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Design of Managed Aquifer Recharge for Agricultural and Ecological Water Supply Assessed Through Numerical Modeling

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Abstract The Walla Walla Basin, in Eastern Oregon and Washington, USA, faces challenges in sustaining an agricultural water supply while maintaining sufficient flow in the Walla Walla River for endangered fish populations. Minimum summer river flow of 0.71 m^3/s is required, forcing irrigators to substitute groundwater from a declining aquifer for lost surface water diversion. Managed Aquifer Recharge (MAR) was initiated in 2004 attempting to restore groundwater levels and improve agricultural viability. The Integrated Water Flow Model (IWFM) was used to compute surface and shallow groundwater conditions in the basin under water management scenarios with varying water use, MAR, and allowable minimum river flow. A mean increase of 1.5 m of groundwater elevation, or 1.5 % of total aquifer storage, was predicted over the model area when comparing maximum MAR and no MAR scenarios where minimum river flow was increased from current level. When comparing these scenarios a 53 % greater summer flow in springs was predicted with the use of MAR. Results indicate MAR can supplement irrigation supply while stabilizing groundwater levels and increasing summer streamflow. Potential increase in long-term groundwater storage is limited by the high transmissivity of the aquifer material. Increased MAR caused increased groundwater discharge through springs and stream beds, benefiting aquatic habitat rather than building long-term aquifer storage. Judicious siting of recharge basins may be a means of increasing the effectiveness of MAR in the basin.

Keywords Managed aquifer recharge · Hydrological modeling · Habitat restoration · Groundwater management · Agricultural water supply · Salmon

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1 Introduction

Many communities face a conflict between ecological and anthropogenic requirements for water. Water resources challenges may be driven by quantity or quality; seasonal availability; accessibility; or simply over-allocated, wherein addressing a problem for one sector may exacerbate a problem for another. In the case of the Walla Walla Basin, USA, dry summer conditions coincide with peak agricultural demand, leading to a depleted river, endangered fisheries, and a declining aquifer. The Walla Walla Basin Watershed Council (WWBWC) is leading efforts to develop a water management strategy utilizing Managed Aquifer Recharge (MAR) to seasonally replenish groundwater to supply summer irrigation, allowing for increased summer flow in the Walla Walla River to improve both fish habitat and riparian conditions.

This research uses a basin scale water balance model as a tool for devising a water management strategy to utilize available water resources to satisfy both agricultural and ecological requirements. The Integrated Water Flow Model (IWFM), a numerical groundwater-surface water model created by the California Department of Water Resources (Dogrul 2013), is applied to evaluate scenarios where the quantity and distribution of recharge water and minimum stream flow requirement for the Walla Walla River are varied to predict the resulting hydrological conditions.

Declining aquifer levels in the Walla Walla Basin and early efforts at groundwater recharge are described by Newcomb (1965). Nearly 40 years later, the WWBWC and local irrigation districts initiated a new MAR program. Goals for sustainable water resource management in the Walla Walla Basin include stabilizing aquifer levels, maximizing summer flows in the Walla Walla River, improving habitat conditions for juvenile fish, and meeting the agricultural water demand.

Bredehoeft (2002) used the following equation to demonstrate a simple analytical approach for evaluating sustainable groundwater use where the water table is not lowered over time.

$$_{d}R - _{d}D - P = _{d}V/_{d}t$$

where $_{d}R$ is the change in aquifer recharge rate induced by pumping operations, $_{d}D$ is the change in natural discharge, P is the rate of pumping and $_{d}V/_{d}t$ is the change in aquifer storage over time.

The definition above requires a sustainable water supply rate to not exceed natural groundwater discharge plus artificial or induced recharge (Devlin and Sophocleous, 2005). Data on groundwater pumping and natural recharge are often lacking, but may be estimated via hydrological modeling (Lin et al. 2013; Chen et al. 2012). In the Walla Walla Basin, water diverted from the river during high flows is stored in the aquifer for agricultural use over the dry summer. Monitoring well records from the WWBWC, USGS, and Oregon Water Resources Department (OWRD), show that aquifer levels in the basin declined an average of 4.8 cm/year from 1950 to 2012, with no abatement expected under current management practices (Patten 2010).

Groundwater pumping can cause streamflow depletion by inducing additional seepage through stream beds (Barlow and Leake, 2012; Fleckenstein et al. 2001), illustrating the need for groundwater management to address broader environmental impact (Zhou 2009). Public support for hydrological restoration is generally strongest when it is tied to the vitality of other biological systems (Hunt and Wilcox, 2005). In the Walla Walla Basin native fisheries are a major concern, as are agricultural water supplies. Water management planning requires addressing the tradeoff between consumptive water use and environmental impact, accounting for the critical needs of both farmers and fish (Alley and Leake 2004). A reliable estimation of the regional water budget and a means of manipulating the timing and distribution of water supplies are vital tools to develop and implement a successful strategy.

