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Impacts of irrigation efficiency on water-dependent sectors are heavily controlled by region-specific institutions and infrastructures

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ABSTRACT

Farmers' investment in more efficient irrigation systems represents a primary adaptation strategy when confronting climate change. However, the regional benefits of these investments and their influence on the conflicting demands among different water dependent stakeholders for intensely irrigated regions remains an open question. Using the Pacific Northwest of the United States as an illustrative region of focus, we show that higher irrigation efficiency has diverse effects across stakeholders that are contingent on many local climatic, institutional and infrastructural factors such as the availability of water storage, the location of hydropower generators, and water rights. These complexities limit simple abstractions of irrigation efficiency as broader policy challenge and are central to its inclusion within the class of "wicked problems". Additionally, we argue that the widely used rebound effect concept, which implicitly discourages irrigation efficiency supporting policies, should not be assumed to fully capture the nuances of the complex suite of regional impacts that emerge from irrigation efficiency investments. Consequently, the evaluation of irrigation efficiency investments requires a broader framing across a diversity of perspectives. policies and actions that are pluralistic, context-specific, and closely engage various groups of stakeholders in the policymaking process.

1. Introduction

More efficient irrigation systems improve the delivery of water to the crop root zone, reduce field application water losses, reduce farm-level incentives for irrigation water diversions, and increase farm-level agricultural productivity, especially during drought years (Schuck et al., 2005; Koundouri et al., 2006). At the regional scale, however, the effect of increases in irrigation efficiency on water availability for other farmers is more complex. Additionally, the impacts of efficient irrigation systems can reach far beyond basin-wide agricultural water availability and affect other water-dependent sectors (Grafton et al., 2018; Sears et al., 2018). New irrigation systems can modify the seasonality and magnitude of streamflow through their impact on diversions, which has implications for aquatic species and hydropower generation. Efficient irrigation technologies also impact the regional demand for energy to run agricultural irrigation systems. An increase in water-efficient irrigation could also have broad socioeconomic implications. For example, the agricultural economy would change with efficient irrigation systems, especially during drought years, and these less labor-intensive systems could reduce the demand for workers in the agricultural sector (Burnham et al., 2015). Evidence also suggests that the indirect impacts of future investment in new irrigation technologies will likely happen alongside the effects of climatic changes, which are projected to increase water stress in many parts of the world (Barnett et al., 2004).

For decades, many governments have promoted and financially supported investment in efficient systems (Perry et al., 2017; Paul et al., 2019). In recent years, however, the potential negative consequences of these policies for neighboring farmers and the conflicts that they can create among water-dependent sectors have attracted considerable attention from the research community (Berbel et al., 2018; Sears et al., 2018; Song et al., 2018; Wu et al., 2018; Paul et al., 2019). Overall, this

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emerging body of literature suggests that increasing irrigation efficiency can lead to an increase in the marginal value of water diversions, creating a "rebound effect" that leads to an increase in total water consumption (Willardson, 1985; Allen et al., 2005; Adamson and Loch, 2014; Grafton et al., 2018). This is consistent with the Jevons paradox (Clark and Foster, 2001; York, 2006; Dumont et al., 2013; Sears et al., 2018), that was originally an energy-efficiency concept (Clark and Foster, 2001; York, 2006; Dumont et al., 2013; Sears et al., 2018). The Jevons paradox analogy in irrigation systems suggests that freed-up water from efficient irrigation systems will be used by the same investing farmers to benefit themselves with increased production. Simultaneously, it can worsen water shortages for other regional farmers and water-dependent sectors. However, caution is warranted and it is important to avoid overgeneralizations of impact of Jevons paradox. Given the often large regional to global scales of many analyses, it important to avoid oversimplifying the impacts of increases in irrigation efficiency as an artifact of system representations (Dumont et al., 2013). There is evidence that the rebound effect might not occur if land is limited or water rights are enforced (Berbel and Mateos, 2014; Grafton et al., 2018).

This study explores how farmers' investments in more efficient irrigation systems affects the distribution of water, regional agricultural productivity, hydropower generation, and aquatic habitats within a basin. We also assess the importance of region-specific infrastructures and institutions by examining how efficient irrigation technologies affect different FEW sectors. This study uses a carefully resolved analysis of an institutionally complex FEW region to broaden our understanding of irrigation efficiency, basin-scale water availability, and agriculture productivity relative to the prior literature (Willardson, 1985; Allen et al., 2005; Dewandel et al., 2008; Berbel and Mateos, 2014; Berbel et al., 2018; Grafton et al., 2018; Song et al., 2018). Our analysis exploits a process-based integrated hydrologic-agricultural-economic modeling platform (VIC-CropSyst-YAKRW-ASEAP (Malek et al., 2016)' (Zagona et al., 2001)) that captures the complex relationships between soil, climate, irrigation processes, land surface hydrology, and river system processes as well as the role of reservoir operations, water rights, regulation, and economic incentives in water allocation and distribution. This allows us to more holistically quantify the impacts of changing irrigation technology on agro-hydrological indicators (e.g., irrigation water supply and demand, crop biomass production, return flow, and streamflow) as well as hydropower generation, farm-level energy demand, and instream flows to support fish species. We also consider the interdependent impacts of climate change and changes in irrigation efficiency. Our test area is Washington State's Yakima River Basin (YRB), a heavily irrigated agricultural basin that has relatively low average irrigation efficiency and contributes substantial return flow to summer water availability. The YRB is a snow-dominated basin and thus is particularly sensitive to climatic warming (Fig. 1).

2. Material and methods

The following sections provide information about the case study area, including food, energy, water systems, and water rights and management in the basin. It also provides information about our simulation scenarios related to investment in efficient irrigation system, and infrastructural and institutional transformations. Also, this section provides information related to our simulation platform, models and input data.

2.1. Yakima River Basin

The YRB (Fig. 1) is an intensively irrigated agricultural basin of the western United States, and agriculture is a significant component of its economy (USBR, 2010). The YRB is located in central Washington State and spans an area of 16,000 square kilometers. The basin-wide annual precipitation is about 680 mm, with the upstream mountainous and downstream regions receiving 2500 mm and less than 200 mm, respectively. The YRB is a snowmelt-dominant basin (Mastin and Vaccaro, 2002; Opitz-Stapleton et al., 2007), and snow contributes to 60–80% of its total precipitation (Rinella et al., 1992). Accumulated snow melts during the warm months and feeds the Yakima River. There are five major dams in the YRB (Fig. 1), which are capable of storing around 30% of the total annual flow (USBR, 2002); they regulate streamflow and play a significant role in meeting irrigation demands. About 10% of employment in the area directly involves the agricultural sector, and irrigated agriculture generates more than one billion in

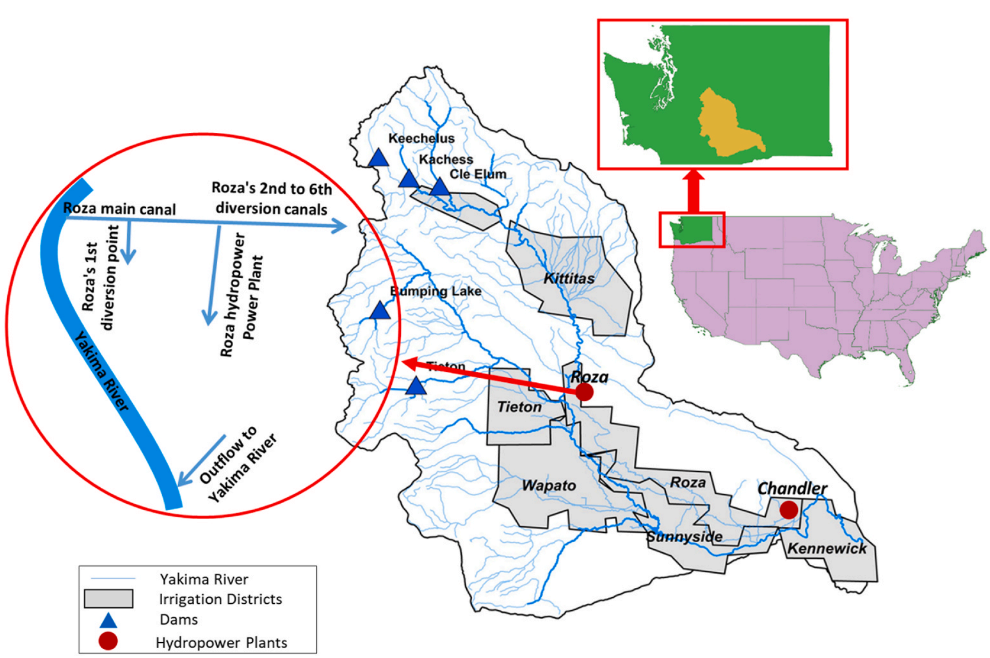

Fig. 1. The Yakima River Basin is in central Washington State, U.S. (see inset). There are five dams, six irrigation districts, and two major hydropower plants in the Yakima River Basin (the Roza and Chandler plants). The left figure roughly represents the canal network of Roza's power plant, which also resembles Chandler power plant's canal network that is located further downstream in the basin.

annual revenue (USBR, 2008b). Yakima County is the state's largest producer of many agricultural commodities (e.g., hops, pears, apples, grapes, and cherries).

