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ORIGINAL ARTICLE

Modeling the impact of aquifer recharge, in-stream water savings, and canal lining on water resources in the Walla Walla Basin

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Abstract

The Walla Walla Basin in Eastern Oregon and Washington, USA, faces challenges in sustaining agricultural water supplies and endangered fisheries in the Walla Walla River (WWR). 11.1 Mm^3/year of managed aquifer recharge (MAR) is currently used in the basin to supplement groundwater with the goal of maximizing instream flow during dry summer months. A numerical groundwater–surface water model was calibrated to observed hydrological conditions and applied to predict future conditions under current management practices (baseline model) and for four alternative water management scenarios. These scenarios were developed to predict how lining canals to eliminate seepage losses and concurrently reducing irrigation diversions from the WWR will impact stream flows and groundwater storage with varying levels of MAR. Model results predict that seasonal low flows in the WWR at the downstream reference location will increase an average of 0.13 m^3/s relative to baseline conditions due to instream water savings with conversion of unlined canals to pipelines (Current MAR-Piped). With MAR increased to 18.0 and 29.9 Mm^3/year and an additional 58 km piping (Increased MAR-Piped and Maximum MAR-Piped scenarios), the predicted flow increases in the WWR-averaged 0.16 and 0.26 m^3/s, respectively. Without MAR (No MAR-Piped), flow is predicted to decrease for the months of August and September relative to baseline conditions. The "No MAR-Piped" and "Current MAR-Piped" scenarios are predicted to reduce groundwater storage relative to the baseline model due to reduced canal seepage. The "Maximum MAR-Piped" scenario is predicted to yield groundwater storage that is greater than baseline conditions, while groundwater storage is predicted to be similar to baseline conditions in the "Increased MAR-Piped" scenario. Model results indicate that canal piping in combination with increased MAR can allow for increased summer flows in the WWR while stabilizing groundwater storage levels for agricultural use and ecological benefits; whereas lining canals without MAR would be detrimental to environmental flows in the WWR and its tributaries.

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

Introduction

The Walla Walla Basin (WWB) is located in a semi-arid region of Eastern Washington and Oregon (Fig. 1), receiving an average of 43 cm of annual rainfall, primarily over the winter and spring months. The WWB has extensive agricultural lands and the Walla Walla River (WWR) is the primary source for irrigation water in the basin for the spring and early summer. Water is diverted from the WWR into several primary irrigation canals which are the Little Walla Walla river, the Gardena, and the Lowden. The canals branch into irrigation networks to serve local farms throughout the basin. As flow in the Walla Walla River declines with the onset of summer, irrigators become more reliant on groundwater, with groundwater becoming the dominant water source for irrigation in late June and remaining so through October (GSA 2015).

Declining groundwater elevations in the WWB due to increasing groundwater use and anthropogenic changes to basin surface hydrology and efforts at groundwater recharge

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This article is part of the special issue on Managed Aquifer Recharge.

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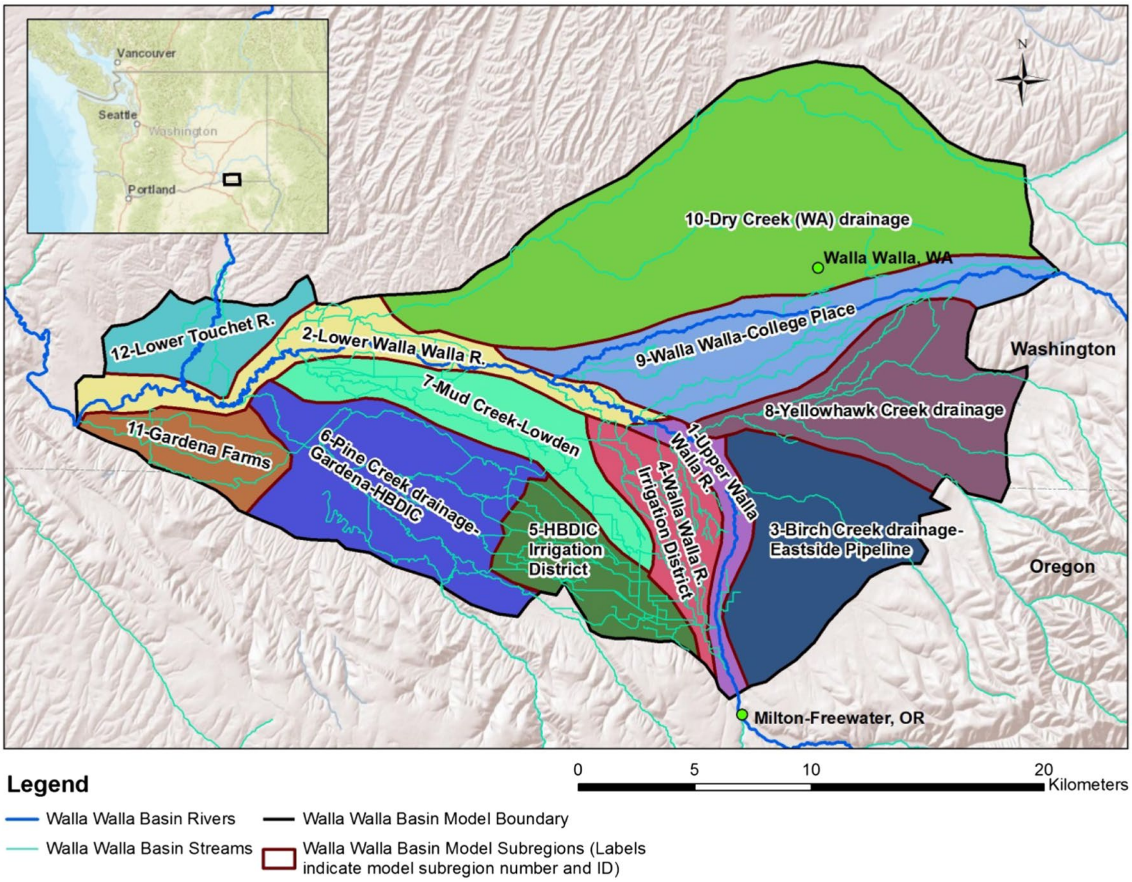


Fig. 1 Walla Walla Basin model location and sub-region boundaries

are described as early as 1965 by Newcomb (1965). Monitoring well records from the Walla Walla Basin Watershed Council (WWBWC), United States Geological Survey (USGS), and Oregon Water Resources Department (OWRD), show that groundwater elevations in the basin declined an average of 4.8 cm/year from 1950 to 2012, with no abatement expected under current water management practices (Patten 2010; Bower and Lindsey 2010). Groundwater losses have resulted in reduced groundwater return flows to the WWR, contributing to low summer flows in the WWR that are known to be limiting to fish passage and are associated with seasonally high stream temperatures that degrade fish habitat (Mendel et al. 2005). More recently, irrigation districts have been converting unlined canals to piped systems to eliminate canal seepage and optimize water available for their customers. The reduction in conveyance system seepage due to piping has resulted in reduced recharge of the alluvial aquifer.

An agreement between local irrigation districts and federal regulators in 2000 established a minimum flow of 0.71 m^3/s in the WWR below the Nursery Bridge, with the objective of promoting viable habitat for endangered fisheries (Mahoney et al. 2011). Nonetheless, flows below 0.28 m^3/s have been recorded at gauges downstream of this point. The coincidence of seasonal low flows and peak irrigation results in water demands that are often in conflict from July through October.