2 Study Site

The Walla Walla river basin, located on the border of Eastern Washington and Eastern Oregon, USA (Fig. 1), is semi-arid in climate with extensive agricultural development (primary crops are alfalfa, wheat, fruit orchards, and wine grapes). Irrigation water is taken from the Walla Walla River and the underlying gravel aquifer. Precipitation averages 43 cm/year, falling primarily in the winter and spring months. Summers are hot (average high temperature in August is 32 °C) and dry (average precipitation from July 1 to Sept 30 is 3.9 cm). This is reflected in the flow regime of the Walla Walla River which can exceed 60 m^3/s during winter months, and drops below 3 m^3/s during the summer (upstream of irrigation diversions). From 1900 until 1999 the entire river was diverted for agricultural use, leading to the extirpation of chinook salmon and to the listing of native steelhead and Bull trout populations on the federal list of endangered species. This status now requires that adequate stream flow and sufficiently low temperatures are maintained to provide year-round viable fish habitat. In 2000, an agreement was reached between federal and state regulators and the local irrigation districts to leave a minimum flow of 0.71 m^3/s (25 ft^3/s) in the Walla Walla river below the diversion for the Little Walla Walla Canal and 0.57 m^3/s (20 ft^3/s) below the Gardena Canal outtake

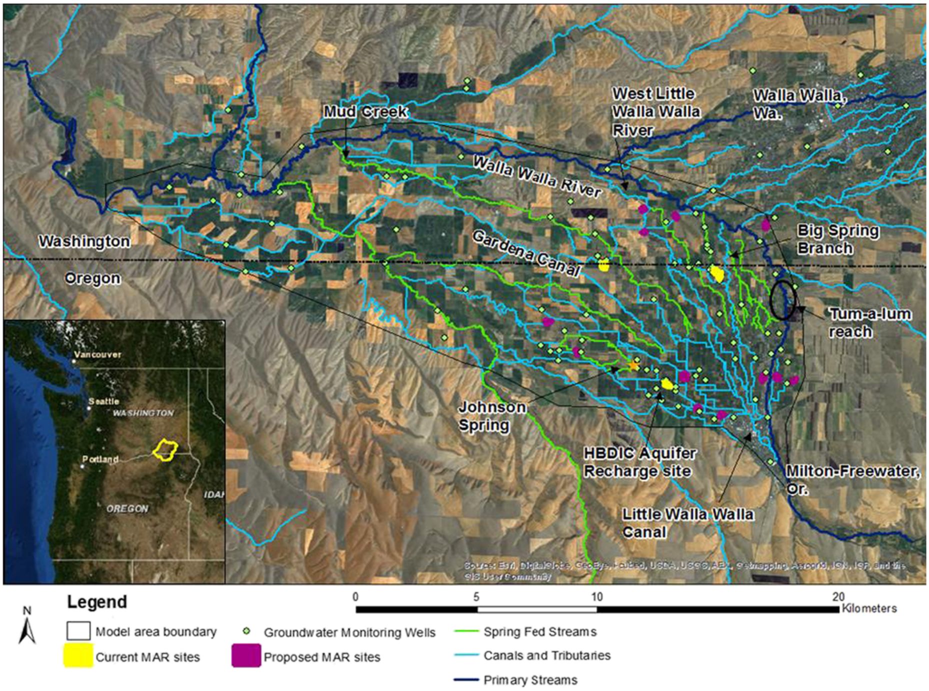

Fig. 1 Reference map for the IWFM model area showing active and proposed aquifer recharge basins during the model development period

(USDFW 2002) with a goal of supporting the endangered native fisheries and reintroduced Chinook salmon (Mahoney et al. 2011).

As much as 20% of streamflow in the mainstem river and canal network is lost to seepage, (Metcalf 2004; Baker 2009). This has led to ongoing efforts to replace earthen canals with pipelines, decreasing the amount of water percolating through canal beds and recharging the water table. While aquifer recharge from seepage is reduced, groundwater resources are under increased pressure to meet the agricultural demand as less surface water is available due to minimum stream flows. These factors combine to exacerbate the decline in aquifer storage.

Groundwater occurs primarily in two gravel aquifers composed of alluvial deposits from the Walla Walla River, subsequently reworked by periods of glacial activity, channel migration, and historic flooding (Lindsey 2007). The aquifers are distinct in character, with the shallower quaternary coarse (QC) unit the more conductive of the two. The deeper miopliocene coarse (MPC) unit is up to 185 m thick while the previously mentioned QC unit is 55 m thick at its maximum. The significantly greater volume of the MPC aquifer makes it the dominant water bearing unit in the basin. Since the aquifers are in direct contact, conditions are hydrostatic between the two. Fine grained deposits occur intermittently above and below theses aquifers and these units are collectively referred to as suprabasalt materials (Lindsey 2007). The Columbia River Basalt formation underlies this material, forming an impermeable lower boundary for the system.