2.2. Water rights in the Yakima River Basin

Two types of water rights are serviced by the U.S. Bureau of Reclamation Yakima Basin Project: 1) proratable and 2) non-proratable rights (USBR, 2010). Proratable irrigation water rights can be curtailed during drought years when there is not enough water to meet all agricultural demands. Non-proratable farmers, on the other hand, will always receive their full water rights, even during significant drought years. In the YRB, the proration rate is set depending on the severity of a drought (i.e., the more severe the drought, the lower the proration rate). Droughts that induce proration rates of less than 70% of the water right are considered to be relatively severe (USBR, 2010). More information on calculations of district-level prorationing is described by Malek et al. (2018). Additionally, water rights are subject to type of use, place of use, and timing of use. Any modifications, such as changes in the timing of use or expansion of irrigated acres, requires a change application to the water right which needs to be approved by the managing agency – the Washington State Department of Ecology - and is subject to the change not adversely affecting any third party. Hence there are institutional and legal impediments to spreading irrigation diversion savings as a result of more efficient irrigation systems on additional acres or over an extended growing season that is beyond the season of use stipulated by the water right.

In this study, we assume static, nontransferable water rights. We also assume that farmers cannot expand their irrigated areas during non-drought years; in other words, extra water resulting from more efficient irrigation systems becomes available to other sectors and farmers. This assumption is consistent with U.S. western water law doctrine which requires water to be used only over the place of use identified by the water right (Western States Water Council, 2012). The only difference is that we do not simulate the possibility of relinquishment for farmers who do not use their diversion rights. Moreover, historical records show that in the Yakima Basin, as irrigation systems became more efficient, diversions decrease, which indicates that this is a valid assumption (Neuman, 1998). Farmers can also use other strategies that enhance their irrigation demand; for example, they can plant water-intensive crops (Grafton et al., 2018). However, in this study we do not simulate changes in crop patterns; therefore, we do not capture such intensification scenarios intended to utilize the freed-up water.

The prior appropriations doctrine that holds that water rights holder risk losing any fraction of their water right that is unused for an extended period of time (Leonard and Libecap, 2019). In this analysis, we do not simulate relinquishment if an irrigator's full water right is not used. However, relinquishment rules are generally not enforced except under extenuating circumstances (Neuman, 1998), Furthermore, some states maintain programs such as Washington's Trust Water Program (Lovrich et al., 2004) that allow water rights holders to retain "unused" diversion rights by effectively leasing them to the state (and accordingly reduce diversions). In principle, programs such as this provide water rights owners to reduce diversions in proportion to irrigation efficiency increases without risking relinquishment. Our assumption that reduction in diversion occurs with lower demand is consistent with non-enforcement of relinquishment rules. Consequently, changes in diversions are driven entirely by the interaction between irrigation efficiency and crop water use.

2.3. Energy supply and demand in the Yakima Basin

Although not a major component of the YRB's economy, hydropower production plays a significant role in meeting the local energy demands of the agricultural sector, and it is sensitive to climatic and anthropogenic stressors. The YRB currently has two major hydropower plants: Roza and Chandler (Fig. 1). Neither is located on the Yakima River's main stem. The Roza hydropower plant can produce 12 MW annually and is located on the Roza diversion dam. The Chandler power plant (11 MW/year) is located downstream of Roza, and its generated hydropower is mainly used to pump the water to irrigate lands at higher elevations (USBR, 2012). Energy production in excess of agricultural needs is sold to the grid, although this is incidental to the primary purpose which is meeting the energy needs of the irrigation districts. Fig. 1 shows a schematic of the Roza power plant whose energy production is taken into consideration in this study. Chandler power plant's flow diagram also generally resembles Roza's.

2.4. Irrigation efficiency scenarios

We define and explore the following three irrigation investment scenarios to capture a wide range of possible ways in which irrigation decisions can impact the FEW nexus. These three scenarios are used to simulate return flow, irrigation demand, and eventually the impacts of irrigation technology on agricultural water supply, streamflow, and hydropower generation.

1) ***No_Action*** is a status quo scenario, meaning the irrigation system would not change in the future. In this condition, the only dimension of the system that changes is climate.
2) ***Irrigation Pattern based on Economic Viability (IPEV)*** is based on simulated irrigation patterns developed and described by Malek et al. (2018). This scenario highlights which investment decision makes sense for farmers when they experience a certain climatic condition. Impacts of farmers' preferences are not included in this analysis.
3) ***All_Switched***, in which all of the farmers with inefficient irrigation systems switch to more efficient technologies, represents the highest extent of impacts of farmers' adaptive irrigation decisions on the FEW nexus of the basin.

2.5. Institutional and infrastructural scenarios (I&Is)

To assess the importance of institutional and infrastructural conditions, we consider three I&I scenarios.

1) ***Scenario-*1** assumes that water rights and regulations will remain the same in the future. In other words, our first scenario is used in tandem with the irrigation efficiency scenarios described in section 2.4 (unless otherwise stated). In this scenario, increasing irrigation efficiency leads to reduced diversions and a decrease in return flow.
2) ***Scenario-2*** assumes that current water rights will be modified to allow farmers to utilize the water saved through efficient irrigation systems by increasing their irrigated acreage. Therefore, for this scenarios, we assume that diversions from Yakima River magnitudes will remain constant.
3) ***Scenario-3*** assumes that a reservoir will be added to the Yakima River. The added reservoir is consistent with the Yakima Basin Integrated Plan (YBIP; Yoder et al., 2017). YBIP proposes several infrastructural and institutional modifications to the YRB's current water system, such as expansion of current dams, improvement in fish passages, change in streamflow regulations, and inter-basin water transfer tunnels. YBIP also proposes the Wymer Dam, which would have a capacity of 162,500 acre-feet. In this study, wymer is the only infrastructural development that we take into account. As with *Scenario-1*, *Scenario-3* also assumes no change in water law, and diversions and return flows both decrease as irrigation efficiency increases. In this study, I&Is simulations were only conducted for the 2030–2060 period and the All_Switched Scenario.

2.6. Data and simulation protocol

2.6.1. Simulation tools

We used the Agricultural Spatial Economic Analysis Platform (ASEAP; Malek et al., 2018), which is a spatially distributed agro-hydro-economic framework that establishes offline linkage between land surface hydrology, river system processes, and agricultural economic decisions (Figure S1). The distributed nature of the ASEAP makes it a powerful tool for capturing how spatial variations in climate, soil, crop type, baseline irrigation system, water rights, and topography impact the viability of farmers' adaptation decisions. The ASEAP has three main components, including 1) a coupled hydrologic and cropping system model (VIC-CropSyst; Malek et al., 2017), 2) a reservoir and water management model (YAK-RW; Fulp and Harkins, 2001; Zagona et al., 2001), and 3) an economic module (Malek et al., 2018). A comprehensive description of all of the simulation tools, and underlying socioeconomic assumptions such as crop price and labor demand used in this study are described by Malek et al. (2018).

Simulation period and spatial resolution: The spatial resolution of our simulation is 1/16th degree. The historical time period is from 1980 to 2010, while the future period spans from 2030 to 2090. The following describes all of the inputs used for the ASEAP simulation.

Climate: Minimum and maximum daily local temperature, precipitation, and wind speed are data inputs for the model. The historical gridded forcings have been created by Abatzoglou and Brown (2012). For the future period, we used outputs of five general circulation models (GCMs) forced by two representative concentration pathways (RCPs): 4.5 and 8.5, which are related to the radiative forcing of 4.5 and 8.5 $\frac{W}{m^2}$, respectively (Moss et al., 2010; Vuuren and van, 2011). We used the method introduced by Brekke et al. (2010) to select these five GCMs from among eighteen that were available. The GCMs used in this study include GFDL-ESM2G (Pacanowski et al., 1991), HadGEM2-ES365, and HadGEM2-CC365 (Collins et al., 2011; The HadGEM2 Development Team: G. M. Martin et al., 2011), INMCM4 (Volodin et al., 2010), and CanESM2 (Flato et al., 2000). These selected GCMs represent extreme changes in mean temperature and precipitation among a larger ensemble of 21 GCMs prepared by Abatzoglou and Brown (2012).

Soil: We used the soil file described by Malek et al. (2017), who used the State Soil Geographic dataset (Schwarz and Alexander, 1995) to develop the soil inputs for the VIC-CropSyst model.

Land Cover: We used the vegetation parameters file (VPF) and crop parameter file (CPF) described and prepared by Malek et al. (2017). The CPF includes information on crop acreage, planting date, irrigation system, crop type (perennial or annual), and proration rate. VPF provides the vegetation class, acreage, root depth, and root distribution in each soil layer.

2.7. Basin-wide agricultural productivity

In this study, the basin-wide revenue of each crop type is assumed to be the product of crop area (hectare), crop productivity (tonnes per hectare), and crop price (USD per metric tonnes). The overall basin-wide agricultural economy is the sum of the revenue of all crop types in YRB. The price of main crop types in YRB can be found in Supplementary Table S1.

2.8. Labor demand

In this research, the labor costs of each irrigation system were calculated based on the assumptions of Hoffman and Willett (1998), using the following equation:

$$L_{irrigation} = N \times T \times h_{irrigation} \quad (1)$$

where $L_{irrigation}(hrs)$ is the annual labor demand of the irrigation system; N is the number of irrigation events each year; $T(hrs)$ is the total hours that the system works during each irrigation event; and $h_{irrigation}\left(\frac{hr}{acre}\right)$ is the hours of labor required to operate and maintain an irrigation system. Hoffman and Willett (1998) assumed that $K_{irrigation}$ is 0.03, 0.32, and 0.25 for center pivot, surface, and solid-set/moving-wheel systems, respectively. Here, we assumed that drip irrigation is as labor-intensive as center pivot (0.03 $\frac{hr}{acre}$).

