Dynamic Representations of Hydrologic-Irrigator Interactions in Planning Models

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14. ABSTRACT

Different levels of complexity for representing hydrologic-irrigator interactions in planning models were investigated. A simplified approach in which irrigator decisions regarding fallowing and irrigating are modeled via reservoir operations and water delivery rules combined with irrigator logic that determines when fallowing is triggered was implemented. Water mass balance is employed to track water flows through the system including the evolution of groundwater storage. For an intermediate level of model complexity, we have proposed and outlined an approach for linking the WRIMS Simplified Model with the physical based IWFM Demands Calculator (IDC) for the representation of soil and root zone processes governing crop water use. Ongoing work by California DWR is aimed at the third level of model complexity through development of CVSOM, a dynamic physically-based model representing the salient physical process and the time-dependent interactions between them and the reservoir operations and water management decisions by irrigators regarding irrigation, fallowing, and groundwater pumping.

Recommended future work is to implement the proposed linkage between the WRIMS Simplified Model and IDC, followed by a comprehensive comparison between the three levels of models to develop guidelines for the types of water management strategy questions that can be answered by each level of modeling.

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Acronyms and Abbreviations

C_f	Crop fraction
CVSOM	Central Valley System Operations Model
DWR	California Department of Water Resources
ET	Evapotranspiration
Flood-MAR	Flood-Managed Aquifer Recharge
GSP	Groundwater Sustainability Plan
IDC	Integrated Water Flow Model Demand Calculator
Reclamation	Bureau of Reclamation
SGMA	Sustainable Groundwater Management Act
WRIMS	Water Resource Integrated Modeling System

Measurements

TAF	Thousand Acre Feet

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Executive Summary

The project documented herein represents initial work at developing tools of varying complexity and a framework for matching modeling complexity with management question/objective to facilitate conjunctive use management strategies in planning for California's water future. Having access to tools that account for the effects of conjunctively managing the integrated surface water-groundwater system is critical to the goal of optimally managing California's water system. Two of the key processes to consider are on-farm recharge and land fallowing. The former can take advantage of available aquifer storage space to capture and store some of the water not being utilized during wet periods for later use (via groundwater pumping) during dry periods; this will improve water system reliability while also guarding against aquifer overdraft. While effective conjunctive use can mitigate periods of water shortage, land fallowing is also expected to be a necessary component of water management in the coming decades. This project addresses the need to consider the impacts of on-farm recharge and land fallowing by considering three different levels of detail and rigor and some associated potential methods for incorporating these processes into water operations planning models. A comparison between the three different levels of methodological rigor may lead to identification of the importance of different levels of physical rigor in planning models.

The three levels of modeling considered are: 1) a simplified approach in which rules for on-farm recharge, land fallowing, and groundwater pumping as a function of groundwater storage are incorporated into a generalized planning model platform such as the Water Resource Integrated Modeling System (WRIMS) modeling code; 2) an intermediate approach in which the WRIMS framework completed in step 1 may be linked with a more detailed representation of agricultural water demands that considers physical processes in the root zone, for example the IWFM Demands Calculator (IDC); 3) a dynamic linkage between WRIMS and the Integrated Water Flow Model (IWFM).

For level 1, we developed a simplified approach via the WRIMS Simplified Model in which irrigator decisions regarding fallowing and irrigating are modeled via reservoir operations and water delivery rules combined with irrigator logic that determines when fallowing is triggered. A simplified water mass balance is employed to track water flows through the system including the evolution of groundwater storage. For the intermediate level of model complexity, we have proposed and outlined an approach for linking the WRIMS Simplified Model with the physical based IWFM Demands Calculator (IDC) for the representation of soil and root zone processes governing crop water use. Ongoing work by California DWR is aimed at the third level of model complexity through development of CVSOM, a dynamic physically-based model representing the salient physical process and the time-dependent interactions between them and the reservoir operations and water management decisions by irrigators regarding irrigation, fallowing, and groundwater pumping. Future work may include detailed testing of the WRIMS-IDC linked model and further collaboration with DWR to complete a comprehensive comparison of the WRIMS simplified model and WRIMS-IDC model with CVSOM.

Introduction

In recent years, there has been an increasing awareness of the importance of conjunctive use management strategies in planning for California's water future. This awareness has been reflected in the passage of the Sustainable Groundwater Management Act (SGMA) and State programs such as Flood-MAR (flood-managed aquifer recharge). On the one hand, it is widely agreed that the impacts of climate change will include (and already are being observed to exhibit to some extent) a shift in precipitation occurring with a higher proportion of rain versus snow and the springtime snowmelt occurring earlier in the year. This translates to a significant loss in snowpack water storage that was used as the basis for design of California's combined Federal-State reservoir system. Also, it is expected that there will be greater meteorological variability (e.g., atmospheric rivers). On the other hand, there also has been an increasing acknowledgment of an overreliance on groundwater (particularly in the Tulare Basin and to a large extent in the San Joaquin Valley as well). This realization coupled with the status of many aquifers experiencing overdraft conditions led to passage of SGMA which requires all aquifers in the State to develop and implement Groundwater Sustainability Plans (GSPs) designed to achieve sustainability on a twenty-year timeline, with critically overdraft basins prioritized to meet this goal by 2040. In sum, we are faced with adapting to the challenges that climate change present to the reliability of our surface water delivery system, which even without these challenges is hard pressed to meet demands without groundwater being depleted to compensate for delivery shortages in dry years.

