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Potential for Managed Aquifer Recharge to Enhance Fish Habitat in a Regulated River

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Abstract: Managed aquifer recharge (MAR) is typically used to enhance the agricultural water supply but may also be promising to maintain summer streamflows and temperatures for cold-water fish. An existing aquifer model, water temperature data, and analysis of water administration were used to assess potential benefits of MAR to cold-water fisheries in Idaho's Snake River. This highly-regulated river supports irrigated agriculture worth US \$10 billion and recreational trout fisheries worth \$100 million. The assessment focused on the Henry's Fork Snake River, which receives groundwater from recharge incidental to irrigation and from MAR operations 8 km from the river, addressing (1) the quantity and timing of MAR-produced streamflow response, (2) the mechanism through which MAR increases streamflow, (3) whether groundwater inputs decrease the local stream temperature, and (4) the legal and administrative hurdles to using MAR for cold-water fisheries conservation in Idaho. The model estimated a long-term 4%–7% increase in summertime streamflow from annual MAR similar to that conducted in 2019. Water temperature observations confirmed that recharge increased streamflow via aquifer discharge rather than reduction in river losses to the aquifer. In addition, groundwater seeps created summer thermal refugia. Measured summer stream temperature at seeps was within the optimal temperature range for brown trout, averaging 14.4 °C, whereas ambient stream temperature exceeded 19 °C, the stress threshold for brown trout. Implementing MAR for fisheries conservation is challenged by administrative water rules and regulations. Well-developed and trusted water rights and water-transaction systems in Idaho and other western states enable MAR. However, in Idaho, conservation groups are unable to engage directly in water transactions, hampering MAR for fisheries protection.

Keywords: climate adaptation; stream temperature; streamflow; Henry's Fork; fisheries; Snake River; Idaho; water rights

1. Introduction

In the Western USA, important aquatic ecosystems and recreational fisheries often occur in river basins with large irrigated agricultural diversions, resulting in conflicts between water for irrigation and environmental streamflow needs [1–3]. Climate change exacerbates these conflicts, as precipitation regimes shift from snowfall to rainfall and evaporative demand increases, leading to flashier streamflow in winter and spring and reduced baseflow through summer and fall [4,5]. Climate warming and reduced baseflow work in tandem to warm stream temperature and are expected to reduce habitat for cold-water ecosystems [6]. Increasing streamflow, particularly during summertime baseflow conditions, cools stream temperatures by increasing the assimilative heat capacity of rivers [7].

Management options to increase streamflow include re-operating reservoirs [8,9], reducing diversions through environmental water purchases [10], or conducting managed aquifer recharge (MAR) [11,12]. MAR is a promising strategy to enhance cold-water habitats while maintaining water resource benefits for people because excess water is intentionally recharged to raise aquifer levels, which increases baseflow, or may subsequently be pumped for irrigation. Groundwater additions to streams are particularly beneficial for cold-water fisheries because they create thermal refugia [13,14]. MAR is often recommended as a strategy to manage water for people and ecosystems with flashier runoff anticipated with climate change [12]. However, the potential of MAR to benefit cold-water ecosystems while maintaining irrigated agriculture requires (1) understanding the physical hydrology between the recharge site and the stream, (2) estimating temperature differences at groundwater seeps in the river and ambient temperatures, and (3) understanding administrative water rules to apply MAR to benefit cold-water habitat.

In streams that interact with local and regional aquifers, winter recharge enhances groundwater storage important for streamflow through the summer [14]. However, systems with shallow, unconfined aquifers are sensitive to climate variability [15] and may experience changes in the timing and magnitude of natural recharge [16], diminishing aquifer storage and groundwater-supported streamflow [16,17]. MAR can capture early rainfall or snowmelt and supplement late-summer return flows [18–20], by raising an aquifer's hydraulic head and creating groundwater seeps and shallow groundwater contributions that return to the stream in gaining reaches. Models have demonstrated that the lag time between MAR and return flow can delay the runoff peak [21–23], buffering a variable runoff regime [23] and potentially alleviating critical low-flow periods [24–26]. However, proportional contributions of MAR to streamflow depend, in part, on recharge site proximity [18,22,23].

Some studies have found that groundwater seeps and return flows mitigate the thermal effects of climate change on riverine habitats [27–29]. For example, measured water temperature at groundwater seeps have been 2–3 °C cooler than ambient river temperatures in the Pacific Northwest [21], and up to 4 °C cooler in Nevada's Walker River [12]. While shallow groundwater temperature is sensitive to long-term changes in air temperature, groundwater temperatures are less sensitive than surface water to changes in air temperature and are generally absent from heating by solar radiation [30–33]. Although studies note that MAR may increase summer baseflows [34], provide cool groundwater return flows to maintain cold-water fisheries during low-flow periods [26], and maintain aquatic ecosystems [18,35], field observations have yet to test these hypotheses. Furthermore, it is important to understand the extent and times that MAR can influence streamflow and stream temperature to maintain cold-water species in regulated rivers with climate change.

In the western USA, MAR must fit into the administrative rules of the Doctrine of Prior Appropriation, which allocates water for beneficial uses based on the seniority that water was first used. In most western states, the senior uses are mining and agriculture. Additionally, states must have well developed market and transfer mechanisms that provide administrative water for MAR within pre-existing allocation systems. However, western states that prioritize MAR, like Arizona, Colorado, California, and Idaho, each have different administration policies regarding which entities can implement MAR. Overall, implementation of MAR includes large-scale projects conducted by centralized public authorities, cities, and private companies in Arizona [36,37], smaller-scale projects implemented by landowners, local agencies, and counties in California [36,38], and a variety of MAR and recovery projects implemented by individual water right holders, local groundwater management districts, and cities in Colorado [37,39]. In Idaho, the state-run MAR program is primarily designed to increase discharge from the aquifer to the river for fulfillment of senior surface-water rights. Water transaction mechanisms in California and Colorado allow effective transfer of water to environmental uses, and conservation organizations can be direct participants in such transactions [40]. However, in Idaho, conservation groups cannot directly participate in transactions like water rental, which inhibits MAR for fisheries protection.

This study aims to understand the potential for MAR to benefit cold-water ecosystems while maintaining irrigated agriculture in Idaho's Henry's Fork Snake River. To do this, existing data and models were integrated and analyzed for a reconnaissance-level assessment. The following research questions were addressed: (1) What quantity and timing of streamflow response can MAR produce? (2) Does MAR increase streamflow by reducing channel loss to the aquifer or by increasing groundwater inflow to the stream? (3) Can groundwater inputs create local areas of decreased water temperature in the stream? (4) What legal and administrative hurdles exist for MAR to be used for cold-water fisheries conservation in Idaho? This research is instrumental to evaluate whether MAR is a water management strategy that has the potential to benefit managed fisheries. MAR is increasingly implemented throughout the western United States to meet human and environmental water objectives. There is a clear need to understand whether implementing MAR to benefit managed fisheries deserves additional effort and resources, and to identify current knowledge gaps when streamflow, stream temperature, and administrative water rules are considered for environmental MAR applications.

2. Materials and Methods

2.1. Study Area

The 93,000 km² upper Snake River basin in Idaho and Wyoming, USA, (Figure 1) is an ideal setting for assessing the potential of MAR to benefit cold-water ecosystems. The basin's water resources support an agricultural economy worth US \$10 billion [41], as well as many ecologically important stream systems and recreational trout fisheries, which contribute US \$100 million to local communities [42,43]. Mean annual surface water supply is 15,000 Mm³ in the basin and 75% is withdrawn for irrigation. Irrigators also withdraw 1600 Mm³ of groundwater from the Eastern Snake Plain Aquifer (ESPA; Figure 1) and 500 Mm³ from tributary aquifers [41]. In a given year, over 10,000 km² of irrigated land produce hay, wheat, barley, potatoes, and dairy products for global companies such as Anheuser-Busch, General Mills, and Clif Bar. The ESPA is a highly transmissive, unconfined, regional aquifer hosted in sediments interbedded within fractured Quaternary basalts [44]. Water generally flows through the ESPA from northeast to southwest and discharges to the Snake River near American Falls Reservoir and in a 100 km reach immediately upstream of King Hill (Figure 1). Water levels in and discharge from the ESPA have been declining for 60 years due to a combination of decreased recharge incidental to surface water irrigation and increased groundwater pumping [41,44,45]. Declining aquifer levels have caused costly legal disputes, increased reliance on reservoir storage to meet irrigation demand, increased groundwater pumping costs, and decreased streamflow for fisheries.