In 2004, the WWBWC and local irrigation districts initiated a Managed Aquifer Recharge (MAR) program to increase groundwater return flows to the WWR and its tributaries, and since that time they have gradually expanded the number of MAR sites and the amount of water allocated for MAR. MAR is achieved in the WWB by diverting water from the WWR through the existing irrigation canal and pipe network when flows are high relative to irrigation demand, typically mid-November to mid-May; with the exception of February when canals are shut down for maintenance. The diverted water is delivered to infiltration basins on the land surface or underground perforated pipes where the water then percolates into the underlying alluvial aquifer. There are currently seven active MAR sites in the basin with the Johnson site receiving up to 0.45 m^3/s, more than triple any of the other MAR sites. MAR has been demonstrated to increase groundwater storage, thereby increasing groundwater available to irrigators and also increasing groundwater return flows to some streams (Bower and Lindsey 2010;

Henry et al. 2013; Scherberg 2012). However, the effects of the MAR program are primarily observed in the proximity of the recharge sites. It is hypothesized that more widely distributed MAR sites will have a more widespread effect on the groundwater resources, and possibly surface water resources, in the basin (Scherberg et al. 2014).

In 2014, the WWBWC and Walla Walla Watershed Management Partnership initiated the WWB Integrated Flow Enhancement Study, an evolution of the Watershed Management Initiative described in Bower and Lindsey (2010). Both programs aimed to organize collaborative efforts among stakeholders to improve in-stream and riparian habitats by enhancing summer stream flows while maintaining the long-term viability of water supplies for irrigated agriculture, residential, and urban use. It is known that groundwater pumping can cause streamflow depletion by inducing increased seepage through stream beds (Fleckenstein et al. 2006; Barlow and Leake 2012), illustrating the need for groundwater management to address surface water–groundwater interactions in terms of broader environmental impact (Zhou 2009). MAR is one means of enhancing groundwater resources through active management. Because data on groundwater pumping and natural recharge in the WWB are sparse, hydrological modeling is necessary to develop a reliable estimate of the regional water budget and to evaluate manipulating the timing and distribution of water supplies (Lin et al. 2013; Chen et al. 2012).

In support of the WWB Integrated Flow Enhancement Study, a calibrated surface water–groundwater numerical finite element model was developed using the Integrated Water Flow Model (IWFM) code (Dogrul 2013). The WWB IWFM is a tool for evaluating the potential impacts of proposed water management scenarios on hydrological conditions in the basin. The WWB IWFM was developed utilizing data sources to define basin topography, geology, precipitation, groundwater and surface water conditions, land use classification, agricultural and urban demand, and soil properties over the portion of the basin where alluvial sediments comprise aquifers used for irrigation supply that are hydraulically connected to the WWR and its tributaries (GSI 2007). The present model was preceded by numerical models developed by Scherberg (2012) and Petrides (2012) for a smaller model area of approximately 231 km^2.

Herein, we present model-predicted surface water and groundwater conditions in the WWB resulting from four alternative water management scenarios as well as the continuation of current management practices (i.e., baseline scenario). The water management scenarios are designed to evaluate the impact of converting canals into pipelines to eliminate canal seepage losses, and are coupled with the reduction of diversions from the WWR into irrigation networks, a practice referred to as water savings. In addition, the scenarios are designed to assess the effect of increasing quantities of MAR on water resources and fish habitat conditions. Each model scenario is feasible given the water resources within the basin (Henry et al. 2013).

Materials and methods

Model domain

The model boundary (Fig. 1) was defined by the areal extent of the alluvial basin deposits and encompasses the land surface and five sedimentary geologic units that overlay the Columbia River Basalt formation within the WWB characterized in GSI (2007). Hydrogeological parameters for the geologic units were determined through model calibration and literature review, and are provided in Table 1. Overall, the model encompasses 619 km^2 and extends to a maximum depth of 287 m below ground surface.

Groundwater inflow occurs primarily from the northern and eastern model boundaries, flowing in a primarily westward direction through the Walla Walla Valley. An arc of springs emerges from the alluvial sediments overlying the basin floor feeding a network of small tributaries to the WWR (Henry et al. 2013). The primary rivers flowing into the model area are the WWR from the southeast, Mill Creek from the northeast, and the Touchet River from the north, the latter flowing into the WWR a short distance upstream from the model outflow.

Table 1 Calibrated hydrogeological parameters for alluvial units included in the WWB IWFM model

Geologic unit (upper to lower)	Unit type	Horizontal hydraulic conductivity (m/day)	Vertical hydraulic conductivity (m/day)	Specific storage	Specific yield
Quaternary fine	Aquitard	0.0	0.5	NA	NA
Quaternary coarse	Aquifer	20.0	6.0	9.50E−06	0.18
Miopliocene coarse	Aquifer	9.8	3.0	6.20E−05	0.14
Miopliocene fine	Aquifer	1.5	0.1	1.00E−04	0.06
Miopliocene basal coarse	Aquifer	5.0	0.6	4.60E−06	0.04

NA not applicable

The model area was divided into 12 sub-regions based on physical characteristics or management entities, which allows for focused evaluation of water use and available resources within a sub-region. The model sub-regions are each assigned a name and number for reference purposes as shown in Fig. 1. The model grid consists of 16,215 triangular elements each representing an area of approximately 4 ha. The mean node spacing over the model area is 306 m. There are 91 stream reaches in the model defined by physical characteristics including inflows, confluences, diversion points, and headwaters (springs). The thickness of each geologic layer is defined for every node in the model and is assigned to be zero if the layer is interpreted to be absent. Groundwater boundary conditions over the model development period, 2007 through 2013, were determined by interpolating measured groundwater elevations provided by the WWBWC. Surface water inflows were determined from gauge data where available and otherwise through regression analysis used to estimate inflows at ungauged streams as a function of gauged flows.

Surface water–groundwater interaction is simulated in the model as a function of the streambed-saturated hydraulic conductivity, surface water head, and groundwater head. The streambed conductivity for the 310 km of simulated streams and canals ranged from 0.1 to 4.0 m/day. The model simulates direct hydraulic connection or disconnection between surface water and groundwater at each time step, depending on groundwater elevation relative to the stream bed. The model was calibrated to 7 years of groundwater, surface water, irrigation diversion, and weather data. The calibrated model had a root mean squared error of 3.3 m for 89 groundwater monitoring locations (GSA 2015). For surface water, the location corresponding to the USGS WWR gauge at Touchet WA is the reference location closest to the model outflow, and therefore, representative of the simulated surface water balance for the model as whole. The mean relative error (mean error/mean flow rate) for monthly average flow rate at this location was 10.1%, with the mean annual flow rate being 19.9 m^3/s. The greatest relative errors (model error/measured flow rate) in predicted WWR flow generally occurred during low-flow conditions. Relative error in model predictions was greater for many of the small tributaries where a 0.03 m^3/s residual could represent a 100% prediction error; however, these errors did not significantly impact the accuracy of predicted flows in the WWR (GSA 2015). Model-predicted stream segment gains and losses agreed with reported seepage run data (Baker 2014). A detailed description of model development and calibration is provided in GSA (2015).

Water management scenarios

Five water-management scenarios were incorporated into the WWB IWFM, representing a range of MAR applications coupled with the conversion of unlined canals into pipelines. The scenarios were designed to predict changes in groundwater storage and WWR flows after piping and water savings were applied in conjunction with varying levels of MAR. Each model scenario was simulated for 10 years using a daily time step. A 10-year simulation period allowed the model to attain equilibrium conditions such that groundwater levels and water budgets shifted in response to applied scenario conditions and reflected a repeating annual cycle. Model initial conditions were taken to be the simulated conditions at the end of the last day of the calibration model, 31 December 2013 (GSA 2015).

Daily variable conditions such as precipitation, evapotranspiration (ET), stream inflows, groundwater boundary conditions, and urban water requirements were taken to be the daily average of the calibrated model inputs for each sequential day of the year. The setup of the model grid and representation of the model domain were the same in all scenarios. The daily average model inputs were applied over the 10-year forward model as an annually repeating cycle of daily data. The four water-management scenarios used the same daily variable inputs, allowing for simulated differences in scenario results to be solely attributable to water-management scenario conditions. It is assumed that the 7-year average record applied in the simulations is sufficiently representative that results from one simulation may be used to deduce relative impacts of the management scenarios on basin hydrology.