Given the situation described in the preceding paragraph, it is imperative that water managers and planners have access to tools that account for the effects of conjunctively managing the integrated surface water-groundwater system. Two of the key processes to consider are on-farm recharge and land fallowing. The former can take advantage of available aquifer storage space to capture and store some of the water not being utilized during wet periods for later use (via groundwater pumping) during dry periods; this will improve water system reliability while also guarding against aquifer overdraft. While effective conjunctive use can mitigate periods of water shortage, it is still expected that there will be years when it is impossible to meet 100% of agricultural demands. Thus, land fallowing will probably be one component of the overall management approach. This project addresses the need to consider the impacts of on-farm recharge and land fallowing by considering three different levels of detail and rigor and some associated potential methods for incorporating these processes into water operations planning models. A comparison between the three different levels of methodological rigor may lead to identification of the importance of different levels of physical rigor in planning models. We are interested in how incorporating the relevant surface-subsurface hydrologic processes and the dynamic aspects of these processes may lead to meaningful differences in planning model results.

In general terms, three levels of modeling are considered: 1) a simplified approach in which rules for on-farm recharge, land fallowing, and groundwater pumping as a function of groundwater storage are incorporated into a generalized planning model platform such as the Water Resource Integrated Modeling System (WRIMS) modeling code; 2) an intermediate approach in which the WRIMS framework completed in step 1 may be linked with a more detailed representation of agricultural water demands that considers physical processes in the root zone, for example the IWFM Demands

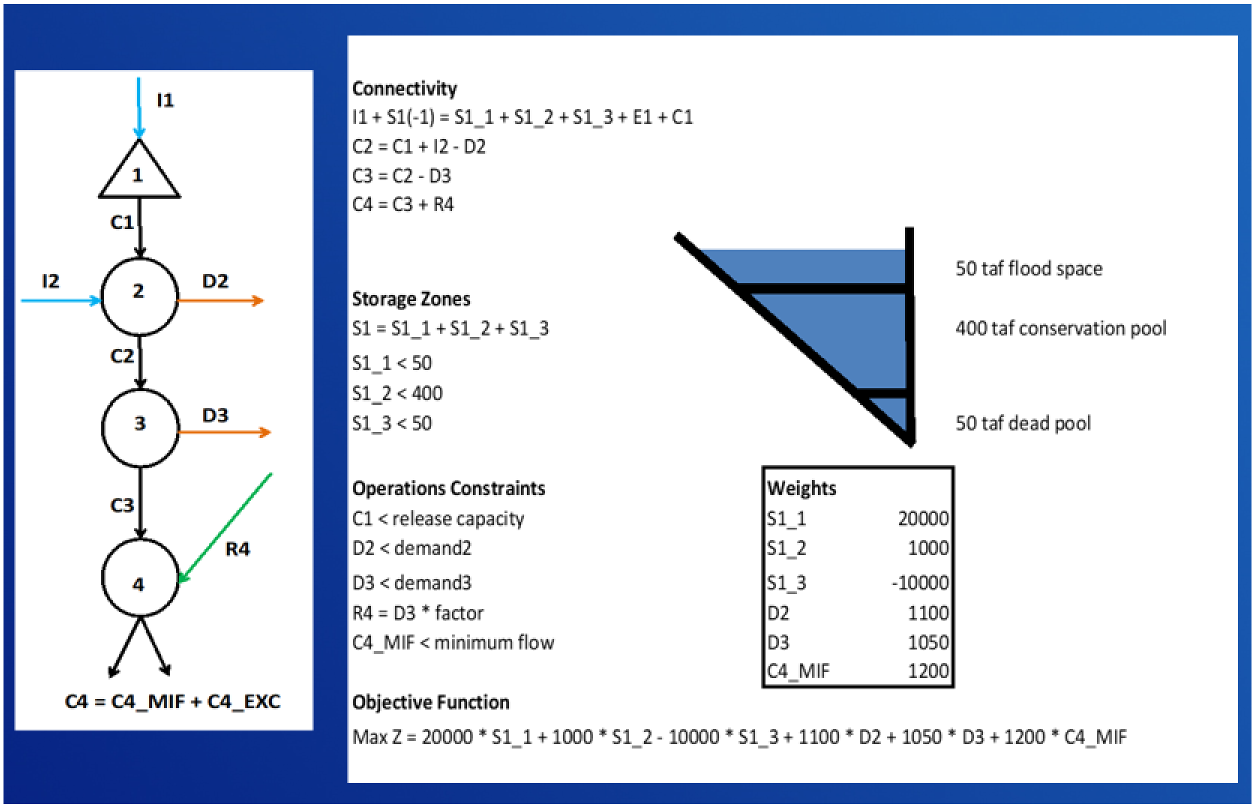
Calculator (IDC); 3) a dynamic linkage between WRIMS and the Integrated Water Flow Model (IWFM). A concise way of stating these three different levels of modeling is: 1) a planning model that incorporates reservoir operations and irrigator decisions via rules while water flows are represented via simple mass balance with other details of the physics ignored; 2) a planning model linked with an agricultural water demands model that incorporates the physics of crop consumptive water use; 3) a dynamically linked model that joins the reservoir operator and irrigator logic with the time-dependent physics of an integrated surface-subsurface hydrologic model (e.g., IWFM which also incorporates the root zone and crop evapotranspiration physics of IDC).

Methods

In this section, we detail the three different levels of model complexity and rigor and the current state of development for each.

WRIMS Simplified Model

For the first methodological approach, logic was developed within the WRIMS modeling framework to account for the primary processes of interest: on-farm recharge and land fallowing as a function of water year type; groundwater storage; groundwater pumping with variable priority weights to incentivize pumping when aquifer storage is high and penalize it when storage drops below a specified sustainable level. To implement a proof of concept for this approach, the WRIMS 101 tutorial model was selected as a base model (Figure 1).