As part of a comprehensive plan to increase storage in and discharge from the ESPA, Idaho has implemented publicly funded MAR, with an annual objective of 330 Mm³ [41]. The primary management goal of the state's MAR program is to increase discharge from the aquifer to the river to fill senior surface water rights, rather than to store the water for future recovery via pumping. Increasing discharge over the long term requires increasing storage in the aquifer to maintain larger hydraulic gradients along connected river reaches. Higher storage volume, in turn, has ancillary benefits such as decreased pumping costs for groundwater users [41]. In addition, irrigation entities, cities, and private companies are using MAR on smaller scales to meet mitigation requirements of a 2015 legal settlement between senior surface water users and junior groundwater users. This settlement requires a specified reduction in groundwater pumping or mitigation with an equal amount of MAR. Concurrently, research describing benefits to aquatic systems from incidental and managed recharge in irrigated landscapes has motivated conservation organizations to consider MAR as a tool for maintaining and enhancing cold-water ecosystems in a changing climate [3,18,46].

An assessment was conducted in the Henry's Fork Snake River watershed (Figures 1 and 2), where the state of Idaho has recently invested US \$1.5 million to expand and improve a MAR site known as Egin Lakes (Figure 1). The Henry's Fork and its tributaries have an annual surface-water supply of 3200 Mm³ and irrigators withdraw ~1500 Mm³ to apply on ~1000 km² of agricultural

land; very little groundwater is used for irrigation in the watershed [47]. When natural streamflow is insufficient to meet irrigation demand—usually early July through early September—streamflow is augmented by draft of Island Park Reservoir, near the river’s headwaters (Figure 1). Nearly all irrigation water is delivered through unlined canals constructed in the late 1800s. Thus, these canals have provided a large amount of incidental recharge to local and regional aquifers via seepage for over a century [48,49]. Historically, irrigation water was applied via flooding or furrow irrigation, but most application was converted to sprinklers in the 1980s and 1990s [49,50]. The lower one-third of the Henry’s Fork, shown as the “modeled reach” in Figure 1, is hydraulically connected to local and regional aquifers. Previous research has shown that this reach gains water seasonally in response to locally increased water tables during irrigation season, but loses water to the regional ESPA during the winter [48,49,51,52]. The conversion to more efficient sprinkler application has reduced both total diversion and groundwater return flows to the river by around 250 Mm³ per year since the late 1970s [49].

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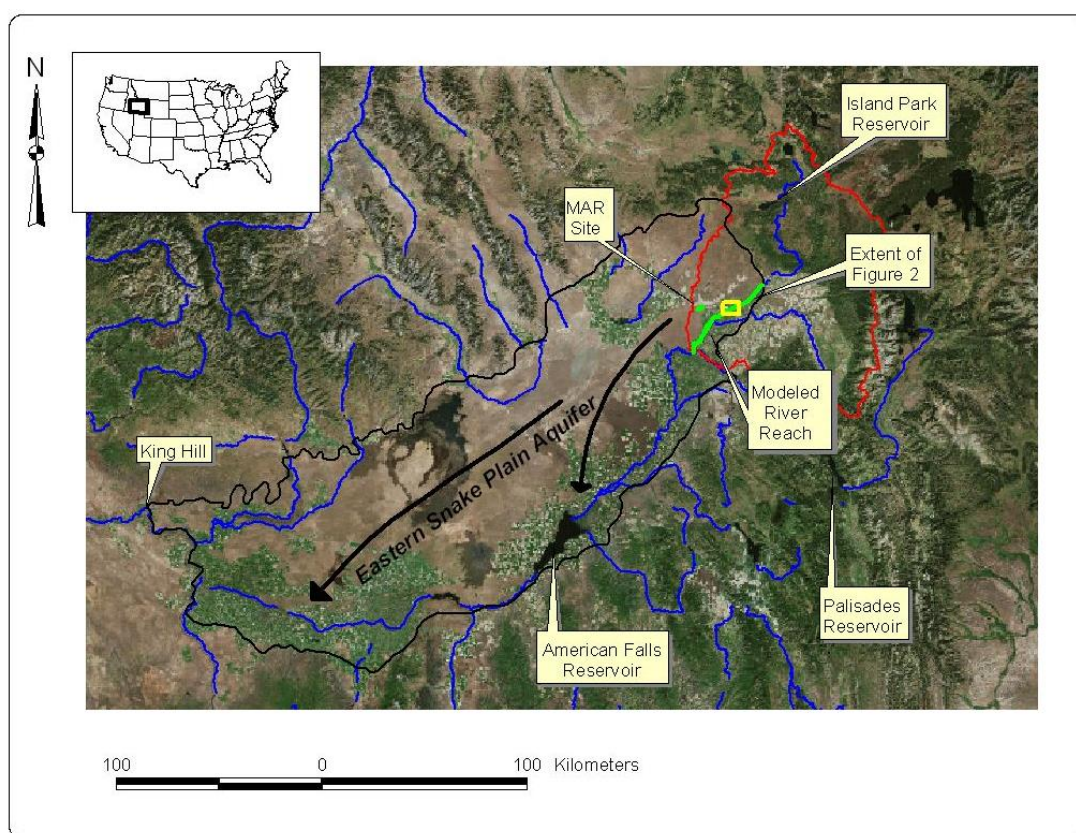


Figure 1. Upper Snake River basin, USA, showing the ESPA, modeled river reach of Henry’s Fork (in green), and a nearby MAR site. The red polygon delineates the Henry’s Fork watershed, and the yellow rectangle shows the area enlarged in Figure 2. Black arrows indicate primary groundwater flow paths on the ESPA. Data credit: Idaho Department of Water Resources.

As part of a comprehensive plan to increase storage in and discharge from the ESPA, Idaho has implemented publicly funded MAR with an annual objective of 330 Mm³ [41]. The primary management goal of the state’s MAR program is to increase discharge from the aquifer to the river to fill senior surface water rights, rather than to store the water for future recovery via pumping when streamflow drops below a specified target at this gage [53]. However, four diversions in the field study reach downstream of the St. Anthony gage substantially reduce streamflow during the summer (Figure A1). The study reach supports an increasingly popular and economically valuable recreational sport fishery for wild brown trout (*Salmo trutta*) [54,55], which has an optimal summer temperature range of 12 °C to 19 °C. Habitat suitability for brown trout decreases as temperature increases above 2015 legal settlement between senior surface water users and junior groundwater users. This settlement requires a specified reduction in groundwater pumping or mitigation with an equal amount of MAR. Concurrently, research describing benefits to aquatic systems from incidental and managed recharge in irrigated landscapes has motivated conservation organizations to consider MAR as a tool for maintaining and enhancing cold-water ecosystems in a changing climate [3,18,46].

An assessment was conducted in the Henry’s Fork Snake River watershed (Figures 1 and 2),

19 °C to the lethal limit of 27 °C [56]. Over the summers of 2016, 2017, and 2018, daily mean water temperatures during July and August ranged from 16 °C to 20 °C at a water-quality monitoring station Henry's Fork, shown as the modeled reach in Figure 1, is hydraulically connected to local and regional aquifers. Previous research has shown that this reach gains water seasonally in response to locally increased water tables during irrigation season, but loses water to the regional EPA during the winter [48,49,51,52]. The conversion to more efficient sprinkler application has reduced both total diversion and groundwater return flows to the river by around 250 Mm³ per year since the late 1970s [49]. Due to high water temperatures, brown trout move either to local areas of groundwater input or out of the reach altogether during the summer [54].