Irrigation demand is calculated by IWFM based on land use, reference ET and crop coefficients obtained from Allen et al. (1998). Groundwater pumping is calculated by IWFM as a function of the discrepancy between prescribed surface water applications and crop demand assuming a well-watered crop, where soil moisture is maintained at or above crop specific minimum requirements. Irrigation from surface water was based on gauge data from the WWBWC and conversations with irrigation district managers. On farm irrigation efficiency was based on irrigation methods (predominantly impact sprinklers in the WWB) and model calibration, and is accounted for with each model diversion (GSA 2015).

MAR is currently applied at seven locations in the WWB. These are collectively referred to as the “Active MAR locations”. An additional 15 locations have been selected for MAR development with licensing applications that are currently in the review process. These are collectively referred to as the “Proposed MAR locations”. An additional 38 “Potential MAR locations” have been identified by the WWBWC as having the potential for MAR development.

The location of "Proposed" and "Potential" MAR locations was determined by the WWBWC based on where MAR is likely to be feasible (e.g., land availability, appropriate hydrogeologic conditions, proximity to surface water conveyance system) and beneficial. There are no current efforts to develop MAR at the potential locations.

MAR is simulated in the model by diverting surface water, primarily from the WWR, into the canal network where it is delivered to surface recharge basins, then percolating to groundwater. Each basin receives a prescribed flow at a rate based on permitted requirements ('Active MAR locations'), proposed rates ('Proposed MAR locations'), or projected available water ('Potential MAR locations'). Figure 2 presents the total volume of surface water inflows into the model area as compared to the volume of agricultural water demand and prescribed irrigation diversions. Diversions exceed agricultural demand over the months of March through May and October through November as local irrigators commonly apply water on their fields to increase soil–water storage (Scherberg 2012). The difference between model inflows and irrigation diversions approximate the water available for MAR, which is far in excess of the Maximum MAR-Piped scenario (0.15 Mm^3/day) during the winter and spring when MAR is occurring. Groundwater is utilized for irrigation during summer months when irrigation diversions are less than agricultural demand (GSA 2015).

In the baseline forward model (BFM) piping was only applied where pipelines currently exist, representing approximately 81 km of piping. The four alternative management scenarios, 'No MAR-Piped', 'Current MAR-Piped', 'Increased MAR-Piped', and 'Maximum MAR-Piped', all include the conversion of selected canals into pipelines to evaluate the projected reduction in irrigation withdrawals from the WWR that could result from decreased conveyance system losses due to canal seepage. A total of 58 km of additional canals are piped under the "piped" scenarios. Canals and pipes in the model convey water at rates determined from daily data collected by the WWBWC or Oregon Water Resources Department gauges, where available. In other cases mass balance calculations or consultation with irrigation district managers was used to determine canal or pipeline flows. Operational periods are variable for canals and pipelines throughout the model area. The earliest operate for irrigation purposes beginning in March and the latest continue operating into December, with additional water diverted for MAR in the winter months (GSA 2015). Diversions are shut off from July through September in many of the model area canals due to low WWR flows.

Confidence in model-predicted surface water flows and groundwater elevations is variable over the model area due to model-calibration error and the inherent limitations of numerical modeling (GSA 2015). The relative differences

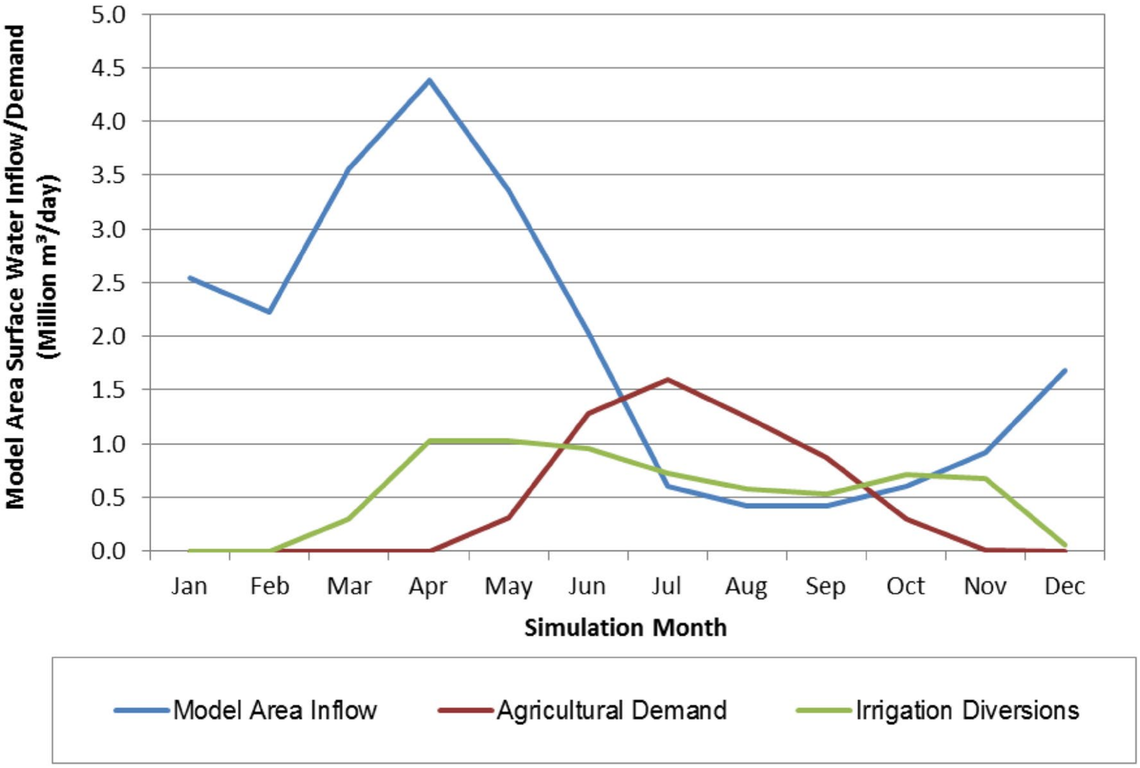


Fig. 2 Model area surface inflows, total agricultural water demand, and irrigation diversions

between flows and water budgets in the simulated scenarios are expected to be indicative of the relative influence of the simulated management practice on water resources within the WWB.

Baseline forward model (BFM) scenario

The BFM scenario is a forward projection of steady state conditions under current basin management practices as implemented in the calibration model (GSA 2015, 2016). This baseline scenario is used to evaluate the impact of alternative water management scenarios. There are 81 km of lined canals in the BFM representing the total length of lined canals in the model area at the time of model development. Water deliveries to the seven active MAR sites shown in Fig. 3 are simulated at their current loading rates of 11.1 Mm^3/year (GSA 2016).

No MAR-Piped scenario

Ongoing efforts to reduce seepage losses by converting permeable canals into pipelines have improved irrigation delivery efficiency. The eliminated canal seepage water volumes (i.e., seepage water savings) are left in the WWR to enhance summer flows. However, the reduction in channel seepage has deprived the underlying near-surface aquifer of an important source of recharge. Previous studies have predicted that large-scale conversion from permeable canals to pipelines will result in reduced groundwater storage within the alluvial aquifer system (Scherberg 2012; Scherberg et al. 2014).

The White Canal and the Gardena Farms Canal, are especially known to lose significant quantities of water to channel seepage (Patten 2015, GSA 2015). Surface water volumes left instream during canal operations as assumed seepage water savings were determined from the relationship between canal flow rate and seepage losses (GSA 2016) and are summarized in Table 2. In the No MAR-Piped scenario a total of 139 km of canals are lined within the model domain. Figure 3 highlights the locations of lined canals in the BFM as well as the canals that are lined in the other scenarios; specifically the Gardena Farms, White, Lowden #2, and Garden City canals. Table 2 shows the associated water savings that is left in stream in scenarios where these canals are lined as well as estimated seepage losses where they are not lined. The No MAR-Piped scenario has no water allocated for aquifer recharge.