3 Methods

3.1 Project Background

The Walla Walla Basin MAR program was initiated in 2004 to restore ecologically important spring flows, reduce river seepage losses, and increasing seasonal groundwater storage. Aquifer recharge was to be achieved by diverting winter and spring flow from the Walla Walla River through the canal network into excavated basins. The water would then percolate into the gravel aquifer system, contributing to groundwater storage. This artificially increases aquifer recharge over the winter and spring to accommodate increased groundwater pumping over the summer, while maintaining aquifer storage levels and promoting groundwater contributions to spring fed stream and riparian habitat. Compared to a surface reservoir, MAR is less costly, avoids harmful environmental impacts, and eliminates evaporative losses.

This application of IWFM has been developed to simulate the entire hydrological system in the portion of the Walla Walla Basin that lies primarily between Milton-Freewater, Oregon, and west of Touchet, Washington. The model was used to assess the relative contributions of different components within the hydrological system, and evaluate potential management strategies with regard to regional water resources and aquatic habitat. The model was developed using a data set from 2007 through 2009 for calibration and data from 2010 was used for validation. Data was incorporated from 62 groundwater monitoring wells and 34 surface water gauges. Calibration was achieved by varying hydraulic conductivity of the MPC aquifer, streambed conductivity, and the fraction of soil water that percolated to groundwater within appropriate ranges. The model outputs provide insight into historic and predicted water resource availability under varying conditions through a set of detailed hydrological budgets for surface water, groundwater, soils, and agricultural uses. The completed model had a standard deviation of 3.2 m and a correlation coefficient of 0.58 for groundwater monitoring wells, and a mean relative error of 23.3% and a correlation coefficient of 0.69 for surface water flow gauges. The gauges on the mainstem Walla Walla River and near the HBDIC aquifer recharge site were well represented by the simulation (standard deviation 1.9 m) due to the higher density of available data, while gauges that were relatively isolated often had larger errors. A complete description of model development is available in Scherberg (2012).

The model estimated water balance (Fig. 2) shows that total applied water (the sum of irrigation from groundwater and surface water sources) closely follows agricultural demand, which accounts for the majority of evapotranspiration. Surface water diversions are the primary source of irrigation in the basin over the spring months, briefly exceeding agricultural demand as irrigators build up soil moisture in anticipation of the dry summer months. Groundwater pumping increases over the summer as surface water resources become scarce, becoming the dominant source of water for irrigation by late June.

Over the simulation period three established MAR sites contributed to groundwater storage producing flow increases in several springs down gradient from the recharge site (Bower and Lindsey, 2010). Monitoring well data clearly shows the groundwater response to recharge operations, however the overall contribution of MAR accounts for a small portion of the total water demand illustrated in Fig. 2. Following the initial successes of the MAR program, 12 additional recharge sites were proposed, and subsequently incorporated into the model (Fig. 1).

3.2 Model Scenario Descriptions

Model scenarios were developed with varying amounts of MAR and minimum flow rates in the Walla Walla River to address the following water management questions. How much MAR would be required to reverse the depletion of groundwater? Can the operation of MAR systems significantly impact late-season stream flows through direct groundwater discharge? Will these systems be sufficient to allow replacement of current surface water consumption with groundwater extraction to maintain late-season stream flow?

Initial conditions for proposed management scenarios were assumed to be equal to those at the end of the model validation period. It was assumed that canal lining had been carried out to completion within the model region, increasing canal flows and reducing aquifer recharge. Agricultural demand and climate conditions were treated as constant factors, using inputs for precipitation, reference ET, streamflow, and groundwater boundary conditions derived by