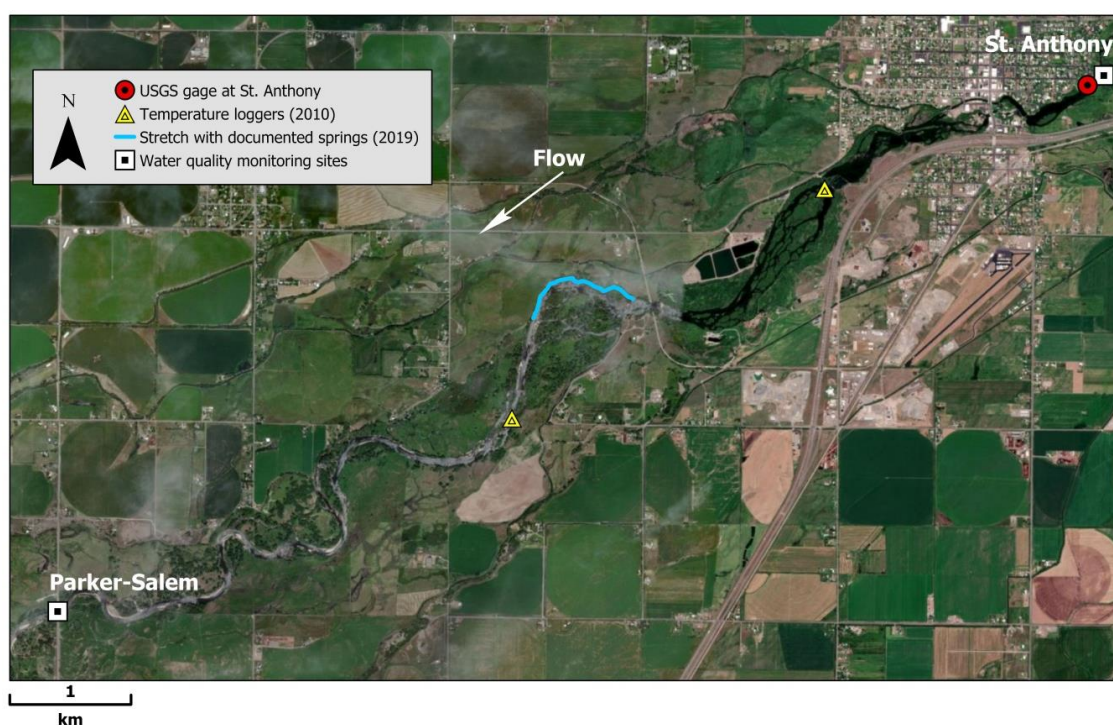


Figure 2. Map of field study reach, showing locations of U.S. Geological Survey (USGS) streamflow gage at St. Anthony, temperature loggers deployed in 2010, water quality monitoring locations, and stretch where springs were documented in 2019. Data credit: ESRI.

The “field study reach” in the study reach of the Henry’s Fork is immediately draft of Island Park Reservoir. Streamflow gage 13050500 at St. Anthony (Figure 2). This gage is the effective flow management point in the lower watershed, triggering additional releases from Island Park Reservoir when streamflow drops below a specified target at this gage [53]. However, four diversions in the transport of suspended material out of the reservoir and resulting high turbidity during the peak field study season, reach downstream of the St. Anthony gage substantially reduce streamflow during the summer (Figure A1). The study reach supports an increasingly popular and economically valuable recreational sport fishery for wild brown trout (*Salmo trutta*) [54–55], which has an optimal summer temperature range of 12 °C to 19 °C. Habitat suitability for brown trout decreases as temperature increases above 19 °C to the lethal limit of 27 °C [56]. Over the summers of 2016, 2017, and 2018, daily mean water temperatures during July and August ranged from 16 °C to 20 °C at a water-quality monitoring station at the top of the field study reach and from 17 °C to 22 °C at a water-quality monitoring station at the bottom of the field study (Figures 2 and A2). Maximum instantaneous water temperature recorded at the lower station over this time period was 27.3 °C, and daily maxima frequently exceeded 22 °C. Due to high water temperatures, brown trout move either to local areas of groundwater input or out of the reach altogether during the summer [54].

2.2. Streamflow Response

Summertime streamflow in the study reach could be increased by increasing draft of Island Park Reservoir. Existing regional groundwater model to estimate response of streamflow in the Henry’s Fork to MAR at the Big Lost sill, located 8 km from the Henry’s Fork site (the watershed in Figure 3, which also reports this result). Modeling was done with the Idaho Department of Water Resources’ peak fishing season, increased water temperatures downstream of the reservoir when it is drafted

Enhanced Snake Plain Aquifer Model Version 2.1 (ESPAM2.1) [52], a regional finite-difference flow model implemented in MODFLOW and configured with a single aquifer layer, monthly temporal resolution, and roughly 11,000 1.6-km grid cells. The model supports both steady-state and transient simulations. Although storage coefficients are typical of unconfined conditions, the transient rendition of the model uses time-constant aquifer transmissivity, making model results additive and scalable. The model was calibrated to 1980–2008 hydrologic conditions, using the first five of these as a burn-in period [52]. Calibration used over 43,000 aquifer water levels, 2000 river gain and loss estimates, and 2000 spring discharge measurements and was performed using PEST version 12.0, a nonlinear parameter estimation program [60]. The model was built specifically to estimate effects of aquifer pumping and recharge on river reaches and springs in hydraulic connection with the aquifer, so calibration optimized groundwater-surface water exchanges rather than hydraulic heads. The model does not simulate solute transport nor thermal changes in the aquifer or its discharge. In the model, the hydraulically connected section of the Henry's Fork is treated as a single, 75-km reach, referred to as the "modeled reach" (Figure 1), whereas our field study reach is only 12 km in the center of the ESPAM2.1 modeled reach (Figures 1 and 2). Monthly model calibration residuals for stream gains and losses in the modeled reach of the Henry's Fork were generally on the order of $\pm 25\%$, but monthly residuals as large in magnitude as -100% were observed early in the irrigation season. Over the period 1985–2008, the model underestimated cumulative river gain by around 10%. Thus, the model is suitable for our reconnaissance-level assessment when applied over long time periods.

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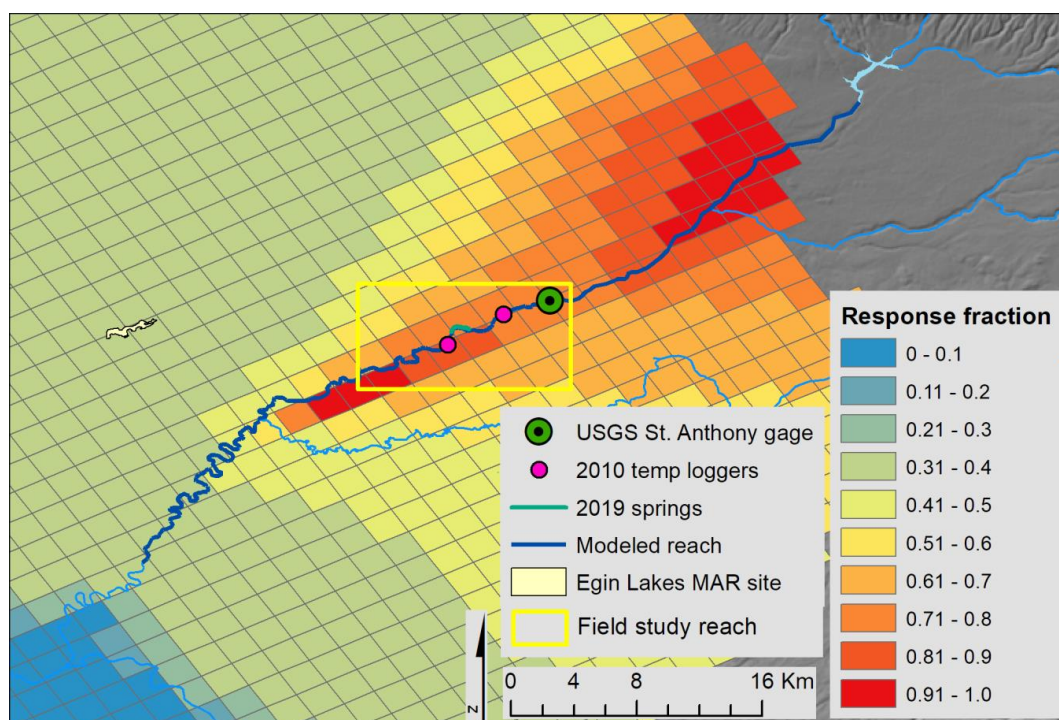


Figure 3. Steady-state discharge response in the modeled river reach to recharge conducted in a given model cell, as a fraction of total recharge volume. For example, a response fraction of 0.45 (white cells) indicates that 45% of the volume of water recharged in that cell will eventually contribute to streamflow in the modeled reach. The yellow rectangle indicates the field study reach.