Connectivity
I1 + S1(-1) = S1_1 + S1_2 + S1_3 + E1 + C1
C2 = C1 + I2 - D2
C3 = C2 - D3
C4 = C3 + R4

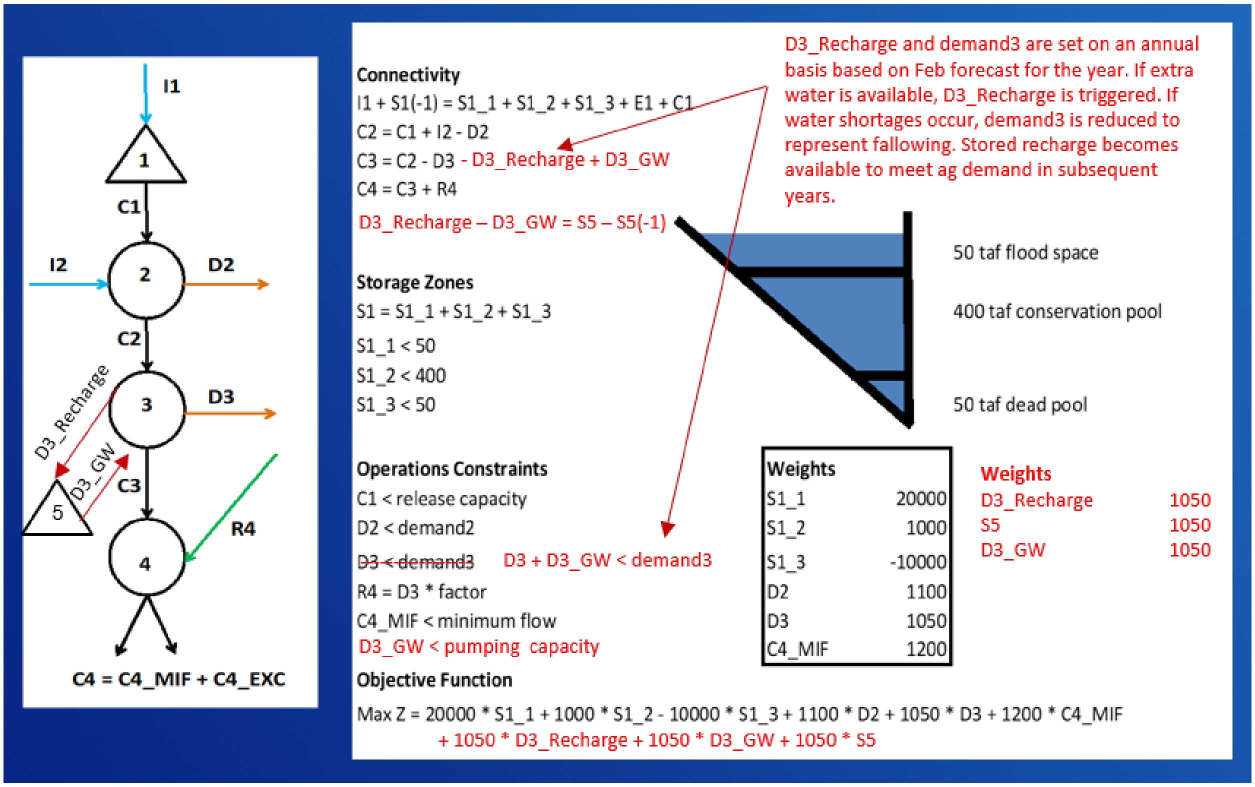
Storage Zones
S1 = S1_1 + S1_2 + S1_3
S1_1 < 50
S1_2 < 400
S1_3 < 50

Operations Constraints
C1 < release capacity
D2 < demand2
D3 < demand3
R4 = D3 * factor
C4_MIF < minimum flow

Weights	
S1_1	20000
S1_2	1000
S1_3	-10000
D2	1100
D3	1050
C4_MIF	1200

Objective Function
Max Z = 20000 * S1_1 + 1000 * S1_2 - 10000 * S1_3 + 1100 * D2 + 1050 * D3 + 1200 * C4_MIF

Figure 1 – Base model for proof-of-concept



Connectivity
I1 + S1(-1) = S1_1 + S1_2 + S1_3 + E1 + C1
C2 = C1 + I2 - D2
C3 = C2 - D3 - D3_Recharge + D3_GW
C4 = C3 + R4
D3_Recharge – D3_GW = S5 – S5(-1)

D3_Recharge and demand3 are set on an annual basis based on Feb forecast for the year. If extra water is available, D3_Recharge is triggered. If water shortages occur, demand3 is reduced to represent fallowing. Stored recharge becomes available to meet ag demand in subsequent years.

Storage Zones
S1 = S1_1 + S1_2 + S1_3
S1_1 < 50
S1_2 < 400
S1_3 < 50

Operations Constraints
C1 < release capacity
D2 < demand2
~~D3 < demand3~~ D3 + D3_GW < demand3
R4 = D3 * factor
C4_MIF < minimum flow
D3_GW < pumping capacity

Weights	
S1_1	20000
S1_2	1000
S1_3	-10000
D2	1100
D3	1050
C4_MIF	1200

Weights	
D3_Recharge	1050
S5	1050
D3_GW	1050

Objective Function
Max Z = 20000 * S1_1 + 1000 * S1_2 - 10000 * S1_3 + 1100 * D2 + 1050 * D3 + 1200 * C4_MIF
+ 1050 * D3_Recharge + 1050 * D3_GW + 1050 * S5

Figure 2 – Proof-of-concept for on-farm recharge, fallowing, and GW storage

The modifications made to the base model are depicted in Figure 2. In the simple schematic of the base model, there is one reservoir that delivers water to three downstream nodes. Node 3 represents the agricultural demand, so that is the focus of our modifications. Two new terms were incorporated into the continuity equation at the node to account for the additional water being delivered for recharge and water being supplied for the agricultural demand via groundwater pumping. A groundwater pumping term is also added to the inequality of the D3 delivery constraint, corresponding to the demand being met by a combination of surface water deliveries and groundwater pumping. Finally, two new terms and associated weights are added to the objective function. We also incorporated a framework whereby the evolution of groundwater storage is tracked over time and the weight applied to D3_GW can be varied based on the storage level at any given timestep. This allows us to prioritize groundwater pumping for meeting demands when storage is high and de-prioritize groundwater pumping when storage is low. The aim of this methodology is to be able to represent how water managers make decisions under policies such as SGMA which require groundwater to be managed sustainably.