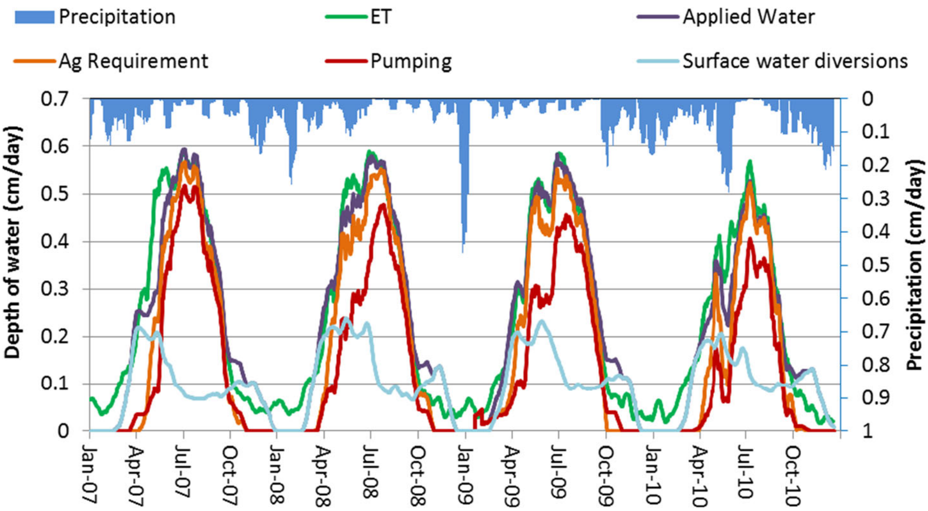

Fig. 2 Estimated water budget for the Walla Walla Basin model area for 2007–2010

averaging daily data over the model development period (2007–2010). These simplifications allow model outputs to be attributed to variations in total MAR and minimum allowable flow in the Walla Walla River.

Ten-year simulations were run to test the impact of several water management strategies. These scenarios were defined by the total amount of water applied to MAR, active MAR basins (existing; existing and proposed; or none), and allowable minimum flow rates for the Walla Walla River (Table 1). The lower rate (0.71 m^3/s) is the current target for minimum instream flow while the higher minimum rate (1.42 m^3/s) was selected to evaluate a management approach optimized for fishery enhancement. These rates were coupled with varying water applied for MAR; a seven-fold increase from current practices, a four-fold increase, and no MAR (Table 1).

In all scenarios with MAR, water was supplied to recharge sites for 110 days per year between November and May, with periodic shutoffs in December and January to account for freezing, and February when all canals are shut off for annual maintenance.

4 Results

Model outputs were evaluated in terms of the total amount, and temporal and spatial distribution of groundwater and surface water under the different scenario conditions tested. Results were assessed in terms of the potential benefits and limitations of using MAR to augment seasonal groundwater storage levels to meet the regional agricultural demand while withdrawals from the Walla Walla River are reduced during critical low flow periods. In addition, predicted flows in the lower reaches of several tributary streams were assessed for the potential

Table 1 Overview of scenarios applied to Walla Walla Basin IWFM model

Scenario ID	Scenario description	MAR allocation (m^3/year)	Allowable minimum flow in WWR[a] (m^3/s)
0-MAR; low WWR	No aquifer recharge; current minimum flow in WWR.	0.00E+00	0.71
0-MAR; high WWR	No aquifer recharge; minimum flow in WWR doubled for improved fish habitat (increasing agricultural demand for groundwater).	0.00E+00	1.42
Status Quo	Current MAR allocation (three recharge sites); current minimum flow in WWR. Similar to current management practices, assuming canal piping is completed.	5.40E+06	0.71
4xMAR; low WWR:	Increased MAR four fold from current practices with expansion to 15 locations; current minimum flow in WWR.	2.20E+07	0.71
4xMAR; high WWR	Increased MAR four fold from current practices with expansion to 15 locations; minimum flow in WWR doubled for improved fish habitat.	2.20E+07	1.42
7xMAR; high WWR	Increased MAR seven fold from current practices with expansion to 15 locations; minimum flow in WWR doubled for improved fish habitat.	3.80E+07	1.42

[a] Walla Walla River

of MAR to improve off channel habitat for juvenile fish by increasing cold water inflows and providing areas of cold water refuge.

Over a 10 year simulation period the model predicts that as more water is used for MAR, aquifer storage will increase whereas the minimum allowable flow in the Walla Walla River had a relatively small impact on groundwater storage (Fig. 3). There is a challenge in retaining water in the basin for summer use after it is infiltrated during winter MAR operation due to the highly conductive gravel aquifers. The difference in aquifer storage between the greatest amount of MAR and none averages 0.07 m, or 1.5% of the total storage volume (Table 2). This translates into a difference of about 1.5 m in mean water table elevation over the model area, though the difference is not evenly distributed and is over three m in the area where the recharge basins are most heavily concentrated.

The amount of water used for MAR has a pronounced effect on the relative contributions of groundwater and surface water to the estimated groundwater budget by influencing the rate and direction of seepage through stream beds (Fig. 4). Modeling results indicate that the potential for building aquifer storage by increasing the amount of water used for MAR may ultimately be limited as increased MAR results in greater seepage rates from aquifers into springs and stream beds. Increased discharge of groundwater to surface water and slightly reduced groundwater inflow combine to partially offset the gains in groundwater storage from increasing MAR.