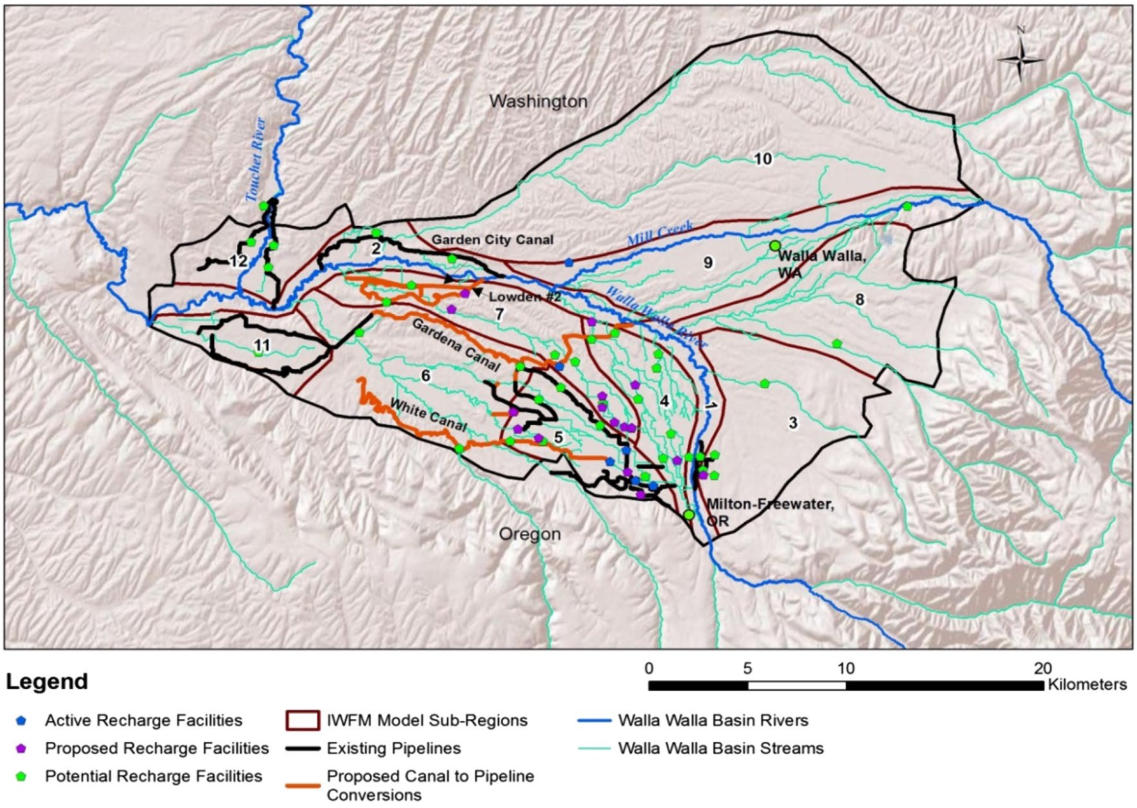


Fig. 3 Existing pipelines within the model area, proposed canals for conversion into pipelines, and locations of active, proposed, and potential MAR sites within the Walla Walla Basin model area

Table 2 Summary of reported seepage losses, MAR, and water savings used in model scenarios

Model scenario	Maximum canal seepage losses (m^3/s)				Maximum WWR water savings (m^3/s)	Total MAR ($Mm^3/year$)
	White[a]	Gardena[b]	Lowden #2[c]	Garden City[c]		
Baseline forward model	0.34	0.57	0.09	0.05	–	11.1
No MAR-Piped	–	–	–	–	0.93	0.00
Current MAR-Piped	–	–	–	–	0.93	11.1
Increased MAR-Piped	–	–	–	–	0.93	18.0
Maximum MAR-Piped	–	–	–	–	0.93	29.9

[a] As reported in GSA 2016

[b] As reported in Patten 2015

[c] As reported in Patten 2014

Current MAR-Piped scenario

The Current MAR-Piped scenario maintains current MAR operations at the seven active MAR sites equal to those in the BFM. Canals converted into pipelines and associated water savings in this scenario are the same as those applied in the No MAR-Piped scenario. This scenario predicts the effect of pipe installation while otherwise maintaining status-quo MAR operations.

Increased MAR-Piped scenario

The scenario for increased MAR uses the same canal to pipeline conversion scheme as the other management alternative scenarios. In the increased MAR scenario, the seven active MAR sites continue with their current operations in addition to water being delivered to the 15 additional proposed recharge sites (Fig. 3). The total volume of MAR used annually in this scenario was 18.0 $Mm^3/year$ (GSA 2016), approximately 62% more than current MAR applications (Table 2).

Maximum MAR-Piped scenario

The Maximum MAR-Piped scenario uses the same assumptions about pipe installation and diversion rates into the Gardena Farms, White, Lowden #2, and Garden City canals as the previous scenarios; however water is delivered to all 60 MAR sites (active, proposed, and potential) that are shown in Fig. 3. This scenario was designed to predict the outcomes of fully realized MAR development. In this scenario, annual MAR applications for the 60 sites totaled 29.9 $Mm^3/year$ (GSA 2016), an approximate 170% increase over current MAR rates (Table 2).

Results

The results of the water management alternative scenarios described in the preceding section are presented below with focus on: low-flow conditions in the WWR (July through October); groundwater storage for agricultural and ecological benefits, and; how available resources can be used to meet agricultural water requirements. Water management alternative scenario results were evaluated in comparison to the BFM, and in terms of changes in resource distribution that are predicted to occur. Simulation results were evaluated for the 12 individual subregions shown in Fig. 1 and for the model area as a whole. All results presented are derived directly from model-generated hydrological budget model.

Predicted surface water conditions

Predicted Walla Walla river flows

Five locations along the WWR, highlighted in Fig. 4, were selected as reference points for tracking simulated surface water flows. Figure 5 summarizes management scenario differences in monthly average flow relative to the BFM during the low-flow season (July through October). Positive value indicates flow that is greater than predicted in the BFM. The change in flow at the most upstream reference location, Nursery Bridge, was similar for all four management scenarios. Greater differences in flow rates were predicted between the four management scenarios moving downstream from Pepper Bridge, with the greatest flow predicted for the Maximum MAR-Piped scenario.

The effect of MAR alone on predicted WWR flow can be determined by comparing scenarios with MAR

