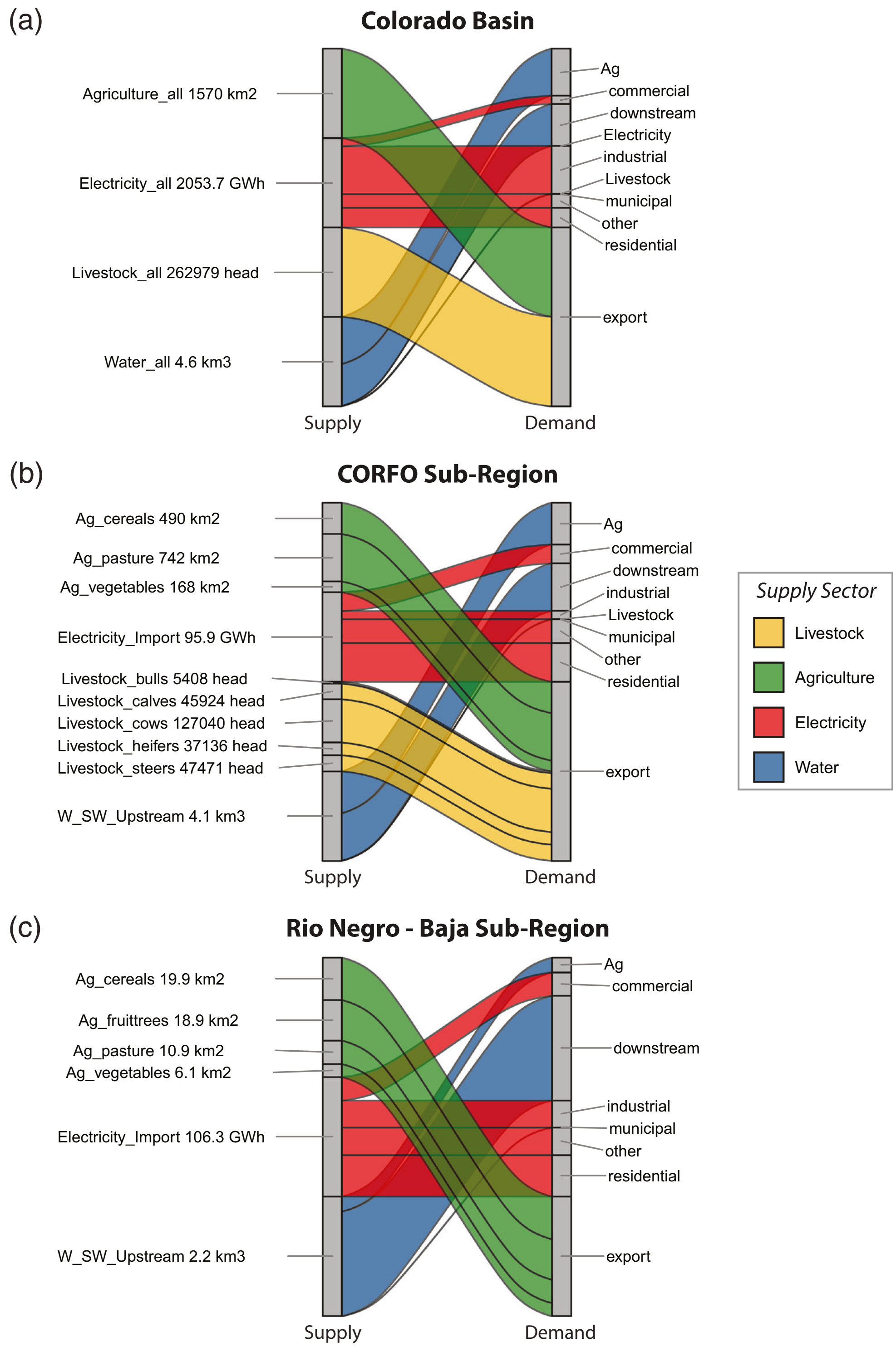

Fig. 3 Reference scenario Sankey diagram for **a** entire Colorado basin, **b** the CORFO sub-region, and **c** the Río Negro-Baja sub-region. Each figure maps supply (left) to demand (right) by sector (colors)

arrive at this result, Metis considers the interaction of the water sector with the land and electricity sectors, rather than isolating the water sector alone. This approach makes the framework more powerful in evaluating the implications of different EWL futures.