The model was used in two ways. First, a steady-state simulation was used to calculate the fraction of total recharge in a given model cell that affects streamflow in the modeled reach of the Henry's Fork. Recharge was simulated in the model cells containing the Egin Lakes MAR site, as well as in other model cells in the vicinity of the lower Henry's Fork to assess whether developing MAR sites in other locations could increase streamflow response to MAR. Second, a 30-year transient simulation was used to estimate streamflow response in the modeled reach to a scenario in which 7.3 Mm³ of water was withdrawn from the river and recharged at the Egin Lakes site in each of March, April, and October and 25.6 Mm³ of water was withdrawn from the river and recharged at Egin Lakes during November. This annual scenario was similar to operation of the Egin Lakes site during 2019 and was repeated in each of the 30 years of simulation. Model output was used to estimate net change to streamflow in the study reach by allocating total streamflow response for the modeled Henry's Fork reach proportionally to the field study reach and including the effect of

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Recharge proximal to the lower Henry's Fork increases hydraulic gradients between the aquifer and the river, but if these gradients were initially negative (i.e., water flows from the river to the aquifer), a positive streamflow response from recharge would occur through decreased river losses rather than through increased river gains. Although the resulting increase in streamflow would be equivalent between the two mechanisms, the first mechanism would not provide the benefit of decreased water temperature during the summer. Thus, summertime water temperature was measured upstream and downstream of a reach known to be hydraulically connected with the underlying aquifer. These measurements were conducted in 2010, a decade after conversion from flood to sprinkler irrigation but six years prior to initiation of MAR at the expanded Egin Lakes site. Canal seepage, which has been roughly constant since 2000, was the only source of local groundwater recharge in 2010. Water temperature loggers were deployed from 1 June 2010 to 31 August 2010 at two locations in the upper half of our field study reach (Figure 2) and secured underneath overhanging riparian vegetation at ~40 cm water depth. The upstream logger was located immediately downstream of a reach through which the river flows over basalt bedrock and has little interaction with shallow groundwater. The other logger was placed 5 km downstream, in a reach where the river is well connected with shallow groundwater. Mean daily upstream temperature was subtracted from downstream temperature to create a time series of temperature differences. After accounting for serial autocorrelation with lag-3 autoregressive terms, two statistical models were fit to the time series—one with hypothesized zero mean and another with a non-zero fitted mean. Statistical significance of the fitted mean was assessed with the likelihood ratio test at a 0.05 level of significance (Appendix B).

2.3. Local Effects of Groundwater Inflow on Temperature

Whereas the 2010 temperature observations were made to assess the nature of summertime streamflow response to recharge solely from canal seepage, a separate field study in 2019 documented the locations and temperature of specific groundwater springs to investigate the potential for MAR to provide cool groundwater return flow to the river. In July 2019, locations of groundwater springs contributing water to the river channel were documented by walking a 1-km length of the right bank of the river, in the lower half of the 5 km reach studied in 2010 (Figure 2). A steep bluff approximately 5–10 m in vertical relief forms the boundary of the active floodplain on the right side of the river. Springs emerged from the face of the bluff and along its base, often between 1 and 50 m from the channel bank, and most spring outputs flowed into a secondary river channel. Each spring site was classified as (1) a single discharge point, where water originating from the bluff face created a separate channel that actively flowed into the river, or as (2) a “wall seep”, where water emerged from continuously saturated sediments along the bluff face and contributed unchannelized flow to the river. At each spring site, a FLIR T450sc thermal infrared camera (FLIR Systems Inc., Wilsonville, Oregon, USA) was used to document differences between the surface temperatures of incoming groundwater springs and the river. The FLIR T450sc camera senses radiant stream surface temperatures in the 7.5 to 13 μ m range, with an accuracy of ± 1 °C or 1% of the range of the reading [61]. To complement the imagery, instantaneous temperatures were measured with a handheld thermometer at three lateral locations: spring emergence, 0.6 m and 6 m into the river channel from where the spring entered the river.

At wall seeps, lateral temperatures were measured at the upstream and downstream extent of each seep. In total, three temperature measurements were recorded at each of 20 spring sites. Temperature differences across the three lateral locations were analyzed with mixed-effects analysis of variance and Tukey's post-hoc test, treating spring site as a random effect. These tests were conducted at a 0.05 level of significance (Appendix B). The temperature analysis was not accompanied by assessments of whether physical habitat at these locations was otherwise suitable for or used by trout.

2.4. Water Administration

Potential streamflow and temperature benefits of MAR will not result in real changes in the river without sufficient availability of water for MAR at appropriate times. Thus, our assessment included analysis of physical and administrative availability of water for MAR in the upper Snake River basin within Idaho's prior appropriation system of water rights. This assessment relied on a formal review of Idaho's MAR program conducted for the Idaho Water Resource Board [62], to which two of the co-authors of this paper (RVK and CNM) contributed substantially. In addition, the state's water rights database, water-rights accounting manual [63], and water exchange procedures [64,65] were reviewed to identify opportunities for and limitations to conducting MAR for fisheries conservation purposes.

3. Results

3.1. Streamflow Response

The steady-state simulation using ESPAM2.1 predicted that 37% of the water volume delivered to the Egin Lakes MAR site will increase streamflow in the modeled reach of the Henry's Fork over the long term, and the balance will benefit other river reaches in the basin (Figure 3). If recharge were conducted closer to the river than the existing MAR site, the model predicted that >90% of recharge is realized as increased streamflow in the modeled reach. The modeled response fraction depended strongly on recharge location and decreased fairly rapidly with increasing distance between the river and recharge location (Figure 3). For example, 90% of water recharged in the red cells contributed to streamflow in the modeled reach, whereas less than 40% of the water recharged in the green cells contributed to streamflow in the modeled reach.

Transient simulation with ESPAM2.1 predicted that streamflow response to spring and fall recharge at Egin Lakes is relatively uniformly distributed over the year, with little month-to-month variability (Figure 4). Initial streamflow response to the spring-fall MAR scenario increased roughly linearly over time to reach 50% of its long-term value 6.5 years after first implementation of the annual MAR regime (Figure 4). Streamflow response increased more slowly after that, reaching ~90% of its long-term value 25 years after initial implementation of the annual MAR regime. Including the effects of water withdrawal from the river for delivery to the MAR site, the annual MAR scenario resulted in a 20%–25% decrease in streamflow during November and a 5%–10% decrease in streamflow during each of October, March, and April, relative to the current median hydrograph (Figure 5). Despite these decreases in streamflow due to withdrawal for MAR, median spring and fall streamflow still remained much higher than summertime lows, even after only five years of MAR. After 20 years of implementation of this annual MAR regime, median streamflow increased by 4%–7% during July and August of the median year (Figure 5), although increases during late June and early July were on the order of 10%–40% relative to streamflow in the dry year of 2016 (Figure A3).

Mean daily water temperature from 1 June 2010 to 31 August 2010 was 0.6 °C cooler at the downstream location influenced by groundwater inputs, and this difference was statistically significant ($\chi^2 = 5.3$, $df = 1$, $p = 0.02$). This indicates that during summer, streamflow response to seasonal aquifer recharge results from inflow of groundwater to the river not from reduced loss of water from the river to the aquifer. Since this result was observed when canal seepage was the only source of aquifer recharge in the vicinity of the field study reach, additional recharge from MAR will further increase flow of groundwater into the river in the field study reach.

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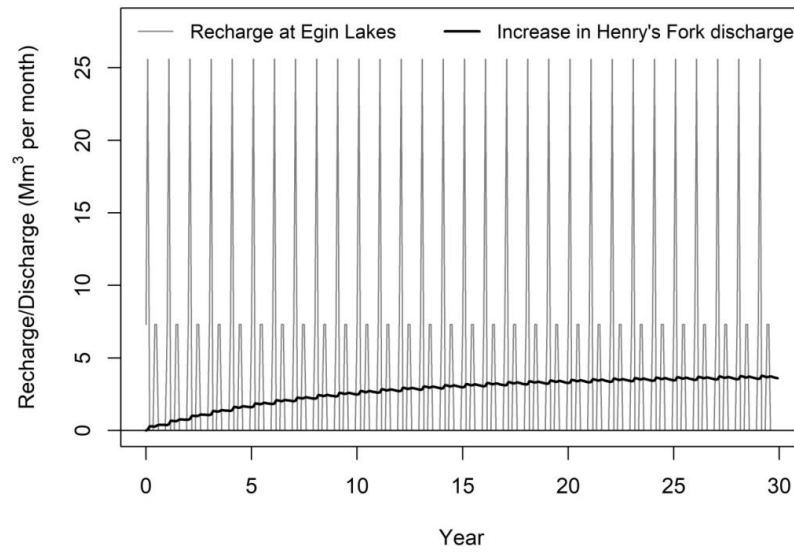


Figure 4. Recharge and discharge for annual MAR scenario of 7.3 Mm³ per month in each of March, April, and October, and 25.6 Mm³ per month in November, repeated every year for 30 years.