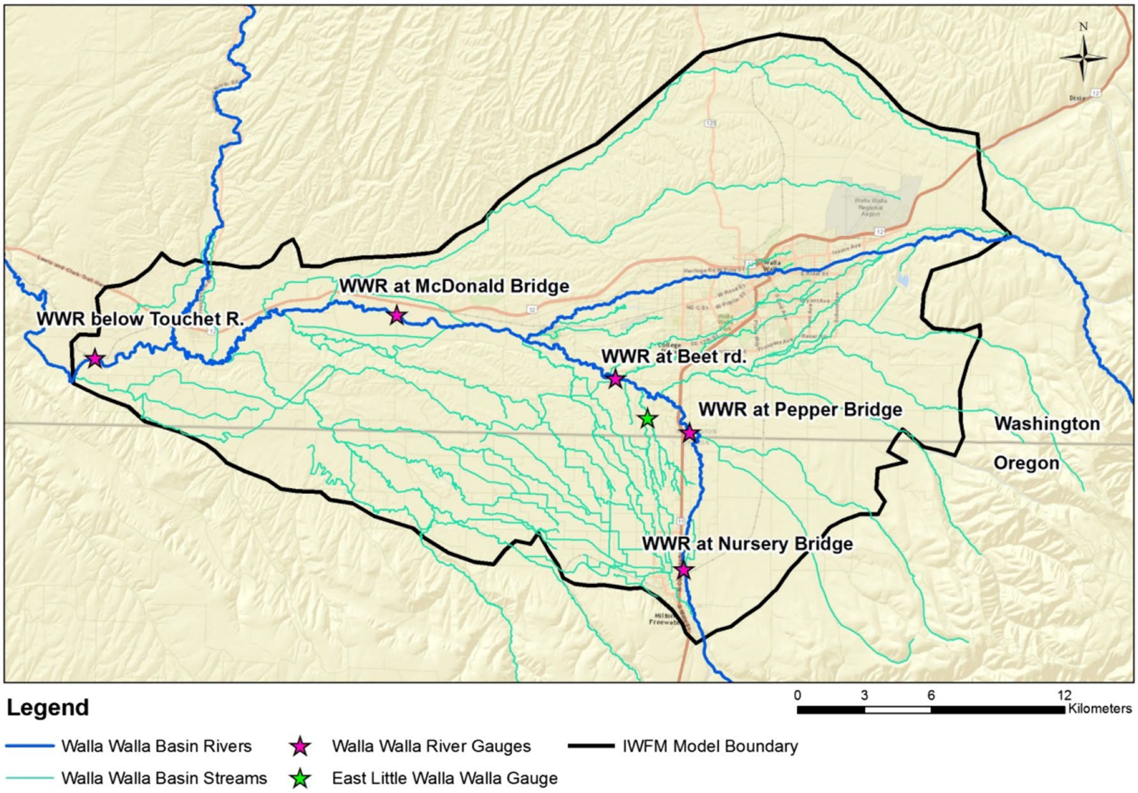


Fig. 4 Reference locations used for analyzing simulated flow conditions in the Walla Walla River

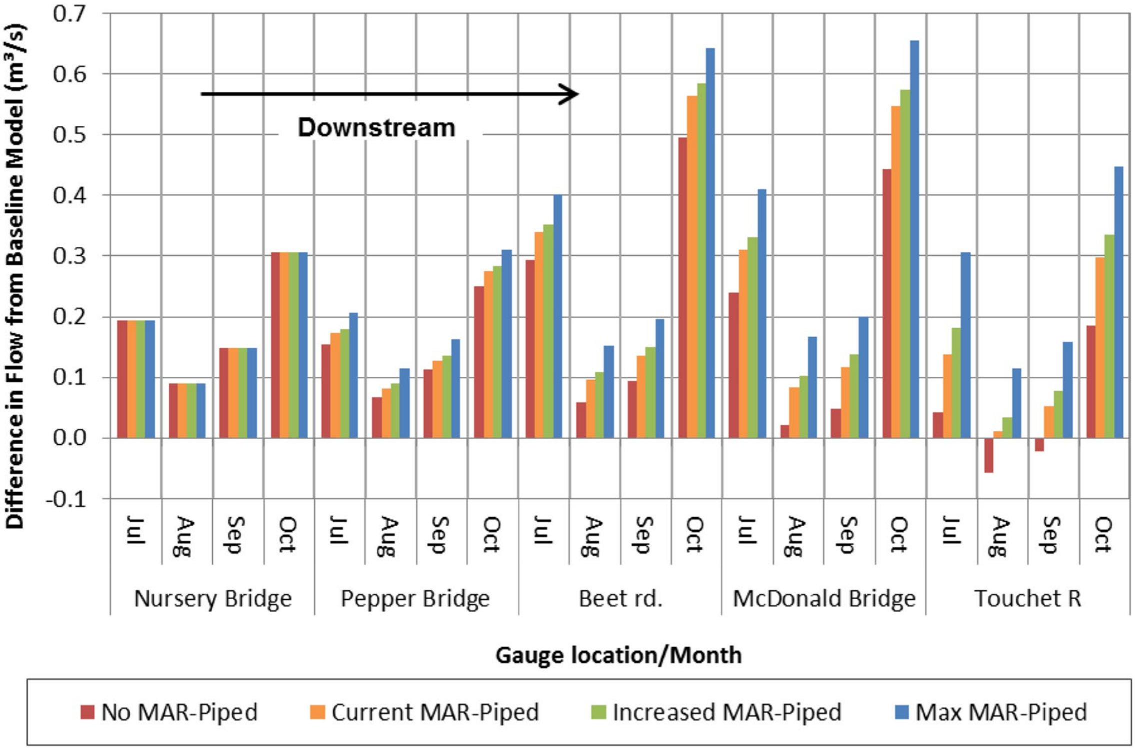


Fig. 5 Management scenario predicted monthly average flows from July through October relative to the baseline forward model

to the No MAR-Piped scenario. Comparing MAR scenario results to the BFM, where piping is limited to currently existing pipelines, shows the combined impact of expanded pipe installation and applied MAR. The impact of MAR was most evident in the McDonald Bridge and Touchet reference locations (Fig. 5). The Maximum MAR-Piped scenario at McDonald Bridge yielded predicted flows that were 0.14–0.23 m^3/s greater than the No MAR-Piped scenario over the July through October period. Maximum MAR-piped scenario predicted flows for this time period were, on average, 0.36 m^3/s greater than in the BFM. At the Touchet River reference location predicted flows in the Maximum MAR-Piped scenario were 0.16–0.38 m^3/s greater than those in the No MAR-Piped scenario for the July through October and, on average, 0.26 m^3/s greater than those predicted for the BFM. The lesser difference between baseline and all MAR-piped scenarios at the downstream location is due to the predicted decrease of groundwater discharge to the lower reaches of the WWR and Pine Creek, a gaining tributary that flows into the WWR upstream of the Touchet reference location, following pipe installation.

Predicted flows for August and September in the No MAR-Piped scenario were, on average, 0.03 m^3/s less than in the BFM. This difference is within the bounds of model error (GSA 2015); however, these results indicate that with canal lining the direct water savings in the WWR applied with pipe installation is likely to be partially or completely offset by decreased groundwater discharge to surface water and, in some instances, gaining reaches becoming losing reaches.

Predicted tributary channel flow

Small channels that contribute flow to the WWR provide important off-channel habitat and cold water refuge for salmonids residing in the WWR system (Wolcott 2010). In many cases, the flow rates in small tributaries are more difficult to predict with certainty compared to flow in the mainstem WWR (GSA 2015). Reasons for this include that typically low-flow rates magnify relative error in predicted flow and that upstream flows are often impacted by irrigation demand with little or no record keeping. It is still informative to evaluate predicted changes in surface water flow under water management scenario conditions relative to the BFM. In the East Little WWR (Fig. 6), a tributary carrying excess canal flows and groundwater discharge, flow rates were on average 56% greater in the Maximum MAR-Piped scenario than in the BFM (Fig. 6). This was a function of the additional recharge sites activated in this scenario increasing groundwater return flow to the stream. Predicted flows in the Current MAR-Piped scenario are nearly identical to those in the BFM because both scenarios do not include piping in this model region. In the No MAR-Piped scenario, the canal