2.9. Ecological metrics

We use eleven ecological streamflow metrics as a proxy to explore how more-efficient irrigation systems affect aquatic ecology of the Yakima River. The streamflow metrics used in this study have been developed by Wenger et al. (2010) and are presented in Table 1.

2.10. Impacts of irrigation efficiency on different indicators

Our simulated results encompass several water-dependent sectors, and we use radial plots (Fig. 6, and Supplementary Figure S4 and S5) to explore their directions of change and tradeoffs. We associate each of these metrics to one stakeholder and we define a favorable direction of change for that stakeholder (Figure S2). Finally, we make the direction of the changes of all metrics consistent in the way that the outward direction shows improvement of that metric, and the inward direction shows movement in unfavorable directions.

Table 1
Streamflow-related ecological indicators considered in this study. More detail can be found in Wenger et al. (2010).

Metric	Description	Unit	Sensitive Species	Favorable Direction
W_99	Number of days with flow in top 99% of annual flow	Number of days	Fall-spawning fishes	Low
W_95	Number of days with flow in top 95% of annual flow	Number of days		low
W_1.5	The probability that a 1.5-year flow event would occur during the winter	Probability of occurrence		Low
W_2	The probability that a 2-year flow event would occur during the winter	Probability of occurrence		Low
S95	Frequency of high flow during summer, Number of days with flow in top 95% of annual flow	Number of days	Spring-spawning fishes	Low
MAF	Mean annual flow	m^3/sec	General	High
MSF	Mean summer flow, Flow condition in low flow condition	m^3/sec	General	High
S15	Number of days with flow less than 15% of MAF	Number of days	General	Low
S20	Number of days with flow less than 20% of MAF	Number of days	General	Low
Q7_10	7Q10 statistics, 7 day low flow with a 10 year return interval	m^3/sec	General	Low
HP	High pulse count, a measure of stream flashiness, the frequency of events that exceed the threshold of 2 times mean annual flow	Probability of occurrence	General	Low

2.10.1. Observed agricultural and hydrologic datasets

In this study we also briefly explore the historical trend of irrigation-efficiency change and its implications for other water-dependent sectors. The datasets used in this analysis were collected from different sources. We obtained the irrigation-efficiency and total irrigated data from the National Agricultural Statistics Service's five-year census (NASS, 2017). This dataset is available at the county level, and we aggregated information from Yakima, Benton, and Kittitas Counties in Washington State. We also extracted our observed diversion information from the USBR (2010) report, and we downloaded our observed streamflow data from the U.S. Geological Survey website for Yakima River at Kiona Station (gage number 12510500). To reduce the impacts of short-term diversion fluctuations, we took a 5-year moving average of the annual diversion and total annual streamflow time series. Crop distribution information was also gathered from USDA crop-land data layers at the county level (NASS, 2016). The dataset was extracted for Yakima Basin's three counties. Crops were categorized into low-and high-value crops.

3. Results

3.1. Irrigation demand, losses, and return flow

Impacts of Climate Change on Irrigation Consumptive Use: Our results show that under the "no-action" condition when we only consider climate change, annual total consumptive irrigation water demand decreases in three of the scenarios (RCP 4.5 and 8.5 in the 2030–2060 period and RCP 8.5 in the 2060–2090 period) and increases in the 2060–2090 period under RCP 4.5 (Fig. 2 a). The reason for this inconsistent behavior is that higher temperatures result in two primary, yet conflicting, impacts (Challinor and Wheeler, 2008; Liu et al., 2013; Asseng et al., 2015; Challinor et al., 2016; Atlin et al., 2017): 1) higher potential evapotranspiration (PET) that increases irrigation consumptive use, and 2) reduction in the length of the actual growing season for some crops (the available growing period increases but warming causes some crops to mature earlier). The second effect of temperature on the length of growing season together with the reducing effect of CO_2 on crop transpiration outcompetes the first impact of temperature (higher PET), thereby reducing aggregate consumptive use over the growing season. Our results show that the seasonality of demand is also impacted (Supplementary Figure S3). Warmer temperatures usually lead to an earlier planting date and faster crop growth, which shifts the seasonality of demand to earlier in the season. We show that early-season (March, April, May) irrigation demand increases by 32% (21%–53%) and late-season irrigation demand decreases by 25% (18%–31%). However, because the early-season irrigation demand makes up only about 16% of the total annual irrigation demand, the overall seasonality of the demand does not fundamentally change under climate change.

Impacts of Climate Change and Irrigation Technology on Irrigation Consumptive Use: Increases in basin-wide irrigation efficiency tend to further reduce irrigation demand (Fig. 2 d) because irrigation losses are lower when farmers use more efficient irrigation systems. Fig. 2 a shows the collective impact of climate change and irrigation technology on irrigation demand reduction, which is −8%, −11%, and −20% under *No-Action*, Irrigation Pattern based on Economic Viability *(IPEV)*, and *All-Switched* scenarios, respectively. The reduction is more significant under more dramatic climate scenarios (RCP 8.5) and more significant changes in irrigation efficiency.

Impacts of Climate Change on Irrigation Losses and Return Flow: Our results (Fig. 2 b-c) suggest that climate change could slightly reduce irrigation return flow by three percent (2030–2090). The reason

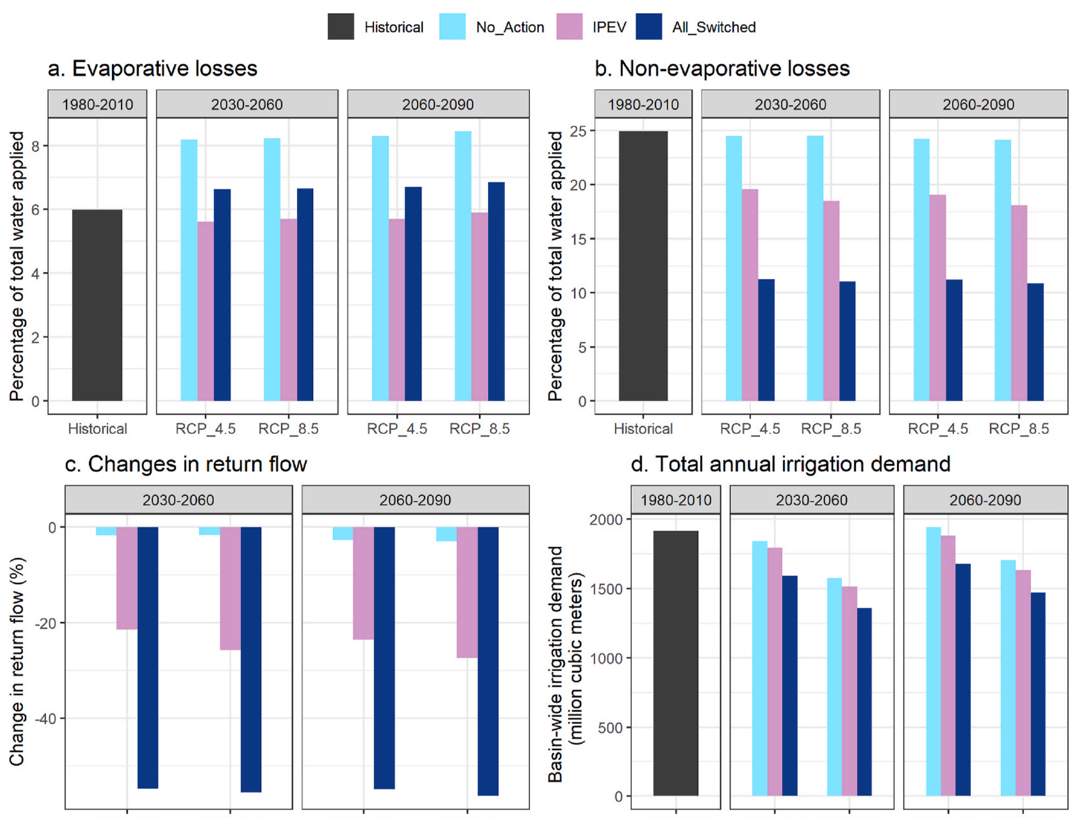

Fig. 2. Irrigation demand, efficiency and return flow. Panels a and b show the impacts of climate change irrigation efficiency on evaporative and non-evaporative losses over the entire Yakima River Basin. Panel c shows a reduction in return flow under various climate and irrigation technology scenarios. Panel d demonstrates changes in diversion demand under various climate and irrigation technology scenarios. The change rates are calculated by comparing each scenario with the average simulated historical return flow (1980–2010).

is that climate change could enhance irrigation evaporative losses (38%; 2030–2090) while reducing non-evaporative losses of runoff and deep percolation (2%; 2030–2090), which leads to reduced return flow.

Impacts of Climate Change and Irrigation Technology on Irrigation Losses and Return Flow: Our results also suggest that a significant reduction in the magnitude of return flow occurs as farmers switch to more efficient systems; 25% and 55% under *IPEV* and *All-Switched* scenarios (2030–2090), respectively. Return flows decrease because more efficient systems (e.g., drip and center pivot) result in significantly lower deep percolation and runoff losses compared to more inefficient systems (Figure b and c). The reduction in deep percolation and runoff can trigger a significant transformation of the farm-level water cycle, which often leads to reductions in the recharge of groundwater system with long-term water-supply implications (Berbel et al., 2018; Grafton et al., 2018).

The seasonality of return flow closely follows the seasonality of irrigation demand. Thus, Supplementary Figure S3 shows an increase in early-season (April) return flow, while a significant reduction in return flow occurs during the rest of the season. Our results also reveal that new irrigation systems do not significantly affect the seasonality of return flow and only modify the magnitude. They also demonstrate that the seasonality of irrigation losses and return flows are closely correlated with the seasonality of irrigation demand.