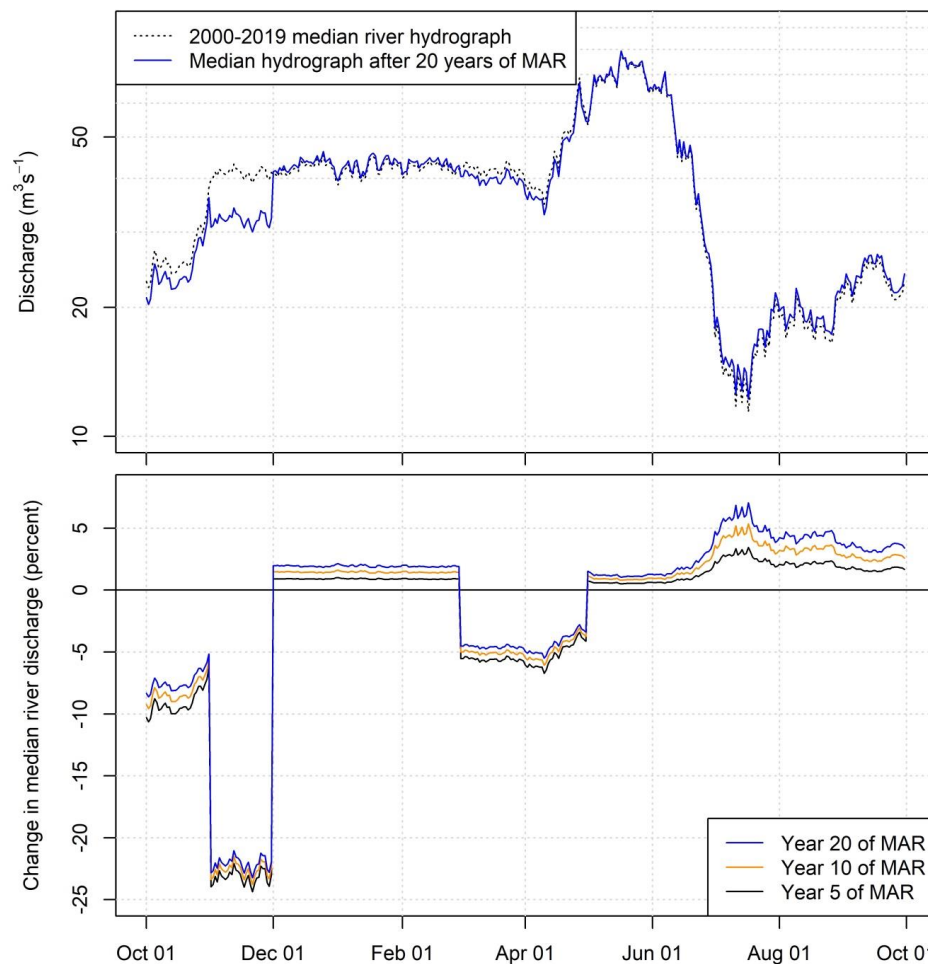


Figure 5. Net change in streamflow for annual scenario in which diversion for MAR from the study reach is 7.3 Mm³ per month in each of March, April, and October, and 25.6 Mm³ per month in November. Top panel shows median water-year hydrograph prior to and 20 years after initiation of annual MAR regime. Bottom panel shows percent change in streamflow 5, 10, and 20 years after initiation of annual MAR regime, respectively.

Mean daily water temperature from 1 June 2010 to 31 August 2010 was 0.6 °C cooler at the downstream location influenced by groundwater inputs, and this difference was statistically significant ($\chi^2 = 5.3$, $df = 1$, $p = 0.02$). This indicates that during summer, streamflow response to seasonal aquifer recharge results from inflow of groundwater to the river not from reduced loss of water from the river to the aquifer. Since this result was observed when canal seepage was the only source of aquifer recharge in the vicinity of the field study reach, additional recharge from MAR will further increase flow of groundwater into the river in the field study reach.

3.2. Local Effects of Groundwater Inflow on Temperature

In late July 2019, thermal imagery identified areas of cool water in the main river and its side channels near the points of spring inflow (Figure 6). Mean instantaneous water temperature at the 20 spring sites differed significantly across the three lateral locations: spring, 0.6 m from the streambank, and 6 m from the bank ($F = 29.7$, $df_1 = 2$, $df_2 = 38$, $p < 0.001$). All pairwise differences among the locations were significant (Tukey's Honest Significant Difference, adjusted $p < 0.001$). Mean water temperatures at the lateral locations, respectively, were 14.4°C , 16.0°C , and 18.3°C (Figure 7). Ambient water temperatures during the time of the field observations ranged between daily minima of 18°C and daily maxima of 23°C at the top of the field study reach and between 18°C and 25°C at the downstream boundary of the study reach (Figure A2).

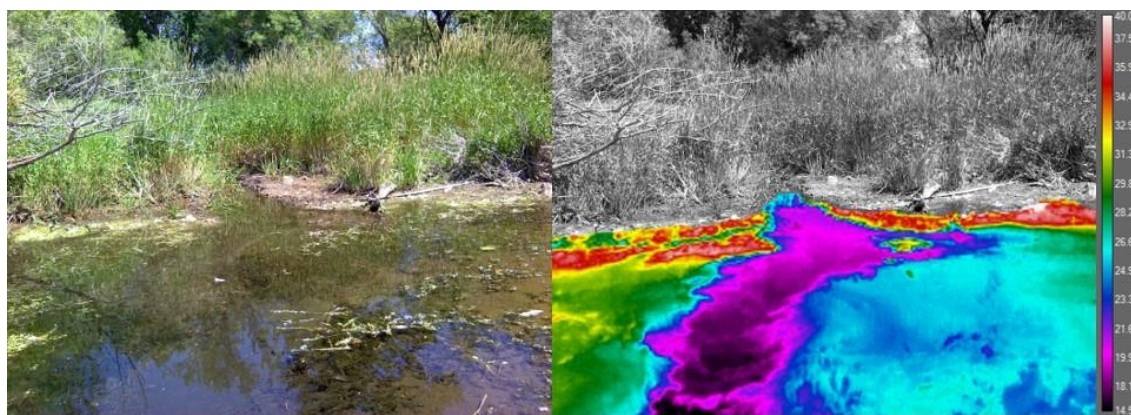


Figure 6. A side-by-side comparison of a visual image (left) and thermal infrared image (right) of the area where outflow from a groundwater spring located at $43^\circ 57' 07.6'' \text{ N } 111^\circ 46' 26.7'' \text{ W}$ entered a side channel of the river (flowing right to left). The photo was taken from a point 1.5 m from the margin of the side channel, looking toward the spring confluence. The spring emerged from the ground ~30 m from the confluence point. Temperature is indicated in $^\circ\text{C}$.

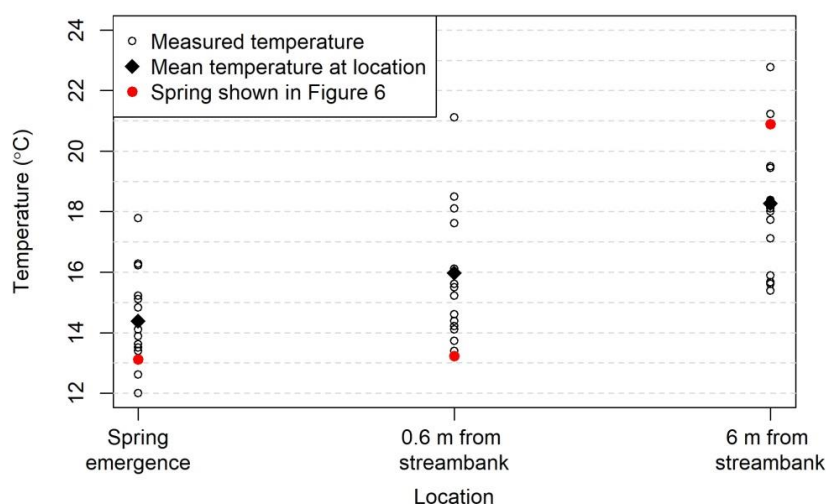


Figure 7. Water temperature at three locations measured at each of 20 distinct springs.