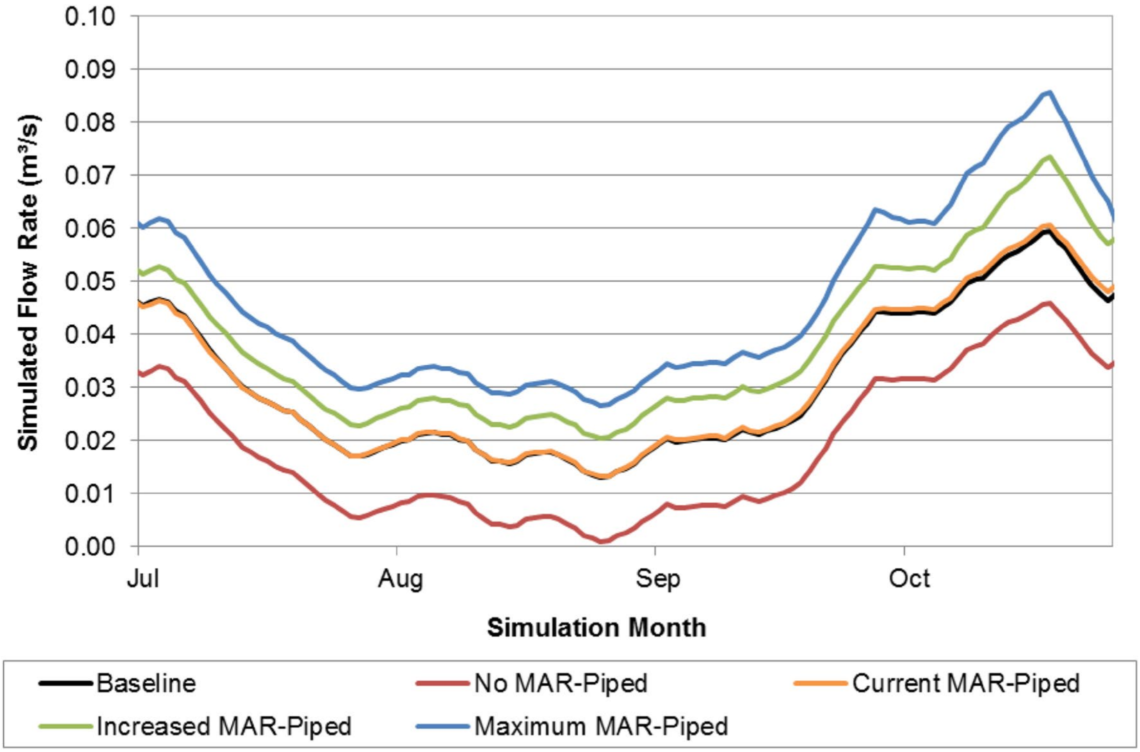


Fig. 6 Simulated flow in the East Little Walla Walla river

is predicted to practically run dry from late July through August, and average 47% less discharge over the low-flow months, July through October, indicating the potential influence of MAR on flows in the East Little WWR. Predicted flow rates in Fig. 6 are low relative to the predictive error of the model, as modest differences in groundwater head can produce significant differences in predicted stream flow; however, comparing the trend in predicted flow provides a general representation of the impact of the different model scenarios on a small stream.

Predicted groundwater conditions

Predicted aquifer storage

Total aquifer storage for the BFM and four water management scenarios after the 10-year simulation period, as well as the predicted difference between the BFM and the other scenarios, is shown in Fig. 7. The Maximum MAR-Piped scenario was predicted to yield 6.5–12.0 Mm^3 (average of 9.0 Mm^3) more groundwater storage than the BFM, with the greatest difference predicted to occur in mid-May at the end of the recharge season. The other three alternative management scenarios were predicted to yield less groundwater storage than the BFM, with predicted storage declining as MAR was decreased. In the No MAR-Piped, Current MAR-Piped, and Increased MAR-Piped scenarios groundwater storage was predicted to average 30.3, 11.0, and 6.3 Mm^3, less than in the BFM, respectively. These differences in groundwater storage translate into a change in mean groundwater head that is less than the model RMSE, therefore, the results should be taken as indicative of trends resulting from the applied management scenarios rather than exact predictions. Results indicate that recharge in excess of that applied in the Increased MAR-Piped scenario is needed to fully compensate for the loss of aquifer recharge from canal leakage following conversion to pipelines.

Predicted groundwater elevations

Figure 8 shows the predicted change in year 10 average groundwater elevations resulting from No MAR-Piped and Maximum MAR-Piped water management scenarios relative to the BFM. These examples were selected because they show the most extreme gains and losses predicted as result of scenario conditions. Groundwater elevation in the northern portion of the model area was predicted to be similar to the BFM in all of the management scenarios.

In the No MAR-Piped scenario, groundwater elevations were predicted to decrease more than one meter over most of the area south of the WWR channel relative to the BFM. Groundwater declines of 3.0–7.3 m were predicted adjacent to MAR sites and canals that served as recharge sources in the BFM. The greatest decline in groundwater elevations were around the Johnson MAR site, in the southern portion of the model area, which was inactive in this scenario but receives the greatest amount of MAR in other scenarios (GSA 2016) (Fig. 8).

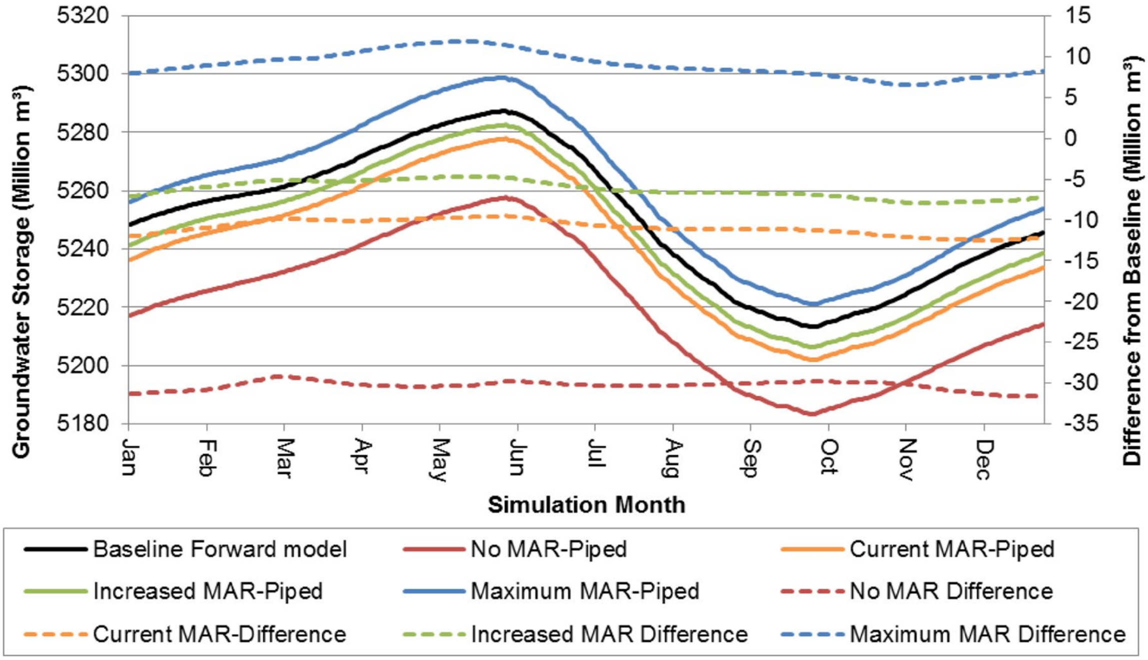
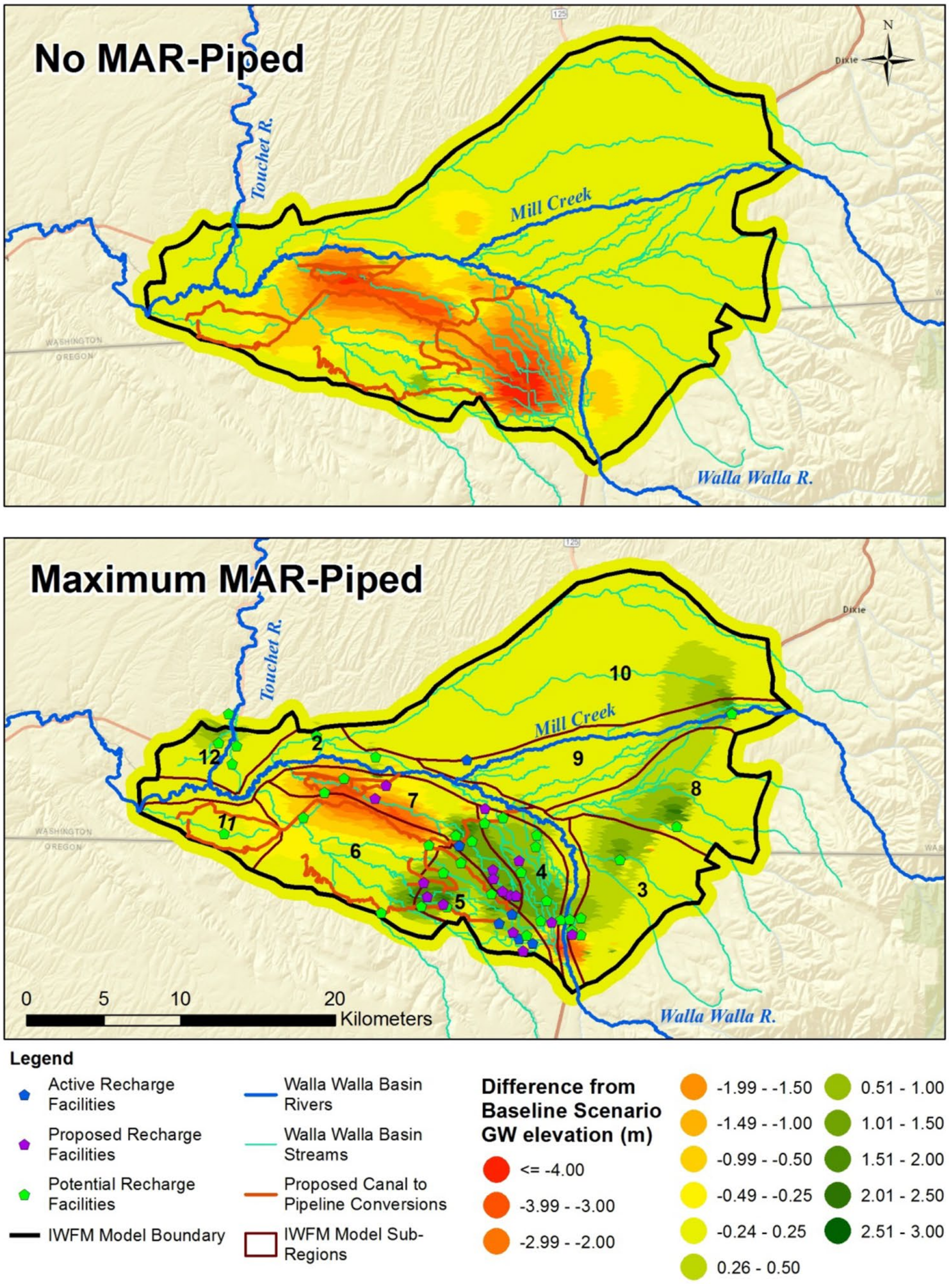