Figure 4 illustrates the difference in aquifer storage and net surface water seepage (averaged daily) for the scenarios with the greatest and least applied MAR. In the '7XMAR; high WWR' scenario, aquifer storage is consistently greater than in the '0-MAR; high WWR' scenario. The '7XMAR; high WWR' is also predicted to augment stream flows. The positive net seepage term for surface water over the majority of the year indicates that on average, streams in the model area are gaining groundwater with maximum MAR scenario (Fig. 4). With no MAR applied (0-MAR; high WWR scenario) net seepage is predicted to be negative for most of the year, corresponding to losing conditions for most streams (Fig. 4). Seepage losses from

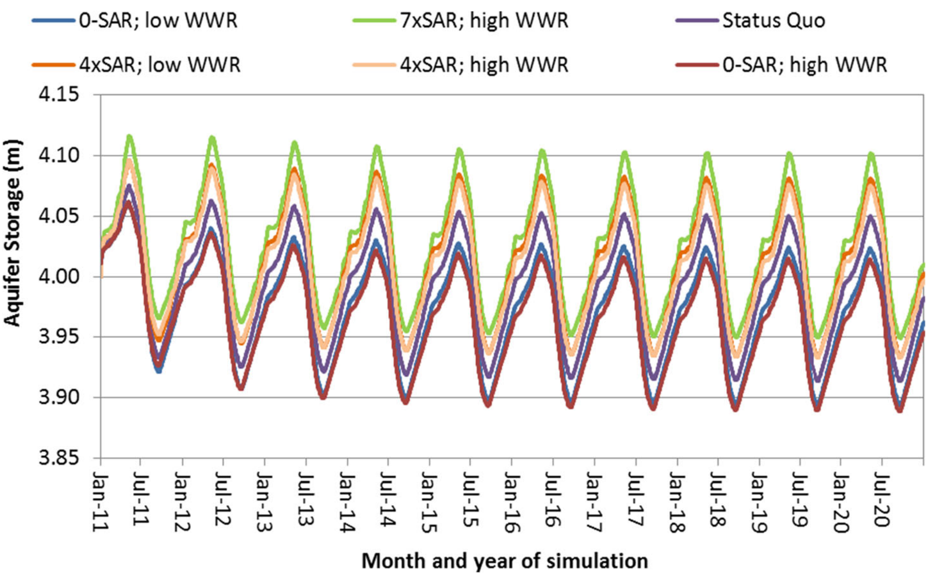

Fig. 3 Depth (m) of water in aquifer storage over the model area for the 10 year simulation period under varying amounts of aquifer recharge (m^3/y) and minimum flow targets in the Walla Walla River (m^3/s)

Table 2 Predicted low flows and average days per year approaching critically low flow in the Walla Walla River over the 10 year simulation period

Scenario description	Mean annual WWR minimum flow (m^3/s)	Days per year with 1 km of river <0.85 m^3/s	Mean groundwater storage (m)	Lower West Little Walla Walla River		Lower Mud Creek		Big Spring Branches	
				Mean annual flow (m^3/s)	Mean August flow (m^3/s)	Mean annual flow (m^3/s)	Mean August flow(m^3/s)	Mean annual flow (m^3/s)	Mean August flow(m^3/s)
0-MAR; low WWR	0.651	11	3.95	0.059	0.032	0.150	0.017	0.162	0.135
0-MAR; high WWR	1.183	0	3.96	0.045	0.010	0.141	0.044	0.148	0.118
Status Quo	0.693	11	3.98	0.071	0.034	0.155	0.017	0.175	0.149
4xMAR; low WWR:	0.733	8	4.01	0.104	0.039	0.166	0.018	0.205	0.177
4xMAR; high WWR	1.257	0	4	0.079	0.014	0.156	0.045	0.192	0.159
7xMAR; high WWR	1.296	0	4.02	0.143	0.020	0.167	0.046	0.213	0.181

