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INCORPORATING WATER MANAGEMENT INTO A PHYSICALLY-BASED HYDROLOGIC MODEL

Laura E. Condon*†, Reed M. Maxwell† and Subhrendu Gangopadhyay*

* Bureau of Reclamation
Technical Service Center
Denver Federal Center Building 67, Denver, CO 80225 USA
e-mail: lcondon@mymail.mines.edu, web page: http://www.usbr.gov/pmts/tech_services/

† Colorado School of Mines
Geology and Geological Engineering Department, Hydrologic Science and Engineering
1516 Illinois St., Golden CO 80401 USA
e-mail : rmaxwell@mines.edu, web page: http://hydrology.mines.edu/

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Summary. Reservoir management decisions are commonly made using surface water models with simplified and/or abstracted physical processes and limited groundwater-surface water interactions. Optimizations with such models might not capture the potential importance of and feedbacks from physical processes such as evaporation and infiltration. This study details how management algorithms of the Water Evaluation and Planning (WEAP) model are incorporated with an integrated hydrology model, ParFlow to simulate reservoir operations for the Upper Klamath Lake in Oregon, USA. ParFlow is a fully coupled physical hydrology model capable of simulating groundwater surface water interactions in heterogeneous porous media. Richards equation is used for variably saturated subsurface flow and the diffusive wave equation is applied for overland flow. The common land model (CLM), which is coupled to ParFlow, simulates land surface processes. Upper Klamath Lake is a large shallow lake with high infiltration rates. Operating policies are highly contentious and must balance the needs of several user groups. Management decisions are evaluated using a variety of multi year simulations and results are compared between the integrated ParFlow model and a simple management model with no physical processes. Differences highlight the sensitivity of management decisions to physical considerations.

1 INTRODUCTION

There is a well-established connection between soil moisture and land energy fluxes[1,2,3]. A large body of research exists exploring the nonlinear relationships between changing soil moisture and land-atmosphere fluxes[1,3,4]. Dirmeyer et al. found a nonlinear sensitivity of evapotranspiration to soil moisture changes that is dependent on vegetative cover[3]. Chen et al. note that the impact of soil moisture with depth varies depending on crop type and root density at depth[1]. In a global study Koster et al. identified transition zones where the surface is neither too wet nor severely moisture limited[4]. In these areas soil moisture is found to exert the most influence over evapotranspiration. Such findings highlight the importance of soil moisture to accurately model land surface fluxes and achieve better closure of the water budget. This is especially important in portions of the northwest and the central Great Plains of North America[4].

Much of the aforementioned research has been conducted using land surface models that generally do not simulate the deeper soil column and lateral groundwater flow. A growing body of work has shown that consideration of groundwater interactions is necessary to close the water energy budget[5,6,7,8,9,10,11,12,13,14,15,16,17]. Spatial distribution and magnitude of surface runoff, evapotranspiration, recharge and groundwater divergence are all partially controlled by the shape and position of the water table[9,10,11]. Groundwater is an important controlling factor for soil moisture, which in turn controls evapotranspiration. It adds heterogeneity on the same spatial scales as topography and land cover and can impact regional water and energy budgets especially in areas where the water table is close to the surface[2,5].

Several recent studies have shown that the sensitivity of a hydrologic system to changes in atmospheric temperature and pressure is a function of groundwater depth[7,13]. Within some critical depth range small changes in water table depth have big impacts on water availability. During seasons when there is a transition from moisture limited to energy limited conditions the sensitivity of the land surface energy balance depends on groundwater land surface feedbacks[7]. Drought timing is often linked to global variables like sea surface temperature, however modeling results suggest that drought duration and intensity may depend on soil moisture and land-atmosphere interactions[13].

Such findings have important implications for irrigation practices and water management. Ferguson and Maxwell used an integrated hydrologic model to examine the feedbacks that occur as a result of irrigation from groundwater pumping, surface water or a combination of the two[18]. They found that irrigation from surface water and groundwater pumping both affect the water energy balance but in different ways. Groundwater pumping has a larger impact on groundwater storage and stream discharge while irrigation is a controlling factor in spatially distributed processes and land energy fluxes[18]. Results demonstrate the need for integrated physical hydrology modeling to fully understand the feedbacks that occur as a result of changes in water management practices.

This study details how management algorithms from the Water Evaluation and Planning (WEAP) model are incorporated with an integrated hydrology model, ParFlow to simulate reservoir operations for the Upper Klamath Lake in Oregon, USA. ParFlow is a fully coupled physical hydrology model capable of simulating groundwater surface water interactions in heterogeneous porous media. Richards equation is used for variably saturated subsurface flow and the diffusive wave equation is applied for overland flow. The common land model (CLM), which is coupled to ParFlow, simulates land surface processes. Management decisions are evaluated using a variety of multi year simulations and results are compared between the integrated ParFlow model and a simple management model with no physical processes. Differences highlight the sensitivity of management decisions to physical considerations.