3.3. Water Administration

There are 84 decreed, permitted, or pending water rights for MAR in the upper Snake River basin, with a combined diversion rate of up to $725 \text{ m}^3/\text{sec}$. However, every senior MAR right is very small, with combined diversion of only $0.59 \text{ m}^3/\text{sec}$. The remaining $724.41 \text{ m}^3/\text{sec}$ are distributed among large water rights with priority dates of 1980 or later, in a prior-appropriation system where the majority of the irrigation rights have priority dates preceding 1910 and most reservoir storage priority dates precede 1940. Diversion for MAR allowed by the junior rights is available on an annual basis only in the winter and then only downstream of American Falls Reservoir (Figure 1). Considering only water rights specific to MAR, water is available for MAR at the Egin Lakes site in about half of all water years, usually between mid-May and early July. During irrigation season (1 April to 31 October), only water delivered to a designated, off-canal MAR site can be accounted as

of the irrigation rights have priority dates preceding 1910 and most reservoir storage priority dates precede 1940. Diversion for MAR allowed by the junior rights is available on an annual basis only in the winter and then only downstream of American Falls Reservoir (Figure 1). Considering only water rights specific to MAR, water is available for MAR at the Egin Lakes site in about half of all water years, usually between mid-May and early July. During irrigation season (1 April to 31 October), only water delivered to a designated, off-canal MAR site can be accounted as MAR, but during the winter, canal seepage also accounts as MAR, since canals would not customarily be delivering irrigation water then. Temporary transfers of senior water rights from irrigation or other uses to MAR occur through the state of Idaho's water supply bank, an administrative exchange bank rather than a physical storage bank such as those in Arizona and California.

A locally administered rental pool allows storage water held in Palisades Reservoir (Figure 1) to be rented for delivery to MAR sites anywhere in the basin, through administrative exchange or physical delivery, and these types of exchanges were used to provide the majority of water for MAR in the modeled scenario. Storage water rented in an administrative year (1 November to 31 October) must be delivered by December 1 and cannot be carried over any further into the subsequent year. Since the 2015 ESPA groundwater-surface water settlement was completed, new administrative rules have been enacted specifically to facilitate efficient but equitable water transactions for MAR. However, entities that do not hold water rights, including most conservation groups, cannot participate directly in water supply bank or rental pool transactions. Furthermore, the Idaho Water Resource Board is the only entity that can hold surface water rights for instream flow, regardless of whether those rights are permanent or temporary. Thus, even if conservation groups could participate in water transactions, there is no precedent for them to hold MAR rights specifically for environmental purposes.

3.4. Limitations

The importance of understanding the temporal response to water management actions is critical to address specific objectives. The one-month temporal resolution of ESPAM2.1 limits its ability to predict streamflow response during shorter time intervals that may be critical to trout survival. Furthermore, the model cannot distinguish between management actions that contribute groundwater and those that reduce streamflow losses to groundwater. Although our limited temperature observations suggest that summertime streamflow response to recharge near the field study reach is realized as groundwater inflow, the existing ESPAM2.1 model cannot predict whether MAR and other recharge strategies will change water temperature. The 1.6 km spatial resolution of the model also limits predictive use, especially in assessing response to MAR at hypothetical sites closer to the river, where response changes rapidly with distance away from the river. However, the greatest spatial-resolution limitation in ESPAM2.1 is the delineation of the river reach itself. The model cannot partition water across the 75 km lower Henry's Fork model reach to different locations, requiring simple proportional allocation to downscale model results, as was done here. Models with finer temporal and spatial resolution can be constructed [49], but calibrating higher-resolution models requires hydrologic observations made at the same scale, which are currently not available. A larger challenge to modeling groundwater flow in the Henry's Fork watershed is that the water budget cannot be closed using surface-water observations alone, whereas that for the larger ESPA can. This requires a priori assumptions about groundwater flux to calibrate parameters specifying boundary conditions. Groundwater flux is the most important model output in this case, so model output would essentially be pre-determined by assumptions required to calibrate boundary parameters.

An alternative approach to constructing finer-scale models is to estimate local groundwater fluxes using fine-scale piezometer data and temperature mixing models, and use those fine-scale models to downscale the coarse aquifer-river interactions predicted by the regional model. Models can be verified by conducting measurements of streamflow gain and loss across short stream reaches. Continuous, high-resolution temperature data are inexpensive to collect and would contribute not only to temperature mixing models but also to identification of thermal refugia across the whole field study

reach. Habitat surveys, observations of fish movement and habitat use, and water-quality analysis at and near areas of cooler water temperatures could then be used to determine whether reducing water temperature alone is sufficient to address factors limiting trout use of the study reach during summer.

4. Discussion

Overall, MAR can improve summer streamflow and stream temperatures for fish in localized areas of the basin. Thirty-seven percent of modeled Egin Lakes MAR returned to the study reach. Streamflow increased most (as a percentage change of baseflow) in the initial years following recharge, with 25–30 years needed to achieve steady-state response to an annually repeated MAR regime. Groundwater seeps confirmed that recharge was contributing to the river rather than merely reducing losses from the river to the aquifer. On average, stream temperature cooled 0.6 °C after traveling 5 km downstream during summer. July 2019 groundwater seep temperatures averaged 14.4 °C and were 16.0 °C about a half-meter from where groundwater seeps entered the river. These temperatures are in the suitable range for brown trout [56]. Average mid-summer ambient temperature was 20.1 °C for 2016 through 2018, which exceeds the optimal thermal brown trout threshold of 19 °C [61]. These findings suggest that MAR provides thermal refugia for managed fish species during summer. A review of administrative MAR rules for fisheries conservation provided more equivocal results. Some water is available for MAR in spring and fall of the wettest half of years, but substantial water for recharge is not consistently available, and canal capacity to the Egin Lakes MAR site limits recharge when water is available. Conservation organizations cannot participate directly in water transactions, but must partner with irrigators or water rights holders on MAR projects.

4.1. Physical and Administrative MAR Implications for Idaho and Henry's Fork

To maintain cool summer water temperatures at the reach scale for cold-water species, MAR volumes will likely need to offset declines in recharge that have occurred from improved irrigation efficiency, as sprinklers and center pivots have replaced flood irrigation over the past few decades. Improved irrigation efficiency typically does not increase streamflow as more land is put into production or junior water rights come into priority [66,67]. Around 250 Mm³ is needed annually to offset lost incidental recharge, which exceeds the physical capacity of the existing MAR site. This volume could be attained if recharge occurred year-round, so that winter canal seepage also contributes. Modeling showed that spring and fall recharge contributes to summer streamflow. Since only 37% of the total volume recharged at the Egin Lakes MAR site returns to Henry's Fork, the benefits to summer streamflow must be weighed against the negative effects of withdrawing larger amounts of water from the river at other times of year. These include negatively impacting aquatic habitat availability, species life history expressions (e.g., spawn timing), or fluvial geomorphic processes (e.g., floodplain maintenance). Developing MAR sites closer to the river could increase streamflow in the study reach per unit of water withdrawn.

Fine-scale field observations conducted in 2019 showed that at seep locations, groundwater inputs can cool ambient stream temperature by over 2 °C during summer, a difference that is biologically significant for trout. Even if cool groundwater inputs are not widespread across river reaches or the contributions are not large compared to river flow, springs may create local thermal refugia for fish, allowing greater survival throughout the summer than would otherwise occur given the same physical habitat availability and streamflow [68]. Further identification of groundwater inflows, their hydrogeologic properties, and their use by fish could inform water and fisheries management actions to enhance groundwater springs for fish populations. Understanding the connectivity of thermal refugia will also help managers understand where fish can become trapped or bottlenecks occur for movement [13,68].