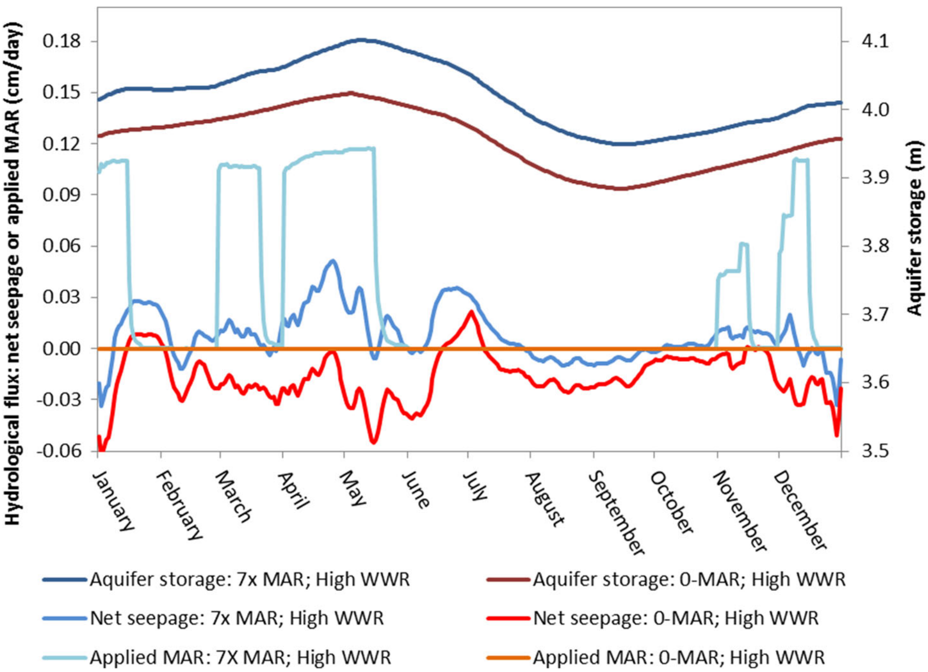

Fig. 4 Comparison of mean aquifer storage and net seepage for surface water from model scenarios with the maximum and minimum applied MAR. Positive seepage values indicate groundwater discharge to springs and streams; negative seepage values indicate stream losses to groundwater through channel seepage

streams are greatest when MAR is turned off because the overall decline of the water table increases the hydraulic gradient between the groundwater and surface streams, inducing more seepage through channel beds in proportion to the calibrated stream bed conductivity.

The connection between MAR and spring flow has been observed at Johnson Spring, down-gradient from the HBDIC recharge site (Petrides 2012). When MAR operations began in 2004 water emerged at the spring after decades of being dry; this has continued each year when the recharge site is in use (Bower and Lindsey, 2010).

The model predicts that aquifers will continue to decline under the Status Quo scenario (continuation of current practices) (Fig. 3). Though a small change in overall storage volume is predicted, a significant redistribution of water is seen with modest gains predicted near the current recharge basins and declines over the majority of the model region where there are no recharge basins (Fig. 5). It is predicted that shutting off all MAR operations and lining canals would lead to a widespread decline in groundwater levels, particularly in the central region of the model area where irrigation demand is highest (Fig. 5). The scenarios in which MAR is increased from current levels result in greater and more widely distributed gains in groundwater elevation where there is the highest concentration of MAR sites. Water table declines persist away from the recharge sites in areas that are primarily down gradient from the recharge source (Fig. 5). Groundwater storage increases at a declining rate as MAR is increased. This is due to the difficulty of retaining infiltrated water as MAR propagates increased groundwater discharge to springs and streams.

Comparing the predicted outcomes of the scenarios tested to the ‘Status Quo’ conditions emphasizes the value of MAR, and points to the benefits of increasing present recharge allocations. After 10 years, scenarios with increased MAR are predicted to lead to water table

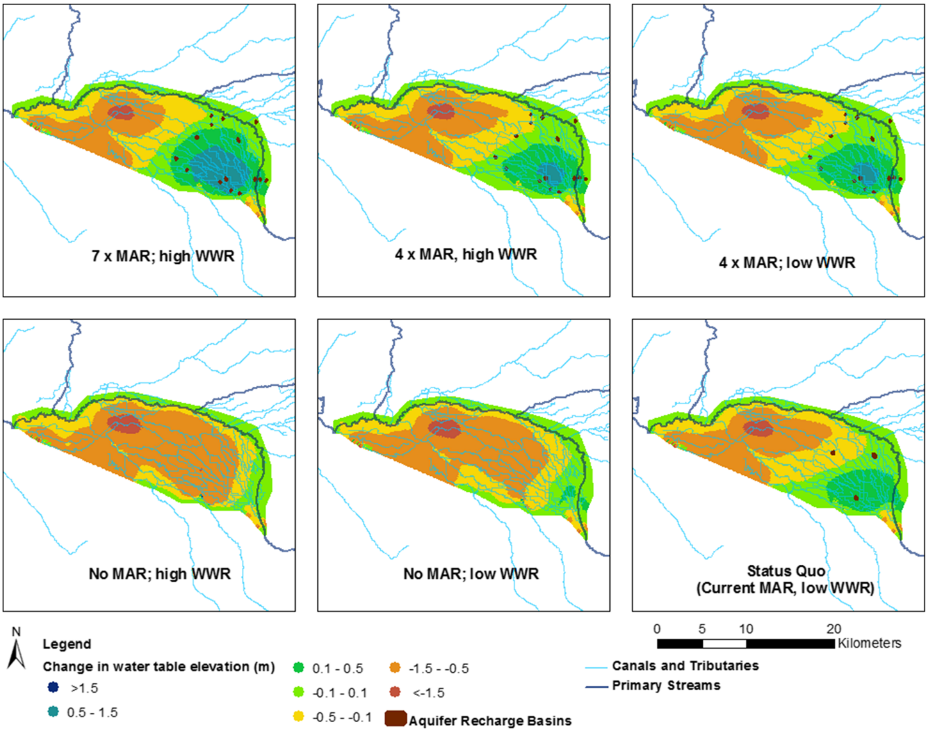

Fig. 5 The predicted change in water table elevation in the model area after 10 year simulations under different management scenarios

elevations one to three meters higher over most of the model area than would be achieved by maintaining current operations (Fig. 6). The model also predicts that the cessation of aquifer recharge would lead to the declines in the water table of close to three meters over the in the vicinity of the recharge basins, and a widely distributed decline of groundwater levels over most of the model area (Fig. 6).