The processes of on-farm recharge and land fallowing are being represented in this simplified WRIMS model via triggering based on water year types (corresponding to what water managers would experience as forecasts every year in the real world). Figure 3 shows the framework for rule setting that implements the triggers.

Table 1 – Rules for triggering on-farm recharge and land fallowing

WY Type	**Recharge**	**Fallowing**
Wet	High	Zero
Above Normal	Low	Zero
Below Normal	Zero	Low
Dry	Zero	Medium
Critical	Zero	High

To test the proof-of-concept model, we ran several cases to demonstrate that the expected relationships were occurring. First, for land fallowing, three cases were run corresponding to no fallowing, a medium level of fallowing, and a high level of fallowing. All these cases include triggers for recharge to occur as well. Then, as a basic test on the effect of including recharge, the high land fallowing case was altered by removing all triggers for on-farm recharge. The results of these cases are given in Figures 4-7. In each figure, two plots are given. On the top is surface water deliveries (blue) and groundwater pumping (red). On the bottom is groundwater storage. Looking at the groundwater storage plots first, we can see that there is a high degree of sensitivity to the land fallowing and recharge processes. Figure 4 shows that with no land fallowing the aquifer is quickly depleted in approximately the first decade of the simulation. In later years, some recovery is shown but the aquifer never fully recovers or stabilizes. Figure 5 shows that with a medium level of fallowing specified (75% of full allocation in below normal water years; 50% of full allocation in dry water years; 25% of full allocation in critical years) the initial depletion of the aquifer is more gradual and then in subsequent years the recovery is better. Figure 6 shows that with a high level of fallowing specified (50% of full allocation in below normal water years; 33% of full allocation in dry water years; 17% of full allocation in critical years) the aquifer is never depleted and in fact its storage increases by approximately three-fold (due to the recharge being triggered in the above normal and wet years). Figure 7 shows that even in the high fallowing case if recharge is turned off, the aquifer is depleted and never recovers (note that for proof of concept, there were no processes of natural recharge or return flow incorporated).