However, it is also important to understand the quality of these groundwater return flows on these groundwater-dependent ecosystems. When conducted on working agricultural lands, MAR risks mobilizing nutrients and increasing chemical constituent loading to streams and riparian soils [20,69–71]. MAR can also facilitate groundwater contamination via crop-mediated aquifer contamination of fertilizers

and pesticides [72]. Whereas aquifer recharge may introduce water quality concerns elsewhere, return flow from the ESPA is of high quality that is suitable for instream habitat uses [73]. This research is supported by monitoring conducted at Egin Lakes in 2019 by the Idaho Department of Environmental Quality that showed no increase in nitrogen or fecal coliform as a result of MAR (Aaron Dalling, Fremont-Madison Irrigation District, 2019, presentation to Henry's Fork Watershed Council, October 22). Thus, MAR operations in the Henry's Fork avoid such groundwater contamination and pollutant leaching by conducting recharge via canal seepage and infiltration at Egin Lakes.

While improved modeling and detailed field work can provide technical understanding of MAR benefits to summer habitat for trout, administrative and logistical hurdles must be overcome for implementation [74,75]. The most basic of these is the junior priority dates of water rights for MAR. In the larger context of prior appropriation and development of Idaho's water resources, MAR is a relatively new administratively-recognized beneficial use of water in a system in which water rights for agriculture and mining date back to the mid-19th century. The Idaho Water Resources Board implemented aggressive groundwater and conjunctive management policies and procedures in the 1980s and 1990s, including obtaining large-volume MAR rights with 1980 and 1998 priority dates. Idaho also has flexible and well-established water transaction mechanisms to facilitate transfer of senior water rights to MAR. In the Henry's Fork watershed, the state's MAR water rights are in priority in only half of all water years and then usually during irrigation season, when the canal system is already near capacity delivering irrigation water. Although new MAR infrastructure has been built throughout the basin since 2009, the majority of conveyance to MAR facilities occurs through the existing irrigation canal system. Additional canal capacity could alleviate this limitation during wet years but would go unused in the other half of years.

Because of summer canal capacity limitations, costs of new infrastructure, and the junior priority of MAR rights, storage water rental and other exchange mechanisms offer the greatest potential to increase MAR volumes. For example, in 2018 and 2019, reservoir storage water rented by groundwater users to meet mitigation requirements of their legal agreement with surface water users was not needed for direct delivery to the surface water users because of good water supply in those years. Instead, the rented water was assigned to the state for MAR, allowing recharge of an additional 84 Mm³ in 2019 over what would have been available using the state's junior MAR rights alone (Wesley Hipke, Idaho Department of Water Resources, 2019, data distributed to stakeholders via email, December 6). The need to manage and administer groundwater and surface water conjunctively to meet the legal requirements of the ESPA settlement creates a pseudo-market to fund such exchanges. In 2017, 2018, and 2019, some of the water recharged at the Egin Lakes site was made available for MAR through water exchanges, including those described above, and delivered in spring and fall, outside of peak irrigation season.

Ideally, conservation groups could facilitate incentive-based irrigation reduction, rent the saved storage water for MAR, and keep that water in reservoirs throughout the summer, thus reducing negative effects of reservoir drawdown. The rented storage water could be diverted for MAR in the off-season, when natural streamflow is sufficient without reservoir releases. The separation of physical and administrative water that makes this possible is routine in Idaho under current administrative procedures. Canal capacity to deliver water for MAR is greater in the winter, when canals are not also delivering irrigation water, although the basin's sub-freezing temperatures present challenges in managing winter canal delivery and frozen soil can impede infiltration [76]. Canal seepage during the winter adds recharge that would not otherwise occur and is not simply an administrative replacement for historical seepage incidental to irrigation that occurs during the summer. Rental pool water is available in larger quantities and at lower prices during wet years, potentially allowing for more MAR during wet years, which would then contribute to streamflow in subsequent dry years. However, changes to water rental rules are needed to allow storage water rented in one administrative year to be diverted for MAR several months into the next administrative year [64]. In addition, conservation organizations cannot implement MAR projects, but instead must partner with irrigation entities or individual water rights holders. To fully capitalize on the high value anglers place on upper Snake

River fisheries, new administrative and transfer mechanisms are required to allow conservation organizations to participate directly in water transactions.

4.2. Physical and Administrative MAR Implications for other States in the Western USA

Most states in the western USA possess some of the physical and administrative features required for MAR to benefit cold-water ecosystems, but few have all of the requisite ingredients. Arizona's progressive and flexible administrative systems have been highly successful in facilitating recharge of Colorado River water, but the sole purpose of this MAR is to store the water for later recovery, not to enhance streamflow [36]. On the other hand, restrictive administrative rules in Colorado limit use of MAR in headwater alluvial aquifers [37], where snowmelt could be captured and recharged with the intent of enhancing streamflow later in the summer, and where Colorado's progressive water markets would allow conservation organizations to obtain this water for environmental uses [40]. California is now conducting "flood-MAR" in depleted aquifers using stormwater [38], but this water is junior to other rights and is available for MAR only when existing water rights and required environmental uses are fulfilled. Some regions of California are considering creating an environmental water account using MAR, although this idea is currently untested.

4.3. MAR as Climate Adaptation Strategy for Fisheries Conservation

Cold-water fish habitat is anticipated to decline substantially with climate change. In fact, brown trout are expected to lose 48% of their habitat in the interior western US by the 2080s [68]. These changes are driven by warmer stream temperature and increasing winter floods, and could have major repercussions for a local economy reliant on a US \$100 million recreational fishery. Additionally, an increase in extreme climate events—i.e., a higher frequency of wet and dry years, with fewer 'normal' years is also expected [77]—which will alter instream conditions for biota [78]. Together, these changes suggest that climate adaptation strategies that provide mechanisms to reduce winter flooding, increase summer baseflow, cool summer stream temperature, and enhance thermal refugia are warranted. MAR for fisheries conservation is one such strategy. MAR is a promising climate-adaptive water management strategy because winter flows can be recharged to underlying aquifers to maintain baseflow and cold-water fish habitat throughout the year. However, junior water right holders will have considerable uncertainty from the increased inter-annual variability inherent with climate change [79]. Although this does not inherently reduce the utility of MAR for fisheries conservation in a warming climate, it does suggest that relaxing current administrative rules for greater flexibility to carry over reservoir rental water between years would improve the utility of MAR for fisheries conservation in a changing climate. Since many important recreational trout fisheries in the Western U.S. are located downstream of reservoirs, renting reservoir storage not used for irrigation in a given season and using it for MAR during the subsequent off-season is an innovative conservation mechanism that could have wide applicability.

5. Conclusions

MAR during spring and fall is expected to increase streamflow by around 5% during mid-summer, but only after 20 years of consistent MAR. Developing MAR sites closer to the river than the existing site would provide greater streamflow benefit per unit of water withdrawn and on shorter time frames. However, even relatively small increases in streamflow could have disproportionately greater benefits to trout, as streamflow response in our study area occurs in the form of increased groundwater inputs rather than decreased losses to the aquifer. July water temperatures were locally 2 °C cooler where groundwater flowed into the river. Because MAR is a new and junior water use in a priority system with irrigation rights dating back to the 19th century, MAR water rights are generally in priority only during late spring and early summer of years of above-average supply. However, administrative exchange that allows reservoir storage to be used for MAR can make water available during spring and fall, when MAR infrastructure capacity is greatest. Changes to current administrative rules could increase the effectiveness of such exchange mechanisms in providing water for MAR.

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Appendix A: Streamflow and Temperature Graphs

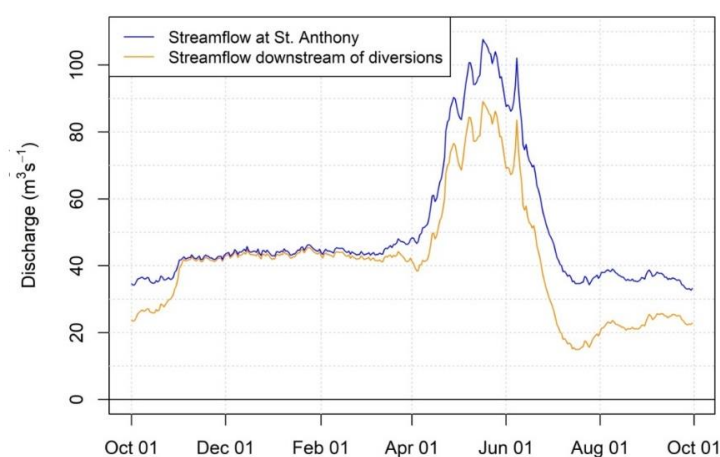


Figure A1. Streamflow at the St. Anthony gauge (top of field study reach) and downstream of all diversions (roughly at the upstream extent of the springs identified in Figure 2).