3.2. Streamflow in YRB

Impacts of Climate Change on Streamflow: Our simulated results (Fig. 3 a and b) show that the magnitude of annual streamflow (the *No_Action* scenario) increases by 7.8% and 9.4% over the 2030–2060 and 2060–2090 periods, respectively. Past studies (e.g., Mote and Salathé, 2010a) have shown that the PNW's precipitation slightly increases in the future, which explains the overall increase in streamflow in the region. The results also indicate that the seasonality of streamflow changes under different climatic conditions in future decades. The *No_Action* scenario shows an increase in winter season streamflow from December through March (as compared to historical streamflow). Spring and summer streamflow, however, declines. Late summer and fall streamflow do not significantly change under future climatic conditions. Higher temperature—which modifies the temporal regime of the snowpack—and change in seasonality of precipitation are the main factors behind this shift. An earlier shift in the timing of water demand in the future also affects this trend.

Impacts of Climate Change and Irrigation Technology on Streamflow: Fig. 3 a and b demonstrate that more efficient irrigation systems can slightly increase annual streamflow. From 2060 to 2090, streamflow at the Kiona gage increases by 1.0% and 1.5% under *IPEV* and *All_Switched* scenarios, respectively. This mainly happens because irrigation diversion decreases under more efficient irrigation scenarios, which frees up more water to stay in the river. However, reduction in return flows has a contrasting effect on the streamflow, partially offsetting decreases in irrigation diversions. New irrigation systems can affect the seasonality of streamflow as well (Fig. 3 c and d), modifying the magnitude of diversions from and return flow to the Yakima River. Changes are generally positive (e.g., 5%; *All_Switched*; 2060–2090) during spring and early summer months and negative (e.g., −4%; *All_Switched*; 2060–2090) during summer months. However, our results suggest that the magnitude of change in response to a new irrigation system may not be as strong as the impacts of climate change. Although smaller, the impacts might be substantive because summer streamflow tends to be low (USBR, 2002; Hatten et al., 2014).

3.3. Ecological consequences of stream flow change

In this study, we explore the impacts of higher irrigation efficiency on eleven ecological streamflow indicators (Table 1; Wenger et al., 2010). Winter flow indicators (W_99, W_95, W_1.5, and W_2) show that the probability of wintertime extreme flow events may be higher in the future (under *"No-Action"* scenario) which can create an unfavorable situation for winter-spawning fish species. The sensitivity of the winter flow indicator to more efficient irrigation systems is significantly lower;

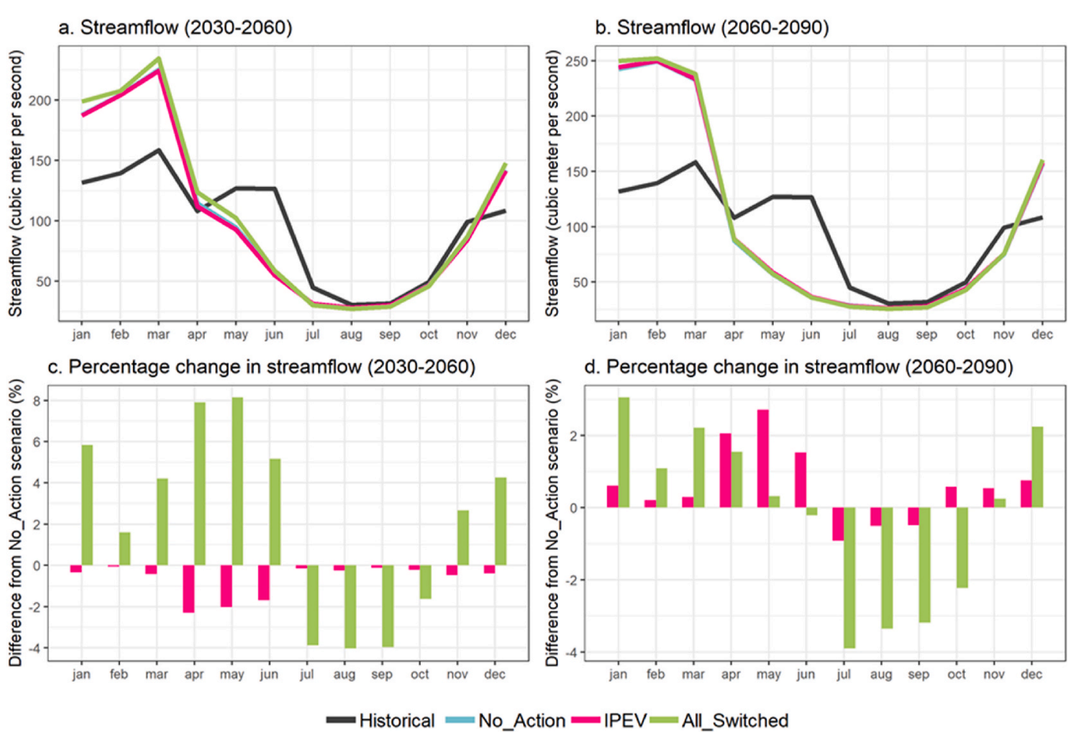

Fig. 3. Streamflow and drought conditions. Panels a to d show the impacts of climate change and irrigation technology scenarios on streamflow (m^3/sec) at the outlet of the Yakima River Basin (Kiona gage). Panels a and b show how streamflow is affected by climate as well as a change in irrigation technology for the two time periods of 2030–2060 and 2060–2090, respectively. The black line represents the baseline historical condition under the "No-Action" scenario.

however, more investment leads to slightly higher extreme events with possible negative consequences for winter-spawning species. The summer flow indicator (S_95) shows that climate change (*"No-Action"*) can significantly reduce the extreme flood event in summer; however, S_95 is not sensitive to increasing irrigation efficiency. Mean annual flow (MAF) tends to increase under both future climate and more-efficient irrigations systems with potential positive ecological implications. Mean summer flow (MSF) decreases as a result of climate change (negative), and slightly improves under higher investment scenarios (positive). Summer low flow indicators (S15 and S20) show a higher number of low flow days that can negatively affect fish. As compared to other indicators, S15 and S20 are more sensitive to irrigation efficiency scenarios, in which a higher irrigation efficiency results in less favorable ecological conditions. The continuous low flow period indicator (7Q-10) shows that streamflow during the seven-day low period increases as a result of climate change (positive) and slightly increases under more efficient irrigation scenarios. The high pulse (HP) indicator increases due to climate change (negative) but slightly improves under higher irrigation efficiency during 2060–2090 period. Overall, the indicators related to daily low flow periods (S15, S20) show increases in dry periods, especially during summertime. This is caused by overall lower streamflow during summer, mainly because the contribution of return flows to the river flow is lower under both climate change and investment scenarios (Fig. 4).

Overall, the results show that the hydrologic impacts of higher efficiency can affect streamflow condition in various ways. These streamflow metrics provide proxies to the well-being of different ecological components of the system (e.g., fall- and spring-spawning fishes Wenger et al., 2010), and various stakeholders (e.g., indigenous people of Yakama Nation (Montag et al., 2014) or water recreation industries in the region (USBR, 2008a)). For example, the reduction in low-flow indicators can create unfavorable ecological conditions for specific species such as spring-spawning fishes. On the other hand, mean annual flow (MAF) and mean summer flow (MSF) increase that lead to positive consequences for ecology of the system and water recreation stakeholders.

3.4. Regional drought implications

Impacts of Climate Change on <u>Basin-wide Agricultural Water Availability</u>: The proration rate reflects the impacts of different climate and irrigation technology scenarios on the amount of water available for irrigation. The proration rate is inversely related to drought magnitude; a lower proration rate indicates less water availability for irrigation. A significant drought in YRB is defined as a proration rate less than 70% (ECONorthwest, Natural Resources Economics and ESA Adolfson, 2012). Our results (Fig. 5 a and b) suggest a significant increase in drought frequency in the future. While the historical frequency of droughts was 21%, the frequency of droughts for the *No_Action* scenario increases to 48% and 75% over the periods of 2030–2060 and 2060–2090, respectively. Our results align with past studies focused on the PNW (Mote et al., 2005; Rajagopalan et al., 2018), and we attribute this higher frequency to less snowfall and higher temperatures, which change the volume and seasonality of snowmelt.