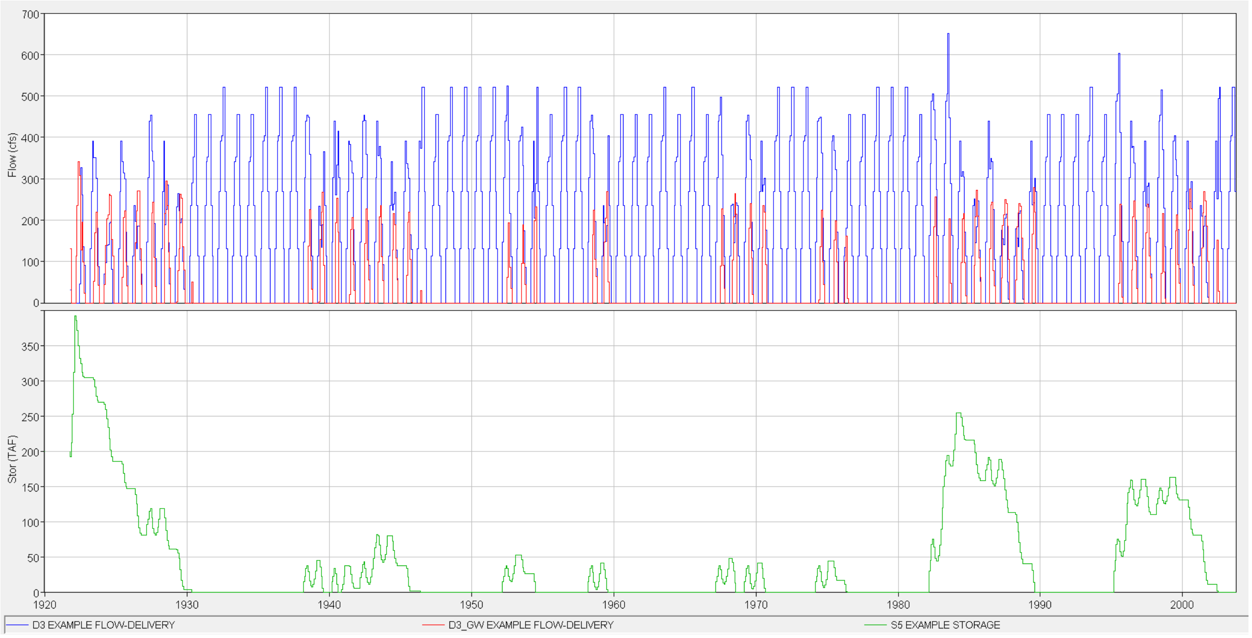


Figure 3 – SW Deliveries & GW Pumping and GW Storage for No Fallowing Case

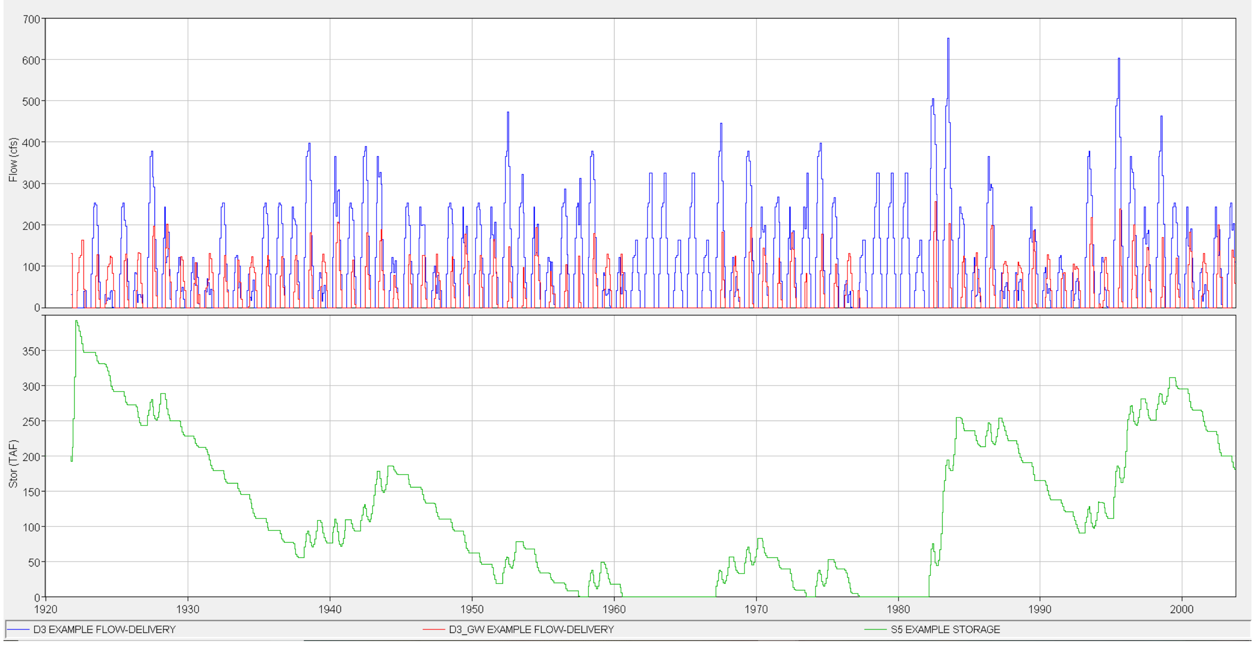


Figure 4 – SW Deliveries & GW Pumping and GW Storage for Medium Fallowing Case

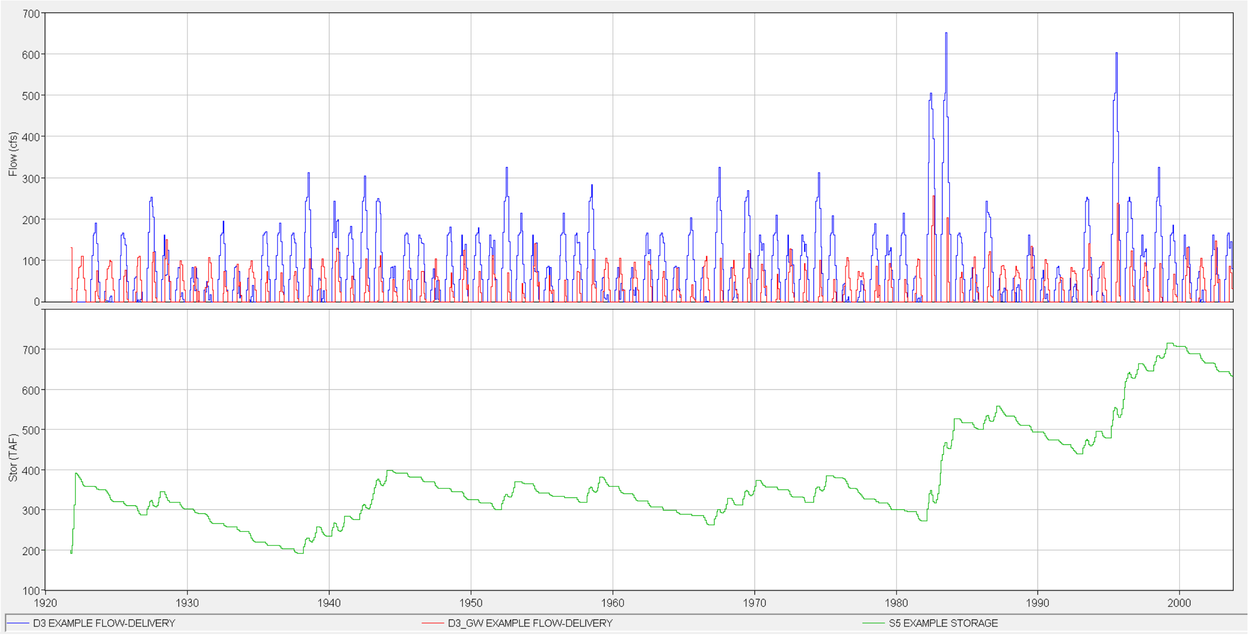


Figure 5 – SW Deliveries & GW Pumping and GW Storage for High Fallowing Case

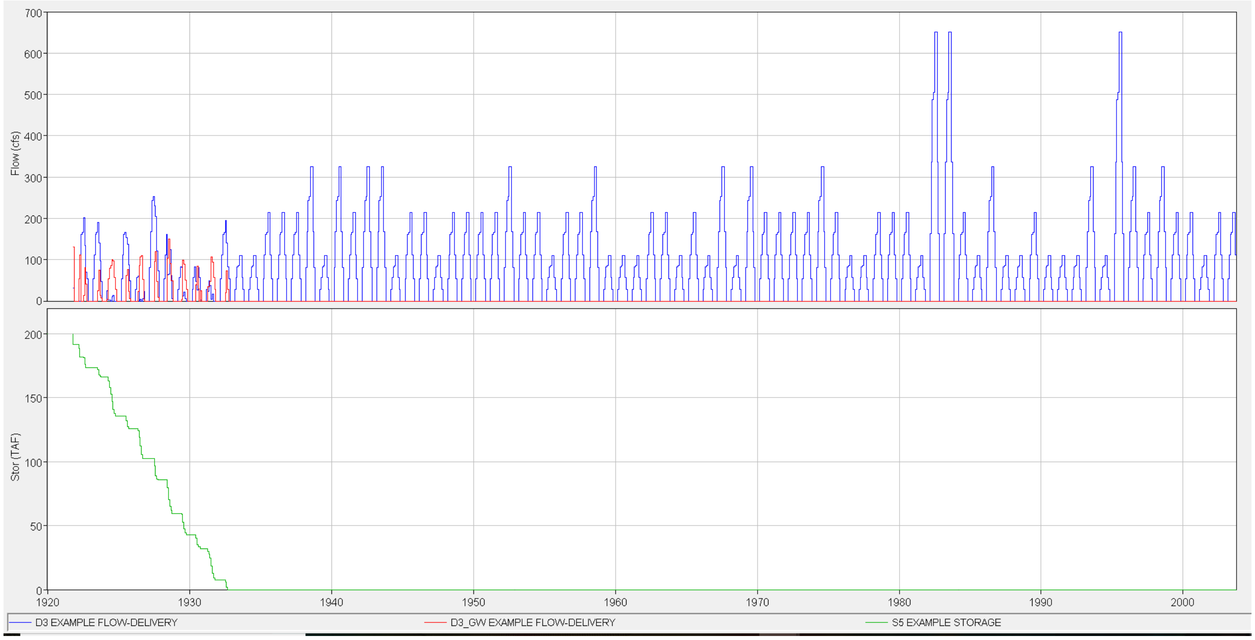
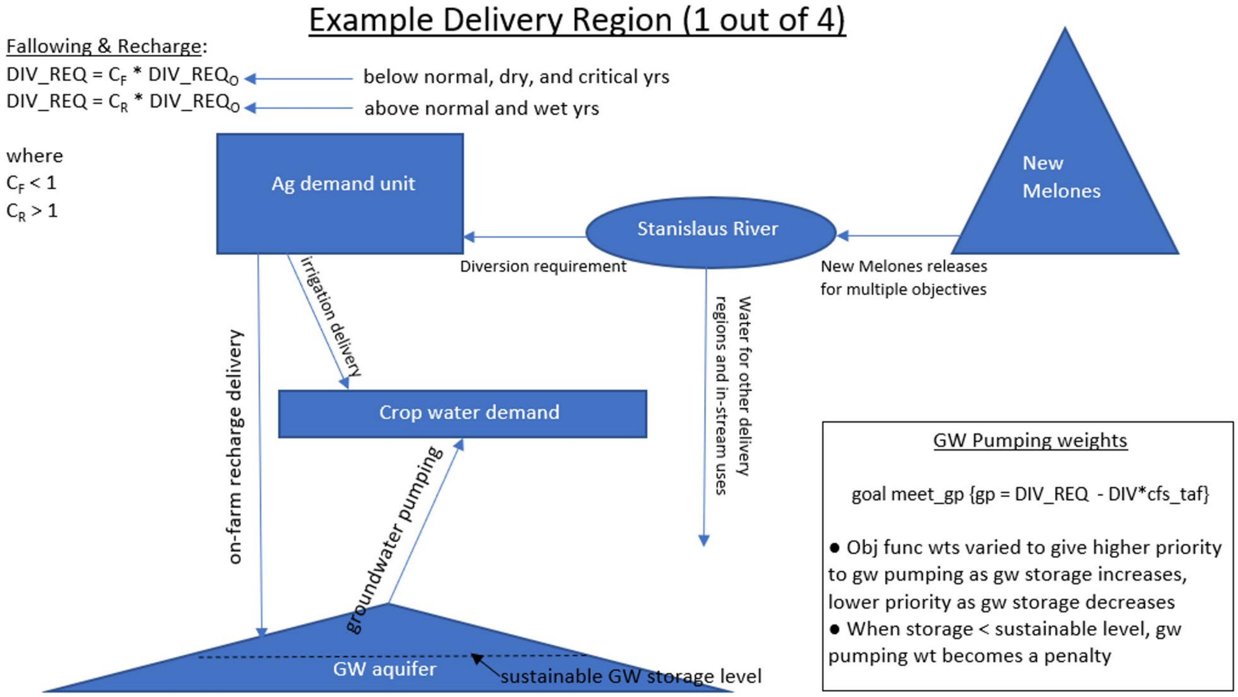


Figure 6 – SW Deliveries & GW Pumping and GW Storage for High Fallowing/No Recharge Case

WRIMS Simplified Model – Application to Subregion 11

Subregion 11 (Stanislaus Basin) was selected as an initial area to apply the logic developed in the WRIMS proof-of-concept model. Figure 8 displays a schematic of the logic for releases from the New Melones reservoir and deliveries to one of four agricultural demand units within the subregion.



goal meet_gp {gp = DIV_REQ - DIV*cfs_taf}

- Obj func wts varied to give higher priority to gw pumping as gw storage increases, lower priority as gw storage decreases
- When storage < sustainable level, gw pumping wt becomes a penalty

Figure 7 – Schematic of logic applied to Subregion 11

A key aspect of this application to the Subregion 11 system is the division of the groundwater aquifer into three different zones corresponding to different levels of priority for groundwater pumping. The zone with the highest level of groundwater storage corresponds to the highest priority of utilizing groundwater pumping to satisfy the crop water demand. The zone with the next highest level of groundwater storage corresponds to a medium level of priority for utilizing groundwater pumping to satisfy the crop water demand. The lowest level of storage is defined as being below a specified sustainable groundwater storage level and when the aquifer drops into this zone, the groundwater pumping weight becomes a penalty. This scheme is designed to provide a means for representing how water managers will attempt to maximize the efficient use of their groundwater resources while also trying to maintain sustainability as required by SGMA.
Representative results of how this groundwater pumping logic operates are given in Figure 9 which shows the evolution of the groundwater storage over the course of a simulation within the three different zones.