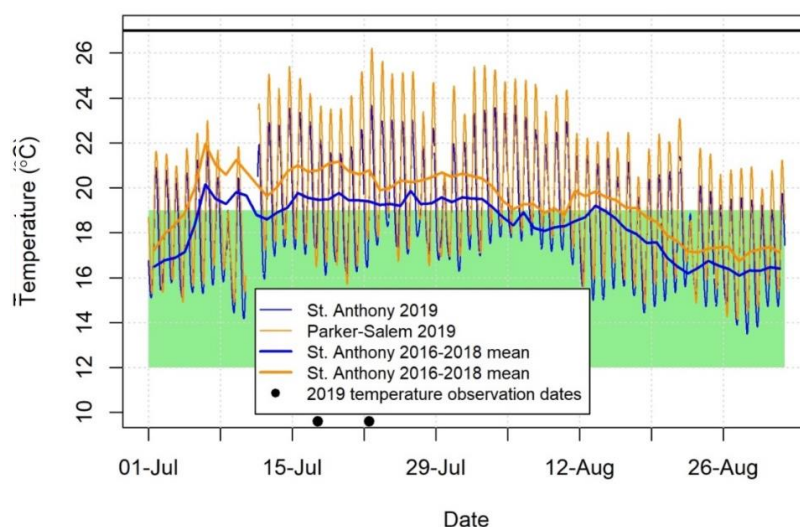


Figure A2. July–August water temperature at the St. Anthony water quality station (top of field study reach) and the Parker-Salem water quality station (bottom of field study reach). Shaded polygon is optimal thermal range for brown trout. Horizontal line is lethal temperature limit for brown trout. The dates of the 2019 temperature observations are shown for reference.

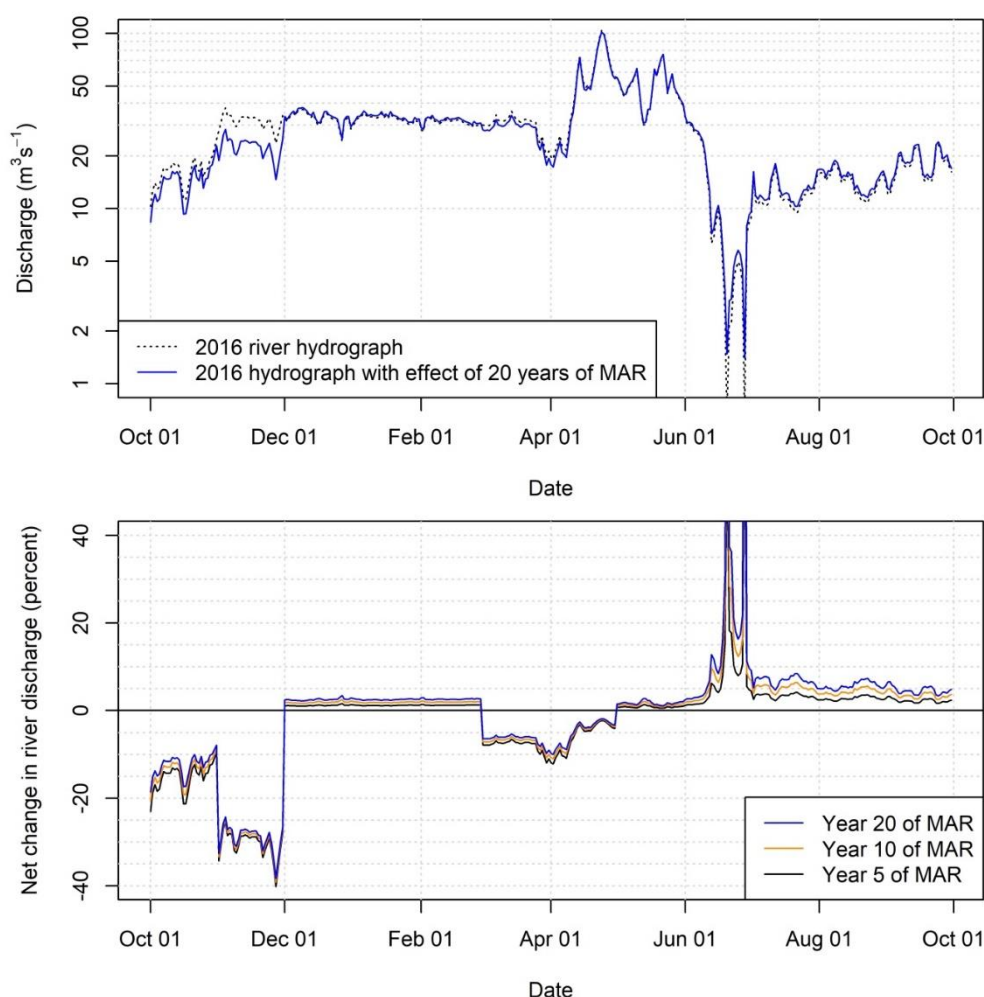


Figure A3. Net change in streamflow in a dry year for annual scenario in which diversion for MAR from the study reach is 7.3 Mm^3 per month in each of March, April, and October, and 25.6 Mm^3 per month in November. Top panel shows the 2016 water year hydrograph and hypothetical effect of MAR implemented 20 years prior. Bottom panel shows percent change in observed 2016 streamflow 5, 10, and 20 years after initiation of annual MAR regime, respectively.

Appendix B. Statistical Methods

Appendix B.1: Time Series Analysis

Statistical hypothesis tests require independent observations for correct distribution of test statistics [80]. In time series such as daily water temperatures, observations are not independent of one another because of correlation between a given observation and the observations that precede it in the time series. This is referred to as serial or temporal autocorrelation. Its effect must be removed to obtain independence of observations before conducting hypothesis tests on time series. Autoregressive (AR) models are used to accomplish this [81]. The simplest AR model is the first-order model:

$$y_t = \mu + \phi_1(y_{t-1} - \mu) + \varepsilon_t, \quad (\text{A1})$$

where y_t is the observation at time t , μ is the mean of the time series, ϕ_1 is the first-order autoregressive coefficient at time t , ε_t is the random, independent, normally distributed error. The autocorrelation is ϕ_1 , independent of t . The autocorrelation hypothesis test ($H_0: \phi_1 = 0$) removes the dependence of y_t on y_{t-1} . In our case, allowing hypothesis tests was highlighted by the observation that our case serially correlated with those was high enough that observations prior correlated with those one, two, and three time steps as Equation (A1), but with broken model relationships. Because observation y_t in our time series was the difference in temperature between the two locations, our null hypothesis was $\mu = 0$. If rejected, we infer $\mu \neq 0$. We used a significance level of 0.05, which is

Equation (A1), but with three autocorrelation terms. Because observation y_t in our time series was the difference in temperature between the two locations, our null hypothesis was $\mu = 0$. If rejected, we infer $\mu \neq 0$. We used a significance level of 0.05, which is the default standard in statistical hypothesis testing. It represents the probability of having made an error in rejecting the null hypothesis, referred to as Type 1 error [80].

Appendix B.2. Tukey's Post-Hoc Test

Analysis of variance tests the single null hypothesis that all group means are equal. If the null hypothesis is rejected at a given significance level, the alternative hypothesis is simply that at least one group mean differs from at least one other. Additional tests must be done to assess which group mean(s) differ from which others. The probability of committing Type 1 error is compounded each time an additional test is performed. In our case, testing all possible differences between three group means requires three tests. If each is performed at a 0.05 significance level, the probability of committing at least one Type 1 error across the three tests is roughly 0.14. Tukey's post-hoc test is a method for conducting the tests for differences across all pairs of groups while maintaining the desired level of significance across the whole family of tests [80].

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