Impacts of Climate Change and Irrigation Technology on <u>Basin-wide Agricultural Water Availability</u>: We show that more efficient systems tend to slightly increase the frequency of years with proration rates less than 70% (e.g., approximately 4% for the "All-Switched" scenario over the 2060–2090 period). This occurs because more efficient systems lead to a significant reduction in return flow that is critical for the YRB's summer water availability. However, the lower water demand associated with more efficient systems during summer offsets some of the negative consequences of lower return flows. Drought severity (mainly under *All_Switched* scenarios), on the other hand, tends to

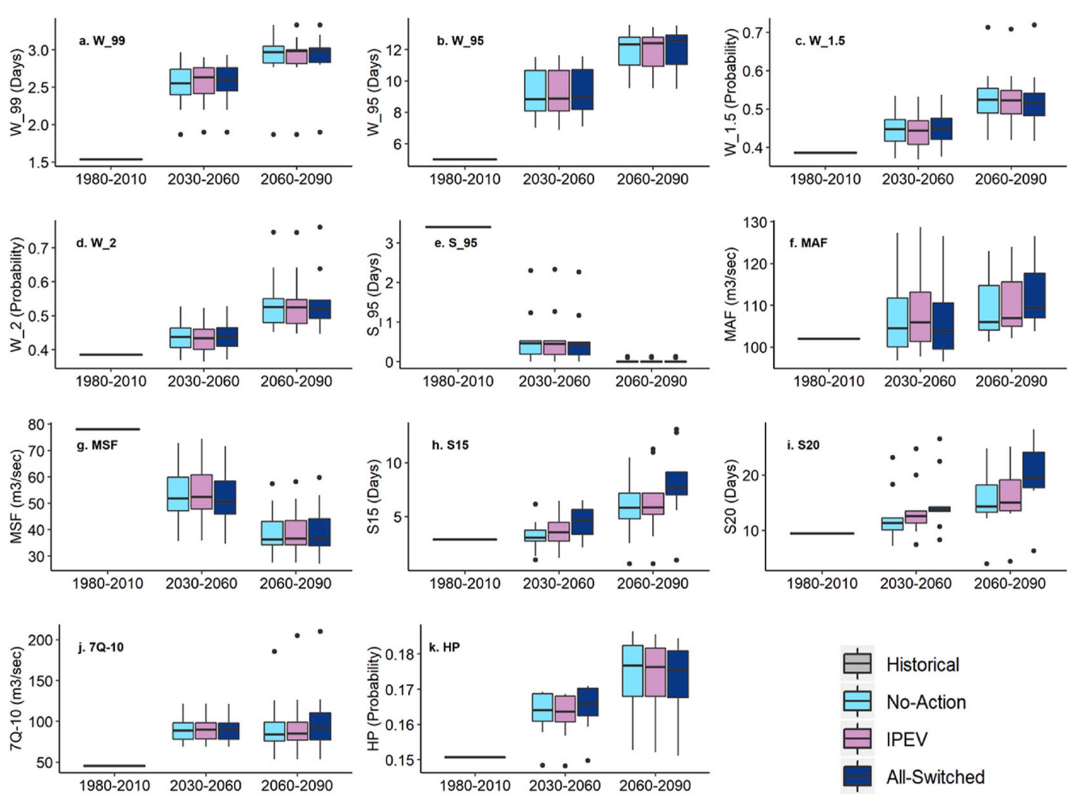

Fig. 4. Ecological flow implications. Eleven ecological flow indicators are considered in this study. W_99, W_95, W_1.5, W_2 are winter extreme flow indicators where lower values are favorable. S_95 is a summer high flow indicator where a lower value is favorable. MAF and MSF are mean annual and summer flow indicators and higher values are favorable. S15, S20 are low flow metrics where lower values are favorable. 7Q-10 is seven-day low flow indicator and a higher value is favorable. HP is a streamflow fluctuation indicator and lower values are favorable. Table 1 provides more information about these ecological flow indicators.

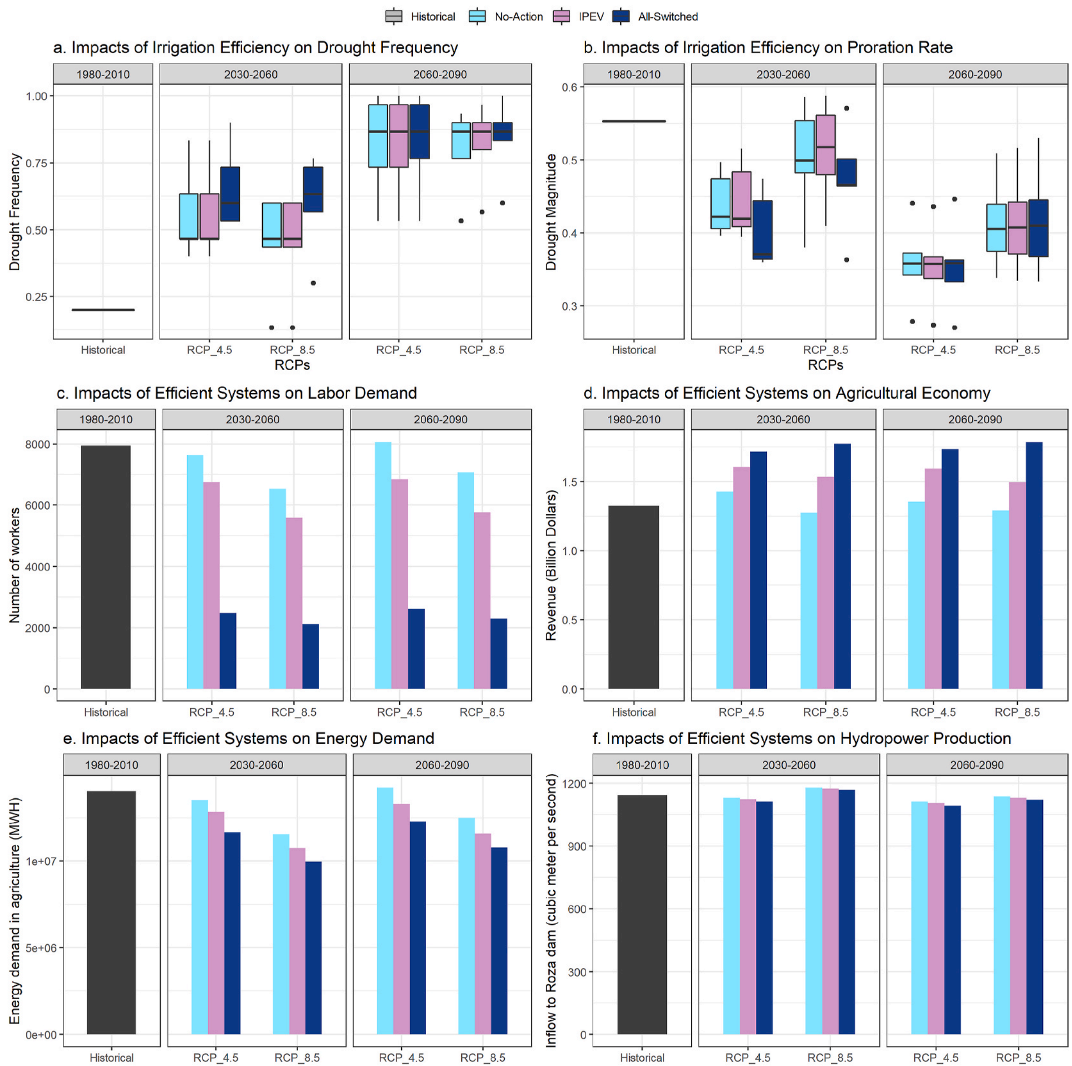

Fig. 5. Impacts on various water-dependent sectors. Panels a and b show the impact of climate and irrigation scenarios on the frequency of drought and the average proration rate in the YRB. Panel a shows the frequency of significant droughts ($p < 0.7$); panel b shows the average proration rate during all the years. Proration rate (%) is the inverse of severity, in other words, a lower proration rate indicates a more severe drought. Panel c shows the impacts of climate and irrigation efficiency scenarios on labor demand in the YRB. Panel d shows impacts of climate and irrigation efficiency scenarios on the basin-wide agricultural economy in the YRB. Panel e shows the basin-wide electricity demand due to pumping of water for irrigation purposes. Panels f demonstrate inflow to the Roza hydropower generators which is a proxy for hydropower energy production.

slightly improve in response to a switch to more efficient irrigation. During extremely severe drought years (where the proration rate is less than 40%), the reduction in overall demand (Fig. 5 d) and the shift in seasonality of demand have a strong positive impact on basin-wide water availability.

3.5. Implications for labor demand

Impacts of Climate Change on Irrigation Labor Demand: We have already shown that climate change tends to shorten the growing season (for some crops) which reduces the number of irrigation events. Therefore, climate change (in isolation as represented in the *No_Action* scenario) decreases labor demand. Also, because the timing of labor demand closely follows the timing of irrigation, labor demand may be shifted in time towards earlier in the year. From the perspective of workers, this could potentially lead to higher chance of unemployment later in the summer.

Impacts of Climate Change and Irrigation Technology on Irrigation Labor Demand: Our results show that the labor demand for irrigation practices declines significantly when farmers use a more efficient system (Fig. 5 c). This reduction in demand is most dramatic (more than 70%) in the *All_Switched* scenario. This is because a more efficient system is normally more automated and less labor intensive. As Malek et al. (2018) have shown, irrigation investment is not homogenous among all crop types; e.g., farmers of annual crops tend to invest less in efficient irrigation technology. This might cause movement of labor across crop types, and potentially a mismatch of skills (e.g., laborers not having skills to work with a specific crop).