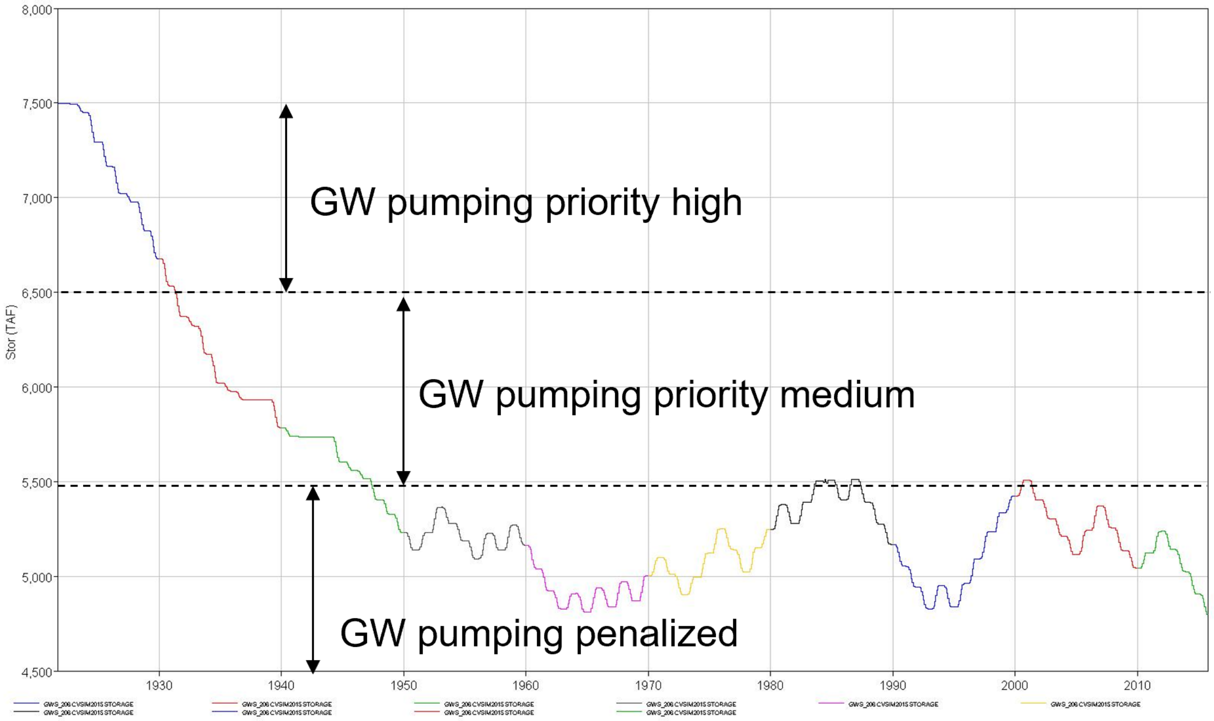


Figure 8 – Groundwater storage as a function of priority zones

In this scenario, the high priority zone was set for aquifer storage > 6,500 TAF, the medium priority zone for 5,500 TAF < aquifer storage ≤ 6,500 TAF, and the penalty zone for aquifer storage ≤ 5,500 TAF. It can be seen that for approximately the first decade of the simulation, aquifer storage drops steeply from its initial value of 7,500 TAF until it falls into the medium zone. While in the medium zone, the rate of storage depletion decreases although the aquifer storage level does keep going down. Finally, when storage drops below the specified sustainable level, the depletion rate decreases dramatically, and the aquifer is able to recover during the wetter years. For the particular simulation presented in Figure 9, this phenomenon is exhibited as an oscillation of groundwater storage going up and down near the sustainable storage level. Incorporating this type of groundwater pumping prioritization scheme into planning models is a first step towards having a modeling tool capable of assessing conjunctive use management strategies that include groundwater sustainability as an objective. The groundwater pumping dynamics reflected in Figure 9 can be contrasted with how groundwater has been treated (both in reality and in planning models) as an infinite reservoir available to make up for shortages in surface water supplies.

As an example of the first level of methodological complexity, we have developed a simplified approach within the WRIMS modeling code of accounting for on-farm recharge, land fallowing, and storage level dependent groundwater pumping designed to maintain groundwater sustainability. Recharge and fallowing are triggered by rules based on water year type to reflect the types of decisions water managers may make based on forecasts prior to the start of the irrigation season. In contrast to past planning models of water operations, groundwater is not treated as an infinite reservoir automatically tapped into whenever there is a shortage in surface water supplies. Instead, the aquifer is divided into zones of variable groundwater pumping priority with a sustainable groundwater storage level defined which is sought to be maintained by the objective function programmed into WRIMS. Initial tests of this modeling framework yield reasonable results displaying the expected relationships between on-farm recharge, land fallowing, storage-dependent groundwater pumping, and groundwater storage.

The next level of methodological complexity involves developing an approach of intermediate rigor in terms of its representation of physical processes. This is made possible by linking the WRIMS model created in Task 1 with the IWFM Demand Calculator (IDC) that provides a rigorous accounting of the physical processes (e.g., evapotranspiration, soil moisture content, crop types) impacting agricultural demands. The linkage would be static in that IDC will be run for given scenarios of land use, meteorological conditions, etc. to produce time series of the relevant demands as input to the WRIMS model. This linkage would provide the capability to account for the impacts of physical processes associated with both the management decisions related to crop water demands and the environmental conditions caused by variable meteorology and hydrology including the effects of climate change, all of which have an impact on agricultural water use.

The third and final level of methodological complexity simulates both the essential physical processes and the time-dependent interactions among them. Such an approach is being developed by our collaborators at the California Department of Water Resources (DWR). DWR is developing a model Central Valley System Operations Model (CVSOM) which includes a dynamic linkage between WRIMS and the physically based hydrologic model IWFM. This dynamic linkage is expected to provide the most robust accounting for the interaction between management decisions and physical hydrological processes. In future work, it may be possible to develop scenarios and representative questions for testing and comparing the three levels of approaches for representing conjunctive use in water planning models. Such a comparative analysis could focus on questions of interest to water managers in California who are concerned with conjunctive use and aquifer sustainability. It would be recommended to ascertain what types of questions can be treated with equivalent accuracy or utility by all three approaches, when the intermediate approach is required instead of the simplified approach, and when the most rigorous approach represented by CVSOM is required. Building on the initial work documented in this report, it could be possible to identify a hierarchy of modeling tools for water managers tasked with developing conjunctive use management strategies. This hierarchy could identify the types of planning and management strategy questions appropriate for the different levels of methodological complexity in modeling for the development of successful conjunctive use strategies throughout the American West.