While these potential policy-induced scarcity impacts are concerning, climate change impacts could further sharpen EWL nexus tradeoffs. To evaluate potential climate-induced future changes in the magnitude and timing of water availability in the Colorado basin, we forced a global hydrologic model, Xanthos (Vernon et al. 2019), with outputs from a suite of global climate models and climate forcing scenarios (Warszawski et al. 2014). Supplementary Fig. S8 shows the alteration in natural runoff in the Colorado basin projected as a

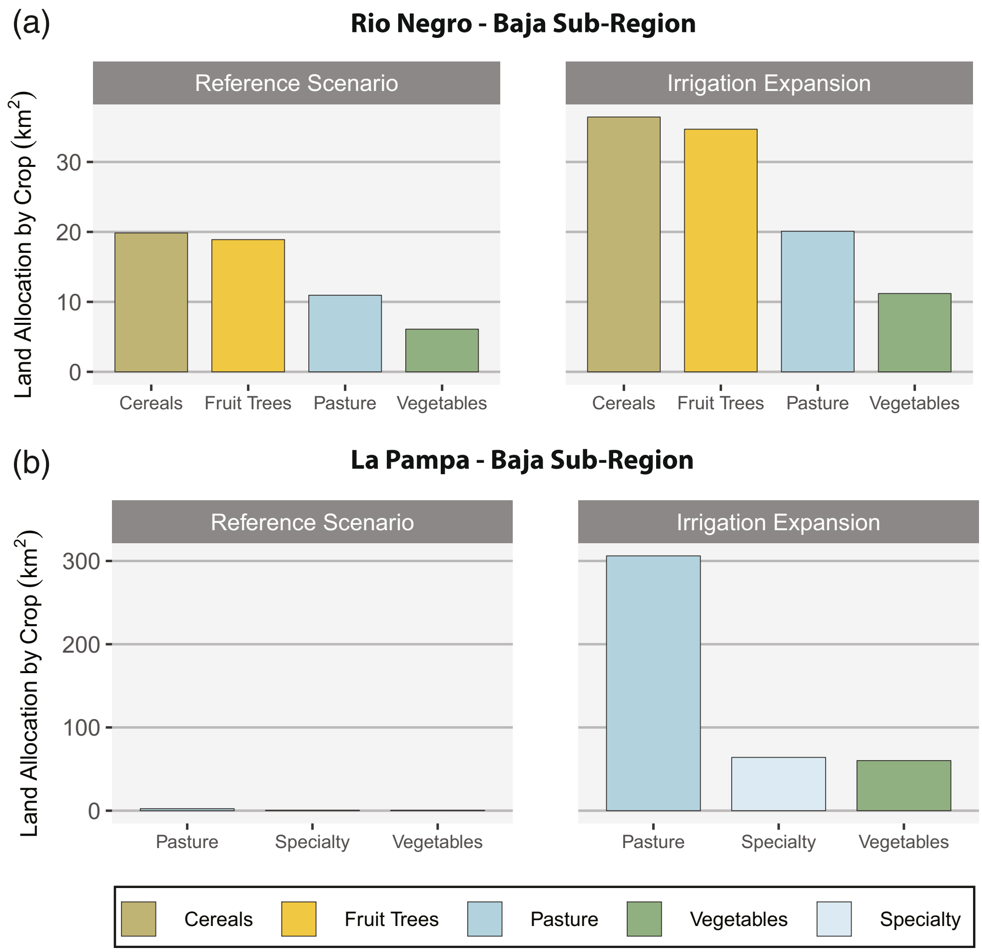

Fig. 4 Comparison of Reference (left) and Policy (right) scenarios with respect to irrigated cropland allocation. Policies are only implemented in two sub-regions: **a** Rio Negro-Baja sub-region and **b** La Pampa-Baja sub-region

result of climate change, expressed as a percentage reduction from 2010 values. Across the 20 climate model and forcing scenarios we considered, Fig. S8 projects reduced water availability across 85% of the scenarios by 2100. Additionally,