3.6. Impacts on agricultural economy

Impacts of Climate Change on Basin-Wide Agricultural Economy: The results of our *"No-Action"* scenario (Fig. 5 d) show that the basin-wide agricultural economy would suffer if the climate changes as projected (Mote and Salathé, 2010b; Abatzoglou et al., 2014) and farmers do not switch to new irrigation systems. This would occur for two main reasons: 1) droughts becoming more frequent and intense in the future, and 2) some crop types (e.g., wheat, corn, and potatoes) undergoing a significant reduction in their optimal productivity (i.e., potential yield) because their actual growing season could be

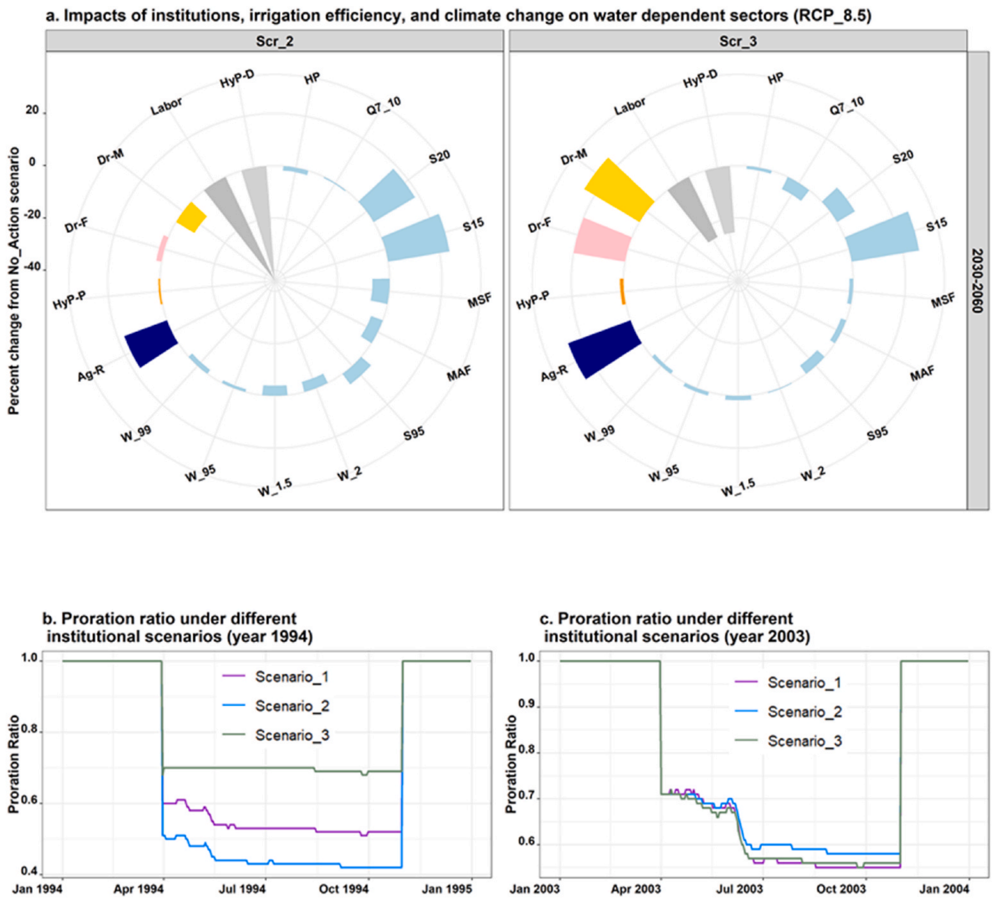

Fig. 6. Impacts of institutional modifications on the irrigation efficiency implications for different water-dependent sectors. Panel a demonstrates the percent difference between the *All-Switched* scenario under status quo condition (Scr_1), and *All-Switched* scenario under change in water right (Scr_2) and adding a new dam to the system (Scr_3), during 2030–2060 period. All indicators in Panel a were adjusted in the way that the outward direction shows favorable and inward direction shows unfavorable direction of change. The light blue color shows the 11 streamflow indicators, including Winter W_99 [W_95] (the number of days with flow in the top 99% [95%] of annual flow), W_1.5 [W_2] (the probability that a 1.5 [2]-year flow event would occur during the winter), S95 (the number of days with flow in the top 95% of annual flow), MSF (mean summer flow), MAF (mean annual flow), S_15 [S20] (the number of days with flow less than 15% [20%] of MAF), Q7_10 (7-day low flow with a 10-year return interval), and HP (high pulse count). Dark blue (Ag-R) shows agricultural revenue; orange (HyP-P) shows water diverted to the Roza hydropower plant; pink (Dr-F) shows drought frequency; yellow (Dr-M) indicates drought magnitude; dark grey (labor) shows labor demand in agriculture; and light grey (Hyp-D) shows hydropower demand. Panel b and c shows simulated impacts of Scr_1, Scr_2 and Scr_3 on proration ratio during an acute (1994) and mild (2003) drought years. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

substantially shorter in response to warming (Malek et al., 2018). This is despite their yield increase in response to increasing CO2 concentrations. However, the potential yield of many crops (e.g., multiple-cutting crops, which are the dominant crop types in the YRB) may significantly improve as temperatures elevate and their growing seasons extend (Karimi et al., 2017; Rajagopalan et al., 2018).

Impacts of Climate Change and Irrigation Technology on Basin-Wide Agricultural Economy: In scenarios wherein farmers use more efficient systems, the agricultural economy improves (Fig. 5 d). The greatest improvement happens under the *All_Switched* scenario, where the overall economy of the basin improves by 22% and 26% over the 2030–2060 and 2060–2090 periods, respectively. While our results show that the frequency of droughts slightly increases under more efficient irrigation scenarios, they also suggest an improved basin-wide agricultural economy. The significant improvement in farm-level water use efficiency (Malek et al., 2018) is the main reason behind this (under the *IPEV* and *All_Switched* scenarios). Also, for multiple-cutting crop types (forages), the primary limiting factor is water availability (Malek et al., 2018); therefore, more efficient systems that increase farm-level water availability lead to significantly higher agricultural productivity. Additionally, we can infer that crop mix plays a significant role in determining whether or not a specific scenario is beneficial; areas with higher acreages of multiple-cutting crops are more likely to benefit from climate change and investment in more-efficient irrigation systems, while areas with higher acreage of annual crops might respond differently.

3.7. Energy supply and demand implications

Impacts of Climate Change on Energy Demand in the Agricultural Sector: Projected climate change impacts tend to reduce the electricity demand of farms; −9.4% and −3.6% during the 2030–2060 and 2060–2090 periods, respectively. A lower irrigation demand (in response to climate change) is the main driver behind this reduction in energy demand (Fig. 5 e).

Impacts of Climate Change and Irrigation Technology on Energy Demand in the Agricultural Sector: New irrigation systems usually lower energy demand. This mainly occurs because irrigation demand significantly decreases when farmers switch to more efficient irrigation technologies. Moreover, efficient methods such as center pivot and drip systems are more energy-efficient as compared to a conventional pressurized system (e.g., solid-set moving-wheel). However, under some scenarios, farmers switch from unpressurized irrigation systems (i.e., gravitational irrigation); this increases electricity demand which negates some of the above-mentioned reductions. The overall reduction in energy demand is 14% and 20% under the *IPEV* and *All-Switched* scenarios, respectively.

Impacts of Climate Change on Hydropower Generation: Our results show that hydropower generation over the YRB could decrease in the future in response to climate change (Fig. 5 f): −2.7% and −7.2% for 2030–2060 and 2060–2090, respectively. This decrease mainly stems from the fact that the major hydropower plants (Roza and Chandler) are located on irrigation channels (not the main stem of the Yakima River) through which water is diverted from the Yakima River. Therefore, the impact of climate change on irrigation demand is the most significant determinant of hydropower production and, therefore, does not increase as streamflow on the mainstem increases. In terms of seasonality, as we showed earlier, climate change tends to shift irrigation diversion demand to earlier in the season. Thus, hydropower production is higher in the spring and lower during the late summer.

Impacts of Climate Change and Irrigation Technology on Hydropower Generation: The impact of farmers' adaptive decisions (*IPEV* and *All_Switched* scenarios) is to slightly reduce the hydropower generation of the basin (over the 2060–2090 period, 0.5% and 1.7% under *IPEV* and *All_Switched* scenarios, respectively) because reduction in demand and increase in drought frequency reduces the water that goes to agriculture; therefore, diverted water that goes to hydropower plants also decline.

3.8. Impacts of institutions and infrastructures

In this section, we explore the impacts of different institutional and infrastructural scenarios (defined in Section xxx) on the ways that the YRB's water-dependent sectors respond to changes in irrigation efficiency. We use radial plots (Fig. 6) to explore the influence of higher irrigation efficiency on different water dependent sectors or interests. We harmonized the plots by defining the favorable direction of change for each metric (Figure S2) to be the outward direction, and inward bars show the degree of unfavorable changes. We take into account 17 indicators of the system that have been discussed in previous sections. The results show that institutional and infrastructural modification in YRB can transform the consequences of higher efficiency for various stakeholders (Fig. 6 a). For example, when farmers are allowed to use their freed-up water (*Scenario-2*) and expand their irrigation acreage, total agricultural revenue of the basin improves (Fig. 6 – a). Drought frequency and magnitude also slightly improve because more diversion increases the total amount of return flow. However, most of the streamflow indicators of the system degrade (e.g., W_99, W_95, W_1.5, W_2, MSF, MAF, S_15, and HP). This indicates that winners and losers of IE policies can change under different institutional regimes. The implementation of the Wymer Dam (*Scenario-3*) also improves water delivery to agriculture. However, overall enhancement of water delivery to agriculture comes at the price of degrading almost all other indicators such as mean annual and summer flow. This demonstrate that even a combination of large infrastructural investment and conservation measures can enhance conflicts among various users.

We also show that, during severe drought years such as 1994 (Fig. 6 b), proration rate can significantly decline under *Scenario-2*. By contrast, during moderate drought years such as 2003 (Fig. 6 c), proration rate slightly increases under the irrigation expansion scenario. This is because, as diversion increases, return flow could also increase, and this increase in return flow may outcompete the negative impacts of increased diversion for basin-wide water availability during moderate drought years. However, in *Scenario-3*, which includes the proposed Wymer Dam, the proportion rate is significantly improved. The implementation of the Wymer Dam increases the storage capacity of the basin and allows it to provide more water for agriculture, especially during significant drought years such as the year 1994 (Fig. 6 b). These behaviors highlight the state-dependency of efficiency and I&I modification impacts in complex infrastructure systems such as Yakima Basin. Overall, these results show the importance of institutional context of the basin, and imply that irrigation efficiency policy recommendations might not be generalizable.