Fig. 7 Simulated aquifer storage and difference from the baseline forward model scenario for January through December

Fig. 8 Predicted change in groundwater elevation relative to the baseline forward model for the No MAR-Piped and Maximum MAR-Piped scenarios



In the Maximum MAR-Piped scenario a widespread increase in groundwater elevations of 1.0–2.6 m higher than the BFM was predicted in the central portion of the model area where MAR sites are concentrated. The water table was predicted to decrease up to 3.6 m around the Gardena, Lowden, and Garden City canals as a result of pipe installation. The predicted groundwater declines were less extensive than predicted for the other three alternative management scenarios and reflect a more broadly distributed benefit of increased groundwater storage in this scenario, partially offsetting the impact of lost aquifer recharge in areas adjacent to pipe installation (Fig. 8).

For both the Current MAR-Piped and Increased MAR-Piped scenarios a decline in groundwater elevation was predicted around the Gardena Canal as a result of pipe installation. In the latter case a modest increase in groundwater elevation was predicted in the vicinity of the proposed MAR sites that were not active in the BFM.

Predicted model water balance

The relative impacts of each water management scenario on the predicted model water balance in simulation year 10 are presented in Fig. 9. Management scenarios were

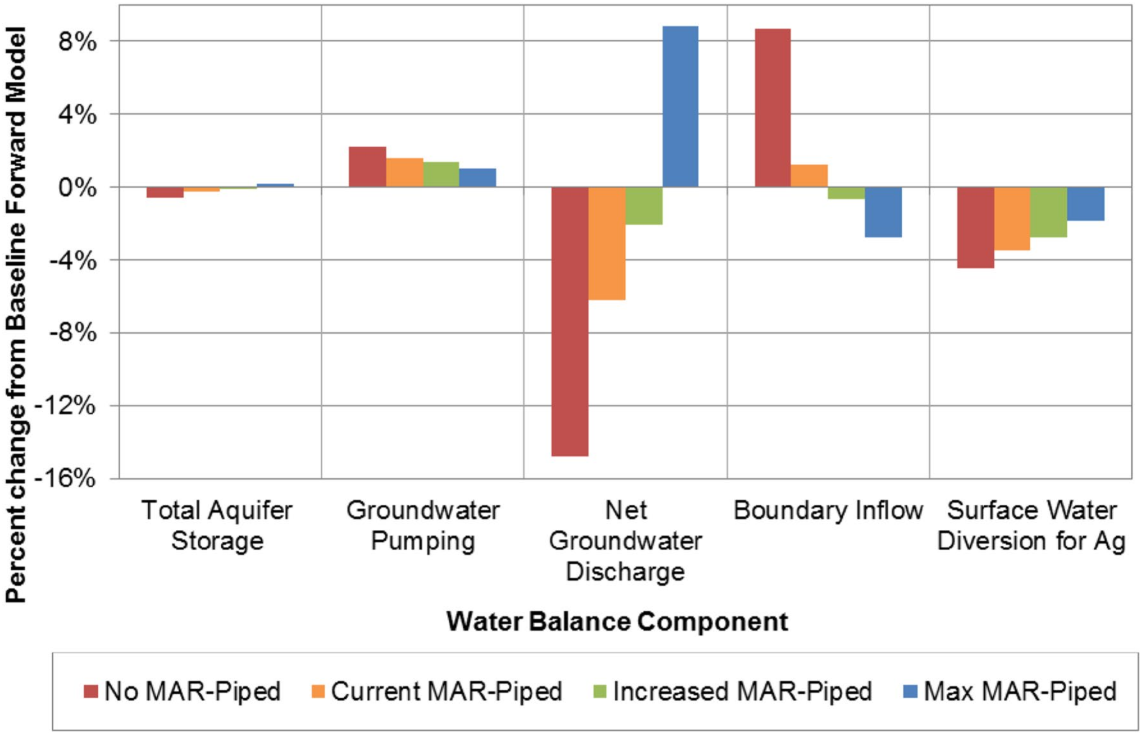


Fig. 9 Simulation year 10 management scenario simulated water budget changes relative to the baseline forward model

predicted to have the largest impact on net groundwater discharge to surface water. Compared to the BFM, the total net discharge from groundwater to surface water was predicted to increase by 8.8% for the maximum MAR scenario and decrease by 2.1, 6.2, and 14.8% for the Increased MAR-Piped, Current MAR-Piped, and No MAR-Piped scenarios, respectively. These results reflect the loss in canal seepage that is predicted to occur with conversion from permeable canals to pipelines. This reduction in groundwater recharge was reduced as MAR was increased; however, groundwater gains from MAR were only predicted to exceed the loss of groundwater input through canal seepage in the Maximum MAR-Piped scenario.