WRIMS-IDC Linked Model Methodology

The second level of methodological complexity focuses on developing an intermediate approach, incorporating more rigor than the WRIMS model but still simplified in comparison to CVSOM. This intermediate approach could be based on a static linkage of the simplified WRIMS model and the Irrigation Demand Calculator (IDC) model that is the physics-based component of CVSOM representing the soil and root zone processes governing crop water demands. Below we present a proposed methodology for accomplishing such a linkage.

Linkage Methodology

In the WRIMS Simplified Model, the critical terms in the water balance are all aggregated values and the physics of water movement is completely ignored. For example, the agricultural demand for a given demand unit is pre-specified and when fallowing is triggered by water year type, it is simply implemented as a pre-specified fraction of the overall aggregate demand. There is no consideration of which types of crops will be fallowed nor the associated evapotranspiration and root zone processes. The WRIMS Simplified Model also assumes that the water saved from the fallowed percentage of demand is directly transferred to groundwater storage. By linking WRIMS with IDC, we seek to incorporate a higher level of physical realism. For example, crops may be fallowed selectively based on assumptions of irrigator preferences. The corresponding reduction in agricultural demand is then calculated by IDC based on the crop parameters. And when on-farm recharge is triggered by the water year type, the extra water that is delivered is routed by a physically based percolation algorithm in IDC. As such, the WRIMS-IDC Linked Model represents a first step for moving beyond the simple accounting approach of the WRIMS standalone model and incorporating the physical processes involved in land.

The first step to develop the WRIMS-IDC Linked Model would be to apply the same overall fallowing percentages from the WRIMS Simplified Model to all 21 of the defined crop types in the IDC model for Subregion 11. Theoretically, this should produce the same result as the WRIMS Simplified Model, since the one constant fallowing percentage per water year type was applied uniformly over all crops just as had been done in the simple model. However, the one difference is that in the WRIMS-IDC Linked Model the physical processes of evapotranspiration (ET) and percolation are simulated. Thus, the actual demand reduction may not be identical to the fallowed percentage since different crops have different ET requirements and the resultant consumptive use is a function of the relative acreages of the different crops. Also, instead of assuming the saved water is transferred directly into groundwater storage, the physical process of percolation is simulated. To test the impact of incorporating these physical processes, one could set the land use acreages in the IDC Subregion 11 model to be consistent with the fallowing percentages in the WRIMS Simplified Model base run for the entire simulation period. Then the results of the two models may be compared for the overall agricultural demand. Next, the simulated percolation values from WRIMS-IDC could be used as input to the WRIMS standalone model to compute the corresponding groundwater storage values to be compared with those generated by the WRIMS Simplified Model.

The linkage methodology proposed here is based on iterations between the WRIMS model and the IDC model to represent a) the aggregate agricultural demand from a given demand unit in WRIMS based on the water operations rules defined therein and b) the more refined and physically based computations of water demand given by IDC. In this manner, we can incorporate both the systems level water operations rules and constraints governed by WRIMS and the farm level physical processes of crop water demand coupled with irrigator decisions on fallowing that are simulated via IDC. The iteration process may be executed as follows:

1) Run WRIMS to generate fallowing percentages based on Water Year (WY) types as described in Task 1.
2) Apply crop fraction (C_f) from WRIMS uniformly to all crops in IDC.
3) Run IDC and compare the water demand per demand unit with the demands generated by WRIMS.
4) If IDC demand per demand unit is < WRIMS demand, increase C_f for crops with highest value/consumptive use.
5) If IDC demand per demand unit is > WRIMS demand, decrease C_f for crops with lowest value/consumptive use.
6) Repeat steps 1-2 until the WRIMS demand and the IDC demand agree withing a specified tolerance.
7) The resulting set of C_f values as a function of crop types gives the optimal distribution of fallowed crops to achieve the water demand reduction goal from the WRIMS fallowing scenario.

WRIMS-IDC Linked Model Methodology – Summary

In this section, we have presented a proposed approach to accomplish the intermediate level of model sophistication and complex wherein the WRIMS Simplified Model would be linked with the IDC crop water demands model. This approach would give a much more realistic accounting of the physical processes governing crop water use and the resultant impacts on groundwater storage, water availability, and irrigation and fallowing decisions made be farmer/irrigators. In the final level of complexity which is being pursued by DWR, this physical realism would be further increased by representing the dynamic interactions between all processes.

Discussion

In this work, we have developed a simplified approach via the WRIMS Simplified Model in which irrigator decisions regarding fallowing and irrigating are modeled via reservoir operations and water delivery rules combined with irrigator logic that determines when fallowing is triggered. A simplified water mass balance is employed to track water flows through the system including the evolution of groundwater storage. For the intermediate level of model complexity, we have proposed and outlined an approach for linking the WRIMS Simplified Model with the physical based IWFM Demands Calculator (IDC) for the representation of soil and root zone processes governing crop water use. Ongoing work by California DWR is aimed at the third level of model complexity through development of CVSOM, a dynamic physically-based model representing the salient physical process and the time-dependent interactions between them and the reservoir operations and water management decisions by irrigators regarding irrigation, fallowing, and groundwater pumping. Recommended future work is to implement the proposed linkage between the WRIMS Simplified Model and IDC, followed by a comprehensive comparison between the three levels of models to develop guidelines for the types of water management strategy questions that can be answered by each level of modeling.

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