2 STUDY AREA

Klamath River originates in southeastern Oregon and flows to the Pacific Ocean through California. The Klamath basin is highly contentious with complicated demands and management practices. Irrigation facilities controlled by the Bureau of Reclamation provide irrigation water to about 1,400 farms spanning 235,000 irrigated acres[19]. The basin is home to the Lower Klamath National Wildlife Refuge, the Tule Lake National Wildlife Refuge and several endangered or threatened aquatic species. Since the early 1990s concern has been growing over the impacts of agricultural surface water diversions on aquatic species. Specifically, two species of sucker fish (Chasmistes brevirostris and Deltistes luxatus) listed as endangered in 1988 and the Coho Salmon (Oncorhynchus kisutch) listed as threatened in 1997[19]. Tensions came to a head in 2001 when all surface water diversions for agriculture were curtailed for the entire irrigation season in an effort to maintain lake levels and river flows in an extremely dry year. As a result of ongoing surface water conflicts there has been a sharp increase in groundwater pumping for agricultural irrigation. From 2001 to 2004 the USGS estimated a 56% increase in groundwater withdrawals[20]. In recent years the Bureau of Reclamation has been working with the National Oceanic and Atmospheric Administration (NOAA) Fisheries and the US Fish and Wildlife Serves (USFWS) to develop management strategies that will meet critical requirements for the species of concern while still allowing for reliable agricultural supplies.

3 METHODOLOGY

3.1 Physical Hydrology Model

ParFlow is a physical hydrology model that simulates variably saturated subsurface flow, fully integrated with overland flow designed for parallel computing. It is solves cell-centered finite differences in space and an implicit backward Euler scheme in time using a Newton Krylov method with multigrid preconditioning. A short summary of the governing equations is provided here for more detailed descriptions refer to; Ashby and Falgout; Jones and Woodward and Kollet and Maxwell[21,22,23].

ParFlow simulates variably saturated groundwater flow using the three dimensional Richards equation[24]. Subsurface flow is integrated with overland flow using a free surface overland flow boundary condition. The diffusive wave equation is solved in two dimensions maintaining continuity of pressure and flux at the boundary. Flow depth-discharge relationships are established using Manning's equation.

The common Land Model is integrated into ParFlow to simulate land surface fluxes [11,25]. In CLM the surface mass energy balance is composed of net radiation, sensible heat, latent heat and Ground heat all of which can be expressed in terms of soil moisture content. The heat transport equation is solved at the interface between the land surface and the lower atmosphere. The subsurface flux is the change in energy stored in subsurface water and porous media as a function of time and is equal to a conductive heat transfer term plus a thermal source sink term. In land surface models the upper boundary condition at the ground surface consists of all thermal fluxes from the land surface. The source sink term is the difference between the net radiation and the sensible and latent heat terms.

Using these relationships CLM is incorporated in a distributed manner such that it is the top boundary of each cell at the ground surface in ParFlow. Subsurface heat transport is coupled with Richards equation through saturation. The soil moisture module in CLM is replaced by moisture distributions calculated by ParFlow at every time step. ParFlow simulated overland flow takes the place of the TOPMODEL based runoff scheme in CLM and in return CLM provides ParFlow with land surface fluxes like evaporation and infiltration from precipitation. The coupled model is mass and energy conservative. ParFlow balances mass in the subsurface and CLM balances mass and energy at the land surface.

3.2 Management Algorithms

The Water Evaluation and Planning System (WEAP) model is an integrated model that incorporates management algorithms with a relatively simple network based physical hydrology model. It was developed by the Stockholm Environmental Institute to be used for integrated water management planning. WEAP has been applied to a wide range of real world water management problems similar to the Klamath Basin in complexity and spatial extent.

Water is allocated in WEAP using an optimization algorithm. Demand coverage is maximized using a linear program subject to priorities, preferences, mass balances, and other constraints[26]. In this framework each demand is assigned an integer priority value and a range of prioritized water supply sources. Solutions are constrained such that the percentage coverage of every demand within a priority group is equal. The system is solved in order of priority so that demand coverage is maximized first for the top priority demands regardless of any lower priority demands. After top priority allocations are made the code loops through each of the lower priority groups in order of descending importance. Within each demand location the algorithm iterates through the supply priorities to maximize satisfaction of demand. Additional constraints can be imposed to limit transmission volumes based on the infrastructure capacity. Each time the allocation algorithm is solved shadow prices for each demand are assessed. If the shadow price for a given demand is greater than zero then the allocation for that demand is optimal and its allocation is set. The problem is iterated until the shadow prices for all demands are greater than zero[26].