Lower groundwater elevations predicted in the No MAR-Piped scenario induced increased groundwater recharge (inflow) along the model boundary based on the specified head groundwater boundary conditions applied to the model. The opposite was predicted in both scenarios with increased MAR due to increased groundwater elevations (Fig. 9). Surface water diversions were predicted to be 4.4% lower in the No MAR-Piped scenario compared to the BFM, a result of the decreased withdrawals from the WWR into the piped irrigation networks (Fig. 9). As MAR was increased, more water was available for surface water diversions from the WWR because of lower canal seepage losses in these scenarios.

Groundwater pumping was calculated by the model as the difference between agricultural demand and the total surface water applied for irrigation. Agricultural water demand was unchanged in all scenarios; therefore, groundwater pumping directly reflects the change in available surface water. The No MAR-Piped scenario predicted a groundwater pumping increase of 2.0% compared to the BFM. Slightly less pumping was required as MAR increased due to additional water predicted to be available in streams from increased groundwater discharge.

Water management scenario predicted sub-region water balance changes relative to the BFM are presented in Table 3. The differences between scenarios are considered to be more reliable than specific scenario predictions. Sub-regions four and five, where active, proposed and potential MAR sites, are most heavily concentrated (Fig. 9), were predicted to see the greatest aquifer storage increases resulting from MAR. Sub-regions six, seven, and 11 were predicted to see declines in aquifer storage resulting from reduced canal seepage losses due to pipe installation; although this loss was offset in sub-region seven in the Maximum MAR-Piped scenario. Sub-regions eight, nine and ten, to the north of the WWR, were predicted to be unaffected by the management scenarios; except in the case of the Maximum MAR-Piped scenario where a slight increase in groundwater storage was predicted in

Table 3 Management scenario sub-region groundwater budget changes relative to the baseline forward model (all scenarios in the table include piping as described in the text)

Sub-region	Total GW storage (m^3/m^2)				Net groundwater discharge (m^3/m^2/year)			
	No MAR	Current MAR	Increased MAR	Max MAR	No MAR	Current MAR	Increased MAR	Max MAR
1	− 0.02	0.00	0.01	0.04	− 0.17	− 0.07	− 0.04	0.07
2	0.00	0.00	0.00	0.00	− 0.09	− 0.07	− 0.05	0.00
3	− 0.02	0.00	0.01	0.06	0.00	0.00	0.00	0.00
4	− 0.19	− 0.02	0.03	0.11	− 0.03	0.04	0.05	0.09
5	− 0.31	− 0.02	0.03	0.07	− 0.09	− 0.08	− 0.06	− 0.02
6	− 0.11	− 0.10	− 0.09	− 0.07	0.07	0.08	0.09	0.10
7	− 0.14	− 0.05	− 0.03	0.00	− 0.16	− 0.14	− 0.13	− 0.10
8	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.02	− 0.01	0.00	0.00	0.00
10	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
11	− 0.04	− 0.04	− 0.03	− 0.02	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.03
Model Area	− 0.05	− 0.02	− 0.01	0.01	− 0.02	− 0.01	0.00	0.01

sub-regions eight and nine because of several MAR sites being activated.

Sub-regions one and two, representing the channel of the mainstem WWR, were predicted to see an increase in WWR seepage losses with canal piping, shown by the reduced net groundwater discharge for these sub-regions in Table 3. There was an exception in the Maximum MAR-Piped scenario, where increased MAR offset the effects of canal piping and groundwater discharge into the WWR was predicted to increase for sub-region one. In sub-region six piping of the White Canal and Gardena Farms Canal brought about a net increase in available surface water within the sub-region as the reduced groundwater discharge in gaining streams was more than offset by the elimination of canal seepage losses from losing streams. In sub-region seven WWR tributary flows are predicted to decrease as a result of eliminating Gardena Farms Canal seepage losses (Table 3). MAR that did not return to surface water as groundwater discharge was used for irrigation (groundwater pumping), or became groundwater storage.

Discussion

Water management scenarios showed a strong impact on predicted net groundwater discharge to surface water in the model area. Conversion of canals to pipelines eliminated seepage losses from those canals and was predicted to lower groundwater elevations and decrease groundwater discharge to streams in these areas. Groundwater elevations were predicted to increase with increased MAR volumes in the areas where active, proposed, or potential MAR sites are located, generating increased groundwater discharge into both the WWR and off-channel tributaries.

The influence of MAR on predicted summer flows in the WWR was negligible in the upstream areas of the model domain in all scenarios compared to the BFM. Lower in the basin, predicted WWR summer flow rates in scenarios that included MAR were greater than the No MAR-Piped scenario, with the difference increasing downstream and with greater applied MAR. This was a direct result of the increase in groundwater discharge to surface water with increasing MAR. An increase in groundwater discharge could have significant potential ecological benefits in the form of increased summer flow rates and improved riparian habitat. It should also be noted that groundwater discharge temperatures are typically colder than the ambient stream temperature during the summer low-flow season and thus have the potential to improve stream habitat by lowering surface water temperature.

Predicted WWR summer flows in the alternative management scenarios were greater than in the BFM due to water savings implemented with pipe installation and MAR where it was increased from baseline conditions. This was not the case in the No MAR-Piped scenario where decreased groundwater discharge following pipe installation was predicted to nearly offset the in-stream flow benefits of water savings in the WWR, underscoring the connection between MAR and surface water flows.

Water savings from increased piping is estimated to result in an approximately 30,500 m^3/day reduction in surface water diversions into the primary irrigation canals for the months of July through October, an 11.7% decrease from the BFM. This translates to 0.53 m^3/day of reduced diversions from the WWR per meter of additional pipeline. Relative to the BFM, the Current MAR-Piped scenario predicts approximately 7800 m^3/day less net groundwater discharge to surface water over the model area from July through October, a 4.3% decrease. Therefore, the model predicts that with the continuation of current MAR practices the net water savings in the WWR following pipe installation would be approximately 22,700 m^3/day after factoring for reduced groundwater discharge. This reduction in groundwater discharge would effectively offset 25.5% of the pipeline water savings in the WWR. Pipeline installation and MAR site development and operation are estimated to cost approximately $600 USD per meter of pipeline and $90,000 USD per MAR site. Based on model predicted flows (which account for reduced groundwater discharge following pipe installation), the costs translate to approximately $27.1 million USD per 0.1 m^3/s of increased flow (July through October) at Touchet for pipeline installation and $3.7 million USD per 0.1 m^3/s of increased flow for MAR installation.

Conclusions

Water management scenario results indicate that converting canals into pipelines is likely to have a negative impact on groundwater resources and limit instream water savings if not combined with increased application of MAR to enhance groundwater storage. Reduced groundwater storage would be detrimental to fish habitat and agriculture, and therefore, contrary to the goals of the WWB Integrated Flow Enhancement Study. This is particularly evident in the declining groundwater levels and discharges to streams predicted in the No MAR-Piped scenario. Increasing MAR to include the currently proposed recharge sites (Increased MAR-Piped scenario) is predicted to nearly mitigate the impact of the simulated canal piping in terms of groundwater storage and groundwater discharge. The Maximum MAR-Piped scenario, which incorporates 60 active, proposed and potential sites, is predicted to provide the most widespread benefits to both fish habitat and groundwater resources by allowing for significantly increased summer flows in the WWR and some tributaries while stabilizing aquifer storage. The use of MAR in the WWB is an opportunity to practice conjunctive management of groundwater and surface water resources to meet conflicting water demands in the basin. Results suggest that increasing application of MAR as a basin water management strategy will increase summer time stream flows and mitigate groundwater declines at a cost less than converting canals to pipelines. Direct water savings with pipe installation is predicted to increase summer flow in the WWR; however, the model predicts that the increase will be mitigated by reduced groundwater discharge to surface water throughout the model area. As MAR development proceeds in the WWB, it is important that recharge water and groundwater quality monitoring is continued to ensure that water quality standards are maintained, as is required by law.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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