Simulations showed minimum flows in the Walla Walla River typically occurred in the critical Tum-A-Lum reach highlighted by Baker (2009) and directly below Gardena Farms Canal diversion point (Fig. 1). The model predicted annual minimum flow rates in the Walla Walla River to occur in late July or August, as is typically observed. The model did not indicate that MAR, at the level simulated, would reduce seepage from the Tum-A-Lum reach.

Several tributaries of the Walla Walla River, namely the Little Walla Walla, the Big Spring system, and Mud Creek (Fig. 1), have historically provided habitat for juvenile fish (Wolcott 2010). A management goal is to restore this function by providing sufficient water in these tributaries to create viable fish habitat. Simulations showed that side channel restoration may respond to increases of MAR or minimum allowable flow in the mainstem river, depending on the location of the channel and its typical water source (Table 2). The West Little Walla Walla River primarily receives water from agricultural runoff and return flows, therefore it receives less water when agricultural withdrawals are reduced to maintain higher minimum flow. As a result it has lower summer flows when a higher minimum flow threshold is applied to the Walla Walla River; however the annual average flow is greater when more MAR is used.

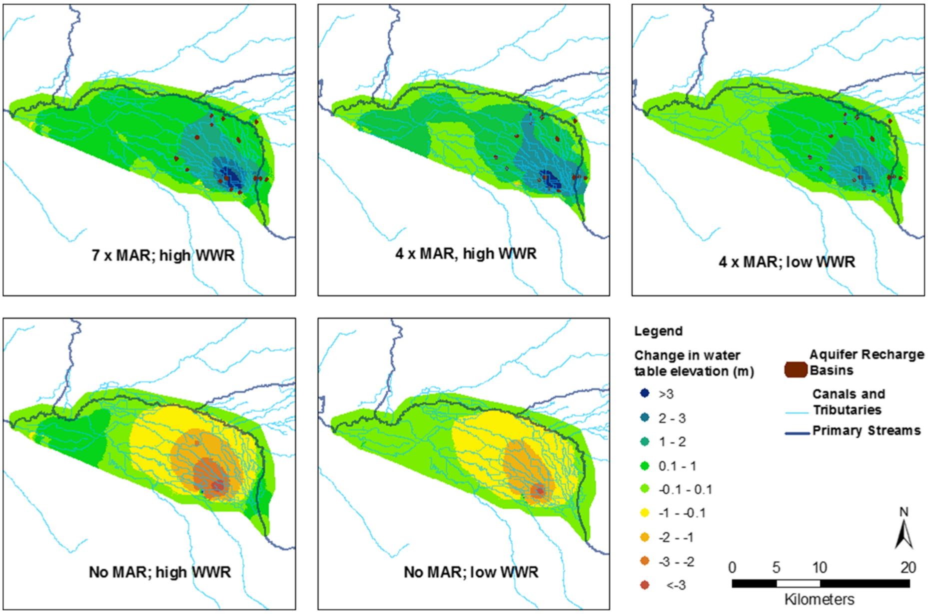

Fig. 6 The difference in groundwater head resulting from 10 year simulations under scenario conditions compared to continuing current management practices (Status Quo scenario)

Lower Mud Creek gains water from seepage from the Walla Walla River and therefore has greater summer flows when more water is left instream, increasing the amount of resulting seepage. The Big Spring branches include several spring fed channels that flow into the Walla Walla River. They are located in the vicinity of several recharge basins and are primarily groundwater fed. Their flow rates are predicted to increase both annually and over the dry summer season with increasing use of MAR.

4.1 Discussion

Supplying water for agriculture and maintaining sufficient summer river flow for fish habitat is an ongoing water management challenge. This is compounded by the issue of long-term aquifer decline, which endangers agricultural production in the basin as well as having negative ecological impacts. These tradeoffs are typical of many agricultural areas where water resources are strained. Here we seek to illustrate how simulation modeling can provide a quantitative basis to evaluate management options based on their ability to satisfy agricultural and ecological requirements.