3.3 Coupled Management Model

The allocation algorithms for the WEAP model are robust however the physical hydrology model is relatively simple and not capable of simulating complex groundwater surface water interactions. For this analysis the water allocation module from WEAP is linked to the ParFlow physical hydrology model. ParFlow provides water supply and physical demand values while the WEAP algorithms are used to allocate water and determine which demands should be met by groundwater pumping versus surface water diversions.

Management from the WEAP model has been linked to other physical hydrology models in the past. Droubi et al. dynamically linked WEAP to MODFLOW (a gridded groundwater physical hydrology model) to analyze water management in a groundwater-dominated region[27]. In their linked model MODFLOW provides groundwater data (i.e. groundwater heads, storage and flow) while WEAP calculates surface variables like groundwater recharge, river stage, irrigation demand and any additional water balance variables. At each time step variables from each of the models are shared using a "linkage-shapefile" which maps MODFLOW grid cells to WEAP elements. The MODFLOW-WEAP linked model was applied to two pilot basins using a range of future scenarios incorporating changes in overall demand and irrigation technology[27]. For this analysis none of the physical hydrology components of WEAP are used because ParFlow is able to calculate surface water variables in addition to groundwater variables. Rather than communicating with the WEAP model the allocation algorithms are extracted and written directly into ParFlow.

3.4 Model Domain and Inputs

A ParFlow model has been developed for the upper Klamath basin, which extends from the headwaters to Iron Gate Dam just south of the California Oregon state line. It covers an area roughly 200 km by 260 km. Horizontal grid resolution is one kilometer in the X and Y directions. A terrain following grid is employed and the model extends to 50m below the surface with a resolution of one meter. For the purposes of this analysis a small test domain is extracted from the larger study area. The test domain encompasses Upper Klamath Lake and a small surrounding area that includes a stretch of river and several irrigated parcels. Irrigation water can be applied from groundwater pumping or surface diversion. The demands to be met are crop irrigation, instream flows and reservoir storage.

ParFlow requires a range of datasets to define the domain from the aquifer to the land surface. All inputs were assembled from publicly available data sources. Every layer was re-projected and sampled to create consistent gridded datasets. With the exception of Upper Klamath Lake the top of the land surface is defined using a national DEM that was processed to eliminate pits and expansive flat areas. For Upper Klamath Lake a more detailed Bathymetry dataset from the Bureau of Reclamation was used. Rivers were identified using the HydroSHEDS dataset. Because the lateral resolution of the model is one kilometer a subset of the most significant rivers in the domain was created. Using this river mask the DEM was further processed to ensure that all river cells are connected and drain correctly. Soil covers the top two meters of the subsurface. Land cover and soil data was derived from USGS data sources. The model is forced with transient observed meteorology from the North American Land Data Assimilation System (NLDAS) dataset.

As is often the case, no comprehensive subsurface mapping exists for the Upper Klamath basin at the necessary resolution. Therefore a variety of subsurface parameterizations were developed using three publicly available data sources: 1) publicly available well logs for the state of Oregon, 2) a U.S. Geological Survey (USGS) report that mapped geologic strata[20], 3) a recently published North American permeability map[28]. The hydrogeologic units mapped in the USGS report and the North American permeability dataset, henceforth referred to as the Gleeson et al. dataset, are translated into consistent gridded model inputs by re-projecting and resampling.

The saturated hydraulic conductivity of each aquifer type in the USGS dataset was calculated as the geometric mean of all well test measurements in the given type. Saturated hydraulic conductivity was directly provided for the Gleeson et al. dataset. For both maps strata were matched by description to soil types from the RAWLS database[29] to determine additional subsurface properties such as porosity and vanGenuchten parameters. A geo-statistical analysis was performed on the well-log point measurements to determine spatial structure and generate two Gaussian Random field inputs. The first random field has the same spatial structure for the entire domain and the second has spatial structure and mean conductivity values that vary with the strata defined by the USGS report. The final subsurface parameterization is a homogeneous field with saturated hydraulic conductivity equal to the geometric mean of all well measurements. Lacking any depth specific data all subsurface fields are modeled as vertically.

4 PRELMINARY FINDINGS

ParFlow CLM has been run on an hourly time-step for six months using historical observed meteorological forcing data from 1980. Results are compared for the five subsurface characterizations. Preliminary analysis shows that different subsurface realizations can significantly impact modeling results even on a regional scale. Average differences in hydraulic conductivity appear to impact regional results more than the spatial distribution within a realization. For the sensible heat flux, latent heat flux and evaporation the variations between scenarios are significant even considering the range of values across the domain. Also the spatial structure of hydraulic permeability and elevation were compared to hydraulic and land surface variables. Findings indicate that subsurface heterogeneity may control the spatial structure of hydrologic variables like surface pressure much more than topography. However, elevation still appears to dominate the spatial correlations of heat flux variables. These findings suggest that variability in subsurface characterization can impact regional water budget calculations, which may in turn effect management decisions.

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