Historically Observed Impacts of Irrigation efficiency in Yakima River Basin.

Over the last few decades, farmers in Yakima Basin have continually switched from inefficient systems (e.g., border, flood, rill, solid-set, wheel lines, and big gun) to efficient sprinklers (e.g., center pivot and linear) and drip systems (Fig. 7, panel a). Our analysis demonstrates that during the same period, the irrigated area of Yakima Basin increased by around 20%. The higher efficiency seems to be at least one of the drivers of this expansion, and this is consistent with the Jevon paradox

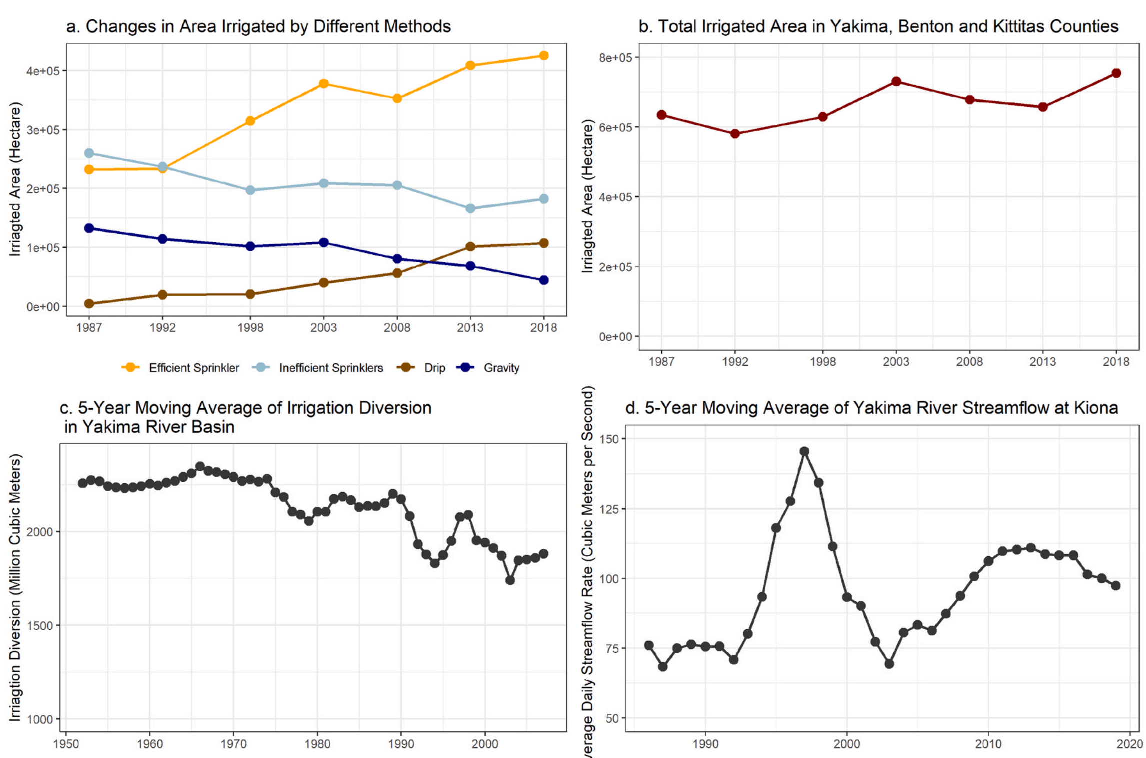

Fig. 7. Historical trend of irrigation efficiency and key environmental indicators in Yakima Basin. Panel a shows change in irrigation efficiency. Inefficient sprinkler systems include solid-set, wheel lines, and big gun types, and efficient ones include center pivot and linear systems. Panel b shows the historical change in irrigated area in Yakima, Benton, and Kittitas Counties. Panel c shows irrigation diversion in Yakima Basin. Panel d shows how the total annual streamflow has changed in Yakima River.

arguments (Sears et al., 2018). However, the historically observed trend of irrigation diversion from Yakima River does not increase as expected from the Jevon paradox premises. This is because the improvement in irrigation efficiency outpaced the expansion of the irrigated area. We also show that during the same time period, the average annual streamflow of Yakima River increased (Fig. 7, panel a). This basically shows that freed-up water increased the streamflow of Yakima River, potentially benefiting other water-dependent sectors (USBR, 2010). This is particularly interesting because previous studies suggested that Western water law doctrine is not rigorously enforced in the region (Kanazawa, 1998; Neuman, 1998).

4. Discussion

This study explores the ways in which climate change and investment in efficient irrigation technology can impact the food-energy-water nexus over an intensively irrigated agricultural region in the western U. S., the Yakima River basin. We show that systems that are more efficient reduce return flow, which is an important component of agricultural water supply in the YRB. However, our results indicate that negative consequences of return flow reduction can be compensated by reduction in irrigation demand. Our simulations suggest that the seasonality of streamflow, irrigation demand, and return flow are important in determining how a shift toward more-efficient irrigation systems affects different FEW sectors. Our results show that a climate change-induced shift in hydrologic seasonality has a stronger FEW footprints than changes in return flow. Furthermore, our analysis shows that more efficient systems could increase streamflow of the Yakima River during the spring but reduce streamflow during the summer (Yakima Nation, 1997; Hatten et al., 2014), which could stress the ecological processes of the Yakima River during the summer months. Our results show that electricity demand in the agricultural sector could decrease due to climate change and a switch to more efficient systems. We also show that energy production could deteriorate (especially in the late summer) as diversions decrease, mainly because the two major hydropower facilities in the YRB are not located on the main stem of the river. This confirms that the configuration of the system, such as the locations of the hydropower stations and subordination water allocation to hydropower is important when projecting how hydropower generation and other components of the FEW nexus are affected by climatic stressors. We further assessed the importance of basin-specific characteristics by exploring two scenarios that contemplate both infrastructure changes (incorporation of the proposed Wymer Dam) and modification of water laws (allowing the expansion of irrigated areas to utilize water saved through more efficient systems). We showed that these details must be taken into consideration, and that if they are not, any judgment about the impacts of efficient technologies might be heavily biased.

4.1. New irrigation technology and the economy of the YRB

We show that when farmers invest in more efficient irrigation systems, despite the negative impacts of higher efficiency on return flow rates, the overall agricultural economy improves. However, as Malek et al. (2018) have discussed, some crops benefit more from investment in new irrigation systems than others. Multiple-cutting crop growers benefit from climate change, while annual crops are likely to undergo a reduction in productivity. This disproportionality might provide an incentive for certain adaptive decisions, such as using a new crop type or double cropping. Additionally, although the economy of the energy sector is significantly smaller than that of the agricultural sector, we project a reduction in its overall revenue, which might have broader socioeconomic implications.

4.2. Socio-economic implications of new irrigation technologies

In addition to crop-type winners and losers, there could also be uneven societal impacts. These impacts may vary across scales and groups (Givens et al., 2018). Our results show that adoption of new irrigation technologies improves the basin-wide agricultural economy and that, with adoption of irrigation technologies, the labor demand for irrigation practices decreases. While declining labor demands may be positive for farmers, this represent a negative outcome for the laborers (due to a reduced number of jobs), and may negatively affect the larger regional economy by creating displaced workers. Another example of uneven societal impacts is that some farmers may have more capacity to invest in efficient irrigation technologies, which could force some farmers out of business and contribute to the trends of increasing farm size and fewer farms (Fuglie and Kascak, 2001). Our results also show that new irrigation technologies might have contrasting implications in different FEW sectors. For example, the agricultural economy (as a whole) may improve while hydropower generation and ecological condition of streamflow could diminish. These results suggest that it is important to consider possible unintended consequences of irrigation technology adoption and uneven socio-economic implications across actors, sectors, and scales.

4.3. Typology of policymaking for irrigation efficiency

Our analysis highlights that irrigation efficiency can create complex and often opposing implications for various water-dependent sectors in Yakima Basin (Fig. 6 a and Figure S4 and S5 in the Supplementary Materials). These competing interests and many other factors contribute to making the efficiency policies nontrivial to develop. In fact we argue that in places such as YRB that has complex institutional and infrastructural setup, it is impossible to treat the irrigation issues as "*tame problems*" (Dentoni et al., 2012; Özerol et al., 2012). Note that a "tame problem" is a problem that can be removed from its environment and solved without affecting the environment (Buchanan, 1992; Grint, 2010). Therefore, straightforward engineering and pragmatic types of decisions that are usually used for tame problems (Caniglia et al., 2020) might not respond to the complex outcomes of change in irrigation efficiency. In contrast, there are many evidences to believe that the irrigation policymaking is a "*wicked problem*". First obvious indication of the wickedness of efficiency problem is its multi-dimensional nature that has been discussed in this paper (Buchanan, 1992). In addition to what has been discussed, another group that have stakes in these policies are irrigation equipment manufacturers and irrigation engineering firms, because any irrigation policy recommendations can directly affect their revenues (Grafton et al., 2018).