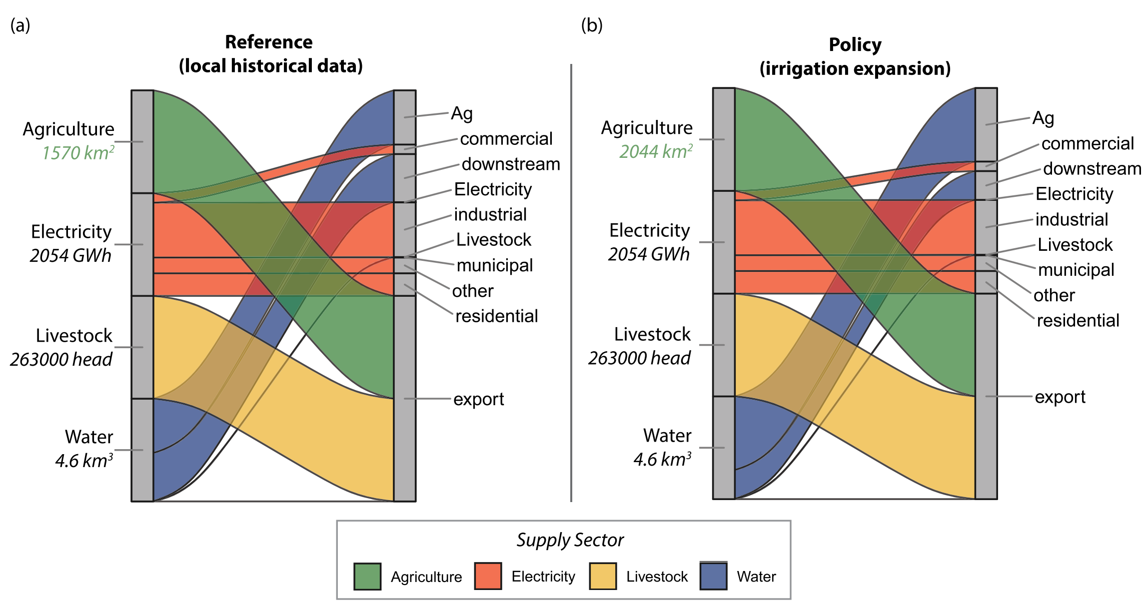

Fig. 5 Sankey diagrams for the reference scenario (**a**) and policy scenario (**b**) for the Colorado basin. The left-hand side of each of the two component figures represents aggregate supply, while the right-hand side represents aggregate demand

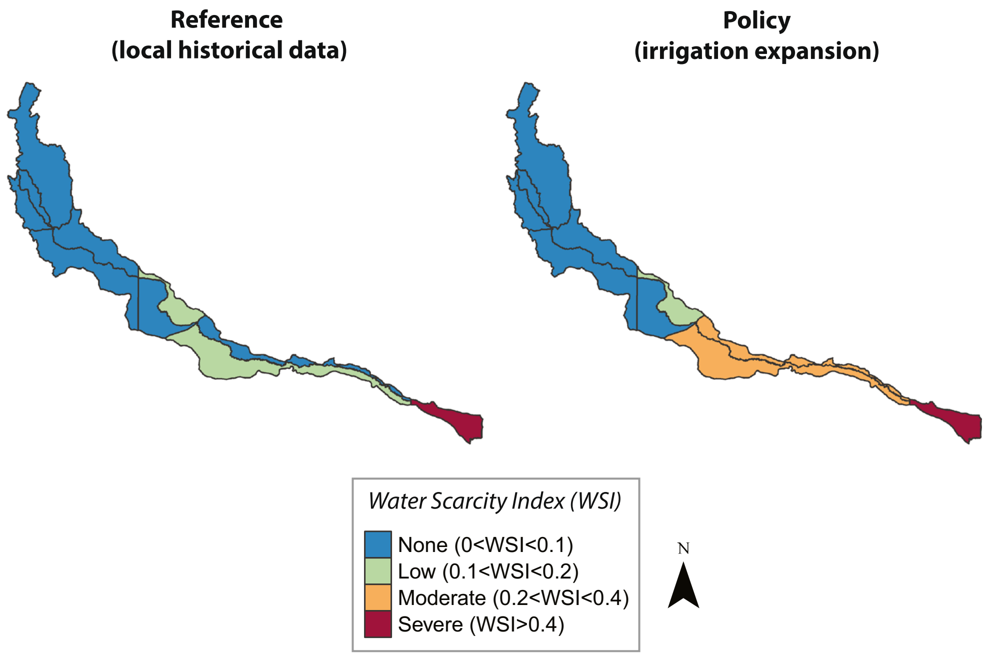

Fig. 6 Water scarcity in the reference scenario versus the policy scenario. Water scarcity in a given sub-region is defined here as the ratio of total water demand to total available water (i.e., supply)

90% of the 20 realizations have a declining trend through 2050. Reductions in basin water availability by 2100 are as large as 20%. Given many basin sub-regions are already experiencing water scarcity, climate change represents a significant threat to the basin's economic outlook, as well as to national development priorities (e.g., mid-century strategies for climate change) that may rely on the basin's continued agricultural production. Indeed, recent water usage patterns, combined with a drought that has plagued the basin for almost the entire previous 10 years, are already placing serious strain on water resources that could eventually propagate into other sectors.