Model predictions indicate that expanded MAR operations in the Walla Walla Basin have the potential to stabilize aquifer levels while increasing the amount of groundwater available for irrigation. This would allow for increased summer flow in the Walla Walla River through lower irrigation withdrawals with greater reliance on groundwater to support agriculture. Since implementation of the agreement to maintain perennial river flow, high summer stream temperatures that are stressful or lethal to salmonids have been cited as a primary limiting factor for fishery restoration in the Walla Walla River (Mendel et al. 2005). Increased spring flows resulting from MAR could create off-channel habitat with cold water inflows, becoming areas of thermal refuge for juvenile salmon.

The continued expansion of MAR operations may be limited by several factors. Typically winter and spring flows are sufficient to supply any of the MAR scenarios included in this report (Henry et al. 2013); however the availability of suitable locations and water rights will determine the limits for aquifer recharge. Diverting water into permeable canals off-season may be an alternative means of achieving aquifer recharge (Pliakas et al. 2005). The difficulty of attenuating water in the basin after it is percolated into the gravel aquifer could limit the potential for increasing water table elevation using MAR. Some of the water delivered to recharge sites will flow out of the basin as groundwater prior to peak irrigation demand in late summer. Increased water applied to MAR will concurrently increase groundwater discharge into springs and streams over the majority of the model area, thereby increasing flows and benefiting aquatic and riparian habitats. If MAR were eliminated, the model predicts significant declines in total aquifer storage, reduced stream flows, and increased seepage from streams and canals.

Currently, active and proposed recharge basins are concentrated in the upgradient portion of the model area where significant increases in water table elevation are predicted with MAR; whereas groundwater declines are predicted to continue in all scenarios in the western (down-gradient) portion of the model area where no recharge sites are located. Future model simulations could test the influence of recharge sites in down-gradient portions of the basin to investigate whether this would reduce the hydraulic gradient and be a more effective means of building long-term groundwater storage.

Fleckenstein et al. (2006) showed that aquifer recharge efforts targeted to restore stream-aquifer connectivity to the most permeable channel reaches have the greatest potential to reduce seepage thereby improving summer flows and stream habitat. Future MAR development in the Walla Walla Basin could be optimized by siting basins where there is potential to increase water table elevation to the point of restoring stream-aquifer connectivity.

Local regulations are an important factor in planning aquifer recharge projects. Developing policies for the implementation of MAR that account all operational stages from water harvesting to end use is necessary for the successful realization of a recharge project (Ward and Dillon 2012). The currently proposed recharge sites are located in Oregon as opposed to Washington because licensing is more easily obtained and water quality monitoring requirements in Washington can be a prohibitiveley expensive operational cost (Morgan 2005; Cole 2012). This can be an obstacle to developing a scientifically sound water management strategy for a multi-state watershed.

5 Conclusion

It is widely recognized that groundwater resources can be vital for agricultural production, ecological function, and municipal water supply. To achieve a management strategy that meets both environmental and societal water demands, surface water and groundwater must be considered as fundamentally connected systems. In the Walla Walla Basin all stakeholders stand to benefit from a carefully planned management strategy that uses groundwater and surface water conjunctively to meet summer demands.

Simulations of hydrological conditions in the Walla Walla Basin under several proposed management strategies shed light on the relative magnitude and distribution of water resources and demands within the basin. It is apparent that the threshold water requirement for fisheries is relatively small compared to the agricultural requirement, and groundwater supply for irrigation is vital to the regions viability as a productive agricultural area. The challenge of maintaining a sustainable groundwater supply can be partially addressed though recharging the regional gravel aquifers with water from the Walla Walla River. This serves a dual purpose by directly contributing water to aquifer storage in the non-growing season so that it can later be used for irrigation, while allowing for increased river flow during critical periods.

The model indicates that total aquifer storage will increase with aquifer recharge, however at a declining rate as MAR contributes increasingly to surface flows rather than groundwater storage as more water is infiltrated. The predicted increase in water table elevation is most pronounced in the vicinity of the recharge locations, and does not persist with distance away from the recharge source. Changing the target low flow for the Walla Walla River has little impact on total aquifer storage, reflecting the fact that late summer contributions from surface water are small relative to the groundwater used for irrigation supply.

Aquifer recharge can provide multi-faceted benefits for water resources in the Walla Walla Basin by contributing to agricultural water supply while promoting improved fish habitat. With MAR, the amount of available water is sufficient for groundwater to supply irrigation requirements while maintaining aquifer levels, and increase the summer flow rate in the Walla Walla River. Without MAR the decline of groundwater resources can be expected to continue or accelerate. Future modeling efforts should investigate questions related to MAR optimization. Specifically, can MAR be used to restore stream-aquifer connectivity with the Walla Walla River in areas with high seepage loss, or potentially reverse the water table decline predicted in the down-gradient portion of the model area through the targeted placement of recharge basins?

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