Apart from plurality of interests, it can be argued that any judgement about the higher efficiency implications heavily depends on where the boundaries of the system are drawn (Anderies et al., 2013). For example, a national-level interest, might lead to disproportional support for improvement in agricultural efficiency comparing to finer spatial resolutions. Also, similar to other wicked problems (Rayner, 2012), irrigation efficiency issue is endless. Even if all the farmers invest in more efficient systems, the need for replacing these systems will emerge after a while. Besides, new technologies that emerge on the daily basis, provide additional incentives to switch. In addition, as our climate change and socio-economic analysis shows, irrigation efficiency implications for each player changes as climatic, institutional, and infrastructural context of the basin transform, which is another indication of the wickedness of this problem (Verweij et al., 2006; Rayner, 2012). Another source of complication that makes efficiency a non-tame problem is the fact that there is often not enough ground to argue which stakeholders (or their representative metrics) should be included or excluded in the efficiency impact analysis. For example, in some areas, switching to more efficient irrigation systems could substantially affect the chemical properties (e.g., the salinity) of soil and water (Bliesner et al., 1977; Letey, 1993; Pearce and Schumann, 2001; Causapé et al., 2006), and including or excluding that aspect of the efficiency in the discussion can transform the entire policy recommendations.

We argue that irrigation efficiency policies should be designed from a wicked problem standpoint. Policymaking for those types of problems should consider the pluralistic nature of the irrigation efficiency, which unavoidably leads to accepting that, similar to other wicked problems, there is no perfect or a final solution (Verweij et al., 2006; Alford and Head, 2017). Therefore, as have been suggested for other wicked problems, irrigation efficiency policies should incorporate various points of views, disciplines and knowledges, while incorporating awareness raising and capacity-building as a part of the process (Verweij et al., 2006; Weber and Khademian, 2008; Brown et al., 2010; Caniglia et al., 2020). In wicked problem literature these solutions are usually referred to as clumsy solutions (Verweij et al., 2006; Rayner, 2012). Also, power asymmetries and social and cultural arrangements should be taken into account to develop effective and sustainable policies. Additionally, as discussed earlier efficiency policies should be always aware of regional institutions, infrastructure, and climate. This necessitate a careful consideration of regional details before reaching to an informed decision about endorsing or discouraging irrigation efficiency improvement. Finally, irrigation efficiency policies should not be assumed to comply with stationarity conditions and might need to be revisited frequently.

4.4. Can the rebound effect concept explain the impacts of irrigation efficiency on the environment?

As discussed earlier, the rebound effect (i.e., the Jevon Paradox) argues that higher IE can lead to higher water use by the efficiency-improving farmers (Clark and Foster, 2001), which can negatively affect other sectors. Recently, studies on this topic have led to policy propositions that mainly recommend against governmental interventions to increase irrigation efficiency (Grafton et al., 2018; Wu et al., 2018; Freire-González, 2019). However, our analysis of historical diversion and average annual streamflow suggests that Yakima Basin has undergone fundamentally different consequences of irrigation efficiency than some of the most widely discussed regions of the world that have experienced a rebound effect (Sears et al., 2018; Song et al., 2018; Wang et al., 2020); such regions include Murray–Darling Basin in Australia (Loch and Adamson, 2015; Wheeler et al., 2020), the U.S. state of Kansas and neighboring regions that rely on the Ogallala Aquifer for water (Li and Zhao, 2018; Pfeiffer and Lin, 2014; Sanderson and Hughes, 2019), and many irrigated regions in China (Fang et al., 2020; Song et al., 2018; Wu et al., 2018). In these regions, irrigators have been improving their efficiency for several decades, but the tendency toward the expansion of irrigated lands and the use of water-intensive crop types has canceled out the savings from more the efficient systems. This implies that although theories such as the Jevon paradox, the rebound effect, and the treadmill of production (Sanderson and Hughes, 2019) can efficiently explain the observed trends in some areas, alternative theories should not be ignored.

In addition, our results indicate that higher IE causes complex regional effects across different water-dependent sectors, and a unified metric such as rebound effect might not be able to capture its entire dynamics. The multi-dimensional and scale-dependent nature of efficiency improvement has already been discussed in energy literature, the birthplace of the rebound effect. For example, several past studies (e.g., Freire-González, 2019) have defined three types of rebound effects: direct, indirect, and economy-wide. Freeman (2018) advocates for broader definitions of rebound effects implications, including economy-wide, transformational (the effect on customers' preferences), frontiers (encouraging new innovative products), and the international aspects of efficiency increase. In environmental studies of the rebound effect, there are example of considering direct, indirect, and economy-wide IE effects (Dumont et al., 2013; Freire-González, 2019); however, most of the IE body of literature perceives the rebound effect as a stressor that influences either the investing farmers or the entire system as a whole. We argue that while these definitions themselves imply the complexity of the problem, they might lack enough conceptual foundation to respond to pluralistic nature of the efficiency issues. Moreover, we show that the impacts of different efficiency scenarios are heavily controlled by local water institutions and infrastructures. Even within a particular sector, the responses can vary by the level of water shortage and the time of year. There are also nontrivial socioeconomic implications that are always specific to a given regional context and that makes policy recommendations non-generalizable. Therefore, we argue that the rebound effect concept or other aggregated metrics that aim at describing the totality of efficiency impacts might not be able to fully capture these complex and intertwined relationships.

4.5. Assumptions and limitations

In this study, we assume that water rights and regulations do not change in the future. The current water law does not allow for expansion of irrigated areas. At the same time, when farmers do not use their water rights, they can be subject to relinquishment. However, historically, the "use it or lose it" law has not been enforced over YRB. Therefore, the freed-up water has become available to other users, an assumption that recorded diversion of the YRB supports. Further studies that consider alternative relinquishment and water regulation assumptions could provide a more in-depth understanding of the implications of more efficient irrigation technologies. Additionally, a more comprehensive analysis of economic factors such as changes in energy price and agricultural demand as well as energy and crop prices could provide a broader perspective on this issue.

Explicit evaluation of the economic impacts of farmers' decisions on physical and chemical condition of fish habitat is beyond the scope of this work. Other studies (Yoder et al., 2017) have projected that improvement in the fish environment would have a significant impact on the economy of the basin. We do not directly quantify the impacts of changes on values of fish and wildlife in the Yakima River because doing so requires detailed simulation of fish migration process, effect of water physical and chemical characteristics (e.g., water temperature) on fish population (Rose, 2000), which are beyond the scope of this paper. Instead, we use streamflow ecological metrics to comment on how changes in streamflow may impact fish. Finally, in this study, we only take into account 11 streamflow metrics, however, there are many other properties and signatures of streamflow timeseries that have been considered in previous studies (e.g., Olden and Poff, 2003; Do et al., 2018; McMillan, 2021) which can be investigated in future.

Another important transformation in Yakima that could interact with the effects of irrigation technology is change in cropping patterns. Our analysis shows that the planted area of low- and medium-value crops (e.g., wheat, potato, corn, alfalfa, pasture, and barely) has declined during the last two decades, while high-value crops (e.g., apple, pear, grapes, and hops) have become more widespread in the region (Supplementary Figure S6). Transitioning to a high-value crop pattern can affect irrigation diversion through two pathways. First, a new crop distribution affects the total consumptive water use, though the overall direction of change in water demand depends on the actual crop mix. Some crop types have higher water demand, but some high-value crops, such as grapes, have lower demand than their low-value counterparts, such as alfalfa, and this can reduce basin-wide irrigation diversion (Davis et al., 2017; Gautam et al., 2021). Second, in drought years, high-value crops tend to reinforce the demand-hardening trend that has been reported throughout the western U.S. (Mall and Herman, 2019; Reisman and Macaulay, 2021), which can increase overall irrigation withdrawal, especially during drought periods. Although exploring the combined effect of cropping patterns and irrigation technology is beyond the scope of this study, further investigation of this issue could lead to a deeper understanding of irrigation-efficiency effects.

5. Conclusions

This study explored how farmers' decisions regarding whether to invest in new irrigation systems impact the basin-wide water cycle and the economy of FEW nexus sectors. Our results indicate that the effects of improved efficiency will not be consistent among different sectors. For example, the overall agricultural economy of the YRB improves under more efficient irrigation systems; however, because return flow decreases, a negative impact can occur on basin-wide water availability. The energy sector can experience a reduction in hydropower generation because the generators are not located on the main stem of the river; therefore, as diversion decreases, the water that goes to the generators decreases. Some of the ecological flow metrics indicate deterioration of fish habitat because of a higher probability of experiencing stream fluctuations and low-flow conditions in summer, while other factors such as mean annual flow improve with higher irrigation efficiency. We also conclude that there can be unintended and uneven socioeconomic outcomes for different participants within the system and at various scales. Reduced labor demand is one example of a predicted consequence of irrigation technology improvements that will create benefits for some and problems for other participants in this regional FEW system. There may also be increased conflict among sectors, which will need to be taken into consideration. In addition, we show that institutional changes allowing the expansion of irrigated agriculture, for example, can have positive impacts on basin-wide water availability during severe drought years and negative ones during moderate drought years. These results suggest that it will be important to carefully evaluate the goals of any system innovation and plan for multiple potential socioeconomic consequences in various contexts. Technological innovation must be used in combination with policies and other interventions to help produce intended outcomes across system participants and sectors. These findings imply that no universal answer explains whether an increase in irrigation efficiency through technological development improves water availability for other sectors. Additionally, the results of this study underscore the fact that local and regional conditions matter, and policies may be put in place that counteract the occurrence of a Jevons paradox, such as policies that enforce water rights and reduce overall demand.

Author roles

Keyvan Malek conducted simulations and wrote the first draft of the manuscript. Jennifer Adam and Patrick Reed supervised the project. Jonathan Yoder supervised the socio-economic parts of the project. All authors including Jennifer Givens, Michael Brady, Claudio Stockle, Tina Karimi, Kirti Rajagopalan, and Mingliang Liu participated in development of the paper's central ideas, its study design, and the manuscript.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.113731.

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