Conclusions and recommendations

The process of assembling, harmonizing, and visualizing data and interconnections across multiple sectors and sub-regions in a single, internally consistent modeling platform is a unique and valuable endeavor in many river basin planning contexts. This study introduces and applies a novel approach to linking together multiple river basin sub-regions, and their constituent energy, water, and land (EWL) systems, in a single platform, Metis (Khan et al. 2020a). Metis characterizes and visualizes EWL resource use, EWL system linkages within and among sub-regions, and the EWL nexus implications of future policies and investments. Data limitations often challenge the effectiveness of such integrated planning efforts. Toward addressing this issue, we use global data sets to create a complete multi-sector data set for any location (e.g., the Colorado Basin). Any components of that global data set can then be overwritten with available local data. Metis is generalizable and could be applied in other regions (e.g., river basins), particularly those with data limitations. We applied this generalizable toolkit to conduct the first-ever holistic evaluation of EWL resource availability and connectivity in the Colorado River Basin in Argentina.

Already water-stressed and drought-stricken for the past decade, the agriculturally oriented Colorado basin is now facing increasing demands for water-intensive agricultural and fossil fuel commodities. To demonstrate how integrated sub-regional river basin planning can be conducted in a way that complements ongoing basin planning efforts, we explored scenarios shaped by diverse stakeholders, including academic researchers, regional development experts, national government representatives, and members of the Colorado River Basin planning committee. By spatially quantifying the basin's current state of resources and the interconnectivity among sectors, this study provides a rich context for future strategic planning efforts by highlighting the sectors and sub-regions in which ongoing and future development activities could create unintended sectoral conflicts. This could improve risk management by preempting negative outcomes. Perhaps more importantly, it provides basin planners with a unique opportunity to explore and promote synergistic coordination (and resulting co-benefits) across currently uncoordinated sectors and sub-regions. The style of integrated multi-sector planning we explore here has not been widely adopted by river basin planning institutions anywhere. Such planning efforts in the Colorado River Basin have the potential to facilitate the adoption of integrated planning in other river basins globally by serving as a successful and demonstrative testbed.

Spatial visualizations of the basin's historical EWL resources across 10 sub-regions revealed that some of the basin's agriculturally oriented sub-regions (e.g., CORFO, Río Negro-Baja, and La Pampa-Media) are already experiencing irrigation-induced water scarcity issues that could threaten the basin's economic development. Using sectoral interconnectivity relationships established with historical EWL resource data sets, we evaluated the EWL implications of a planned 30% expansion in land allocated to irrigated agriculture in the La Pampa-Baja and Río Negro-Baja sub-regions. The stylized policy we explored here is intended to serve as a simplified but relevant representation of planned future development activities. Results demonstrate that water scarcity could be worsened by agricultural development activities, depending on the location and nature of their implementation, as well as on the presence of complementary policies such as irrigation efficiency. Results show that this conflict could be further worsened by climate change impacts, which may register strongly in the Colorado basin via (1) physical climate impacts, such as reductions in snowmelt-driven runoff from the historical baseline by as much as 20% in some scenarios (Fig. S8); and (2) indirect impacts, such as through climate-induced alterations in global crop yields that place economic pressure on the Colorado Basin to produce water-demanding crops (e.g., biomass) (Baker et al. 2018).

Numerous factors could collectively influence the evolution of future EWL dynamics in the Colorado basin in a complex and nonlinear manner, such as socioeconomic change, technological change, climate change mitigation and adaptation policies, climate change impacts, regional and national development policies, and agricultural trade patterns. The relative influence of these various forces, both individually and in combination, should be considered in follow-on studies in the Colorado basin (e.g., Dolan et al. 2021). Such analyses should explicitly consider the relative contributions of multi-sector (i.e., EWL) and multi-scale (i.e., global to sub-regional) forces across both human and natural systems (Liu et al. 2007). This underscores the importance of Metis' ability to consider sub-regional EWL dynamics within a broader regional-to-global context, as well as its design to support uncertainty and sensitivity analysis (e.g., scenario discovery) techniques (e.g., Lamontagne et al. 2018). Better understanding EWL interactions across scales under uncertainty is central to the emerging MultiSector Dynamics research community (US DOE (United States Department of Energy) 2020; Fisher-Vanden and Weyant 2020).

In addition to exploring a wider range of future basin forces, follow-on efforts seeking to build on this pilot study could benefit from several enhancements. First, water rights, restrictions (e.g., environmental flow requirements), and other policies among sub-regions dictating the quantity and quality of water allocated to different users could be represented with higher fidelity in the modeling platform. This plays an important role in evaluations of water scarcity, as the available supply of water should be constrained to what is legally available to be withdrawn. Second, several local data sets could be improved, particularly related to the extent of the basin's oil and gas extraction and related requirements for water. These more detailed data sets may enable a more credible representation of the interactions between sectors and sub-regions that were not captured in this study. Finally, rather than simply exploring the potential for future challenges to arise, the modeling framework we introduce here could be used to identify solutions. This may include factors such as water-efficient irrigation systems, water storage expansion, water transfers, and electricity system expansion options. Future versions of Metis would benefit from such advances.

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