Supplement for

Assessing the resiliency of surface water and groundwater systems under groundwater pumping

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Text S1.

PIHM is a fully coupled, physically-based, spatially distributed hydrologic model. It simulates six hydrologic states (canopy interception storage, snow water equivalent, 2-D overland flow, soil moisture in the surface layer, unsaturated zone soil moisture and groundwater levels) on each unstructured element of the watershed using a semi-discrete finite-volume approach (Kumar, 2009; Kumar et al., 2009; Qu and Duffy, 2007). Figure S1 demonstrates discretization of a watershed into triangular and linear mesh elements in PIHM. Streamflow simulation in the model is based on a depth-averaged 1-D diffusive wave equation. Surface flow uses a depth-averaged 2-D diffusive wave approximation of the Saint Venant equations, and subsurface flow is based on depth-averaged, moving boundary approximation of Richards's equation (Kumar, 2009). The partial diferential equations (PDEs) governing each of these processes are locally reduced to ordinary differential equations (ODEs) by integration on a spatial unit element. The generic semi-discrete form of ODE that defines all the hydrologic processes incorporated in PIHM is represented as

$$A_i \frac{d\overline{\psi}}{dt} = \sum_j \vec{n}.\vec{G}_j A_{ij} + \sum_k \vec{n}.\vec{F}_k A_{ik} + \overline{S}_\psi V_i$$

where $\overline{\psi}(L)$ is average volumetric conservative scalar per unit planimetric control volume area A_i, $\overline{S}_\psi$ is average source/sink rate per unit control volume, and $\vec{G}$ are $\vec{F}$ vertical and lateral flux terms respectively, and $\vec{n}$ is normal vector to the surface *j* of the control volume *i*. Relevant ODEs for all the hydrologic processes in the PIHM control volume are shown in Table S1. For more details about the individual process equations, readers are referred to (Kumar, 2009). The model has been successfully applied at multiple scales and in diverse hydro-climatological settings in both North America and Europe (Chen et al., 2015; Shi et al., 2013; Wang et al., 2013; Yu et al., 2014).

Figure S1. Discretization of a watershed into triangular and linear mesh elements in PIHM. Interacting hydrologic processes are coupled within each control volume and between neighboring mesh elements (Bhatt et al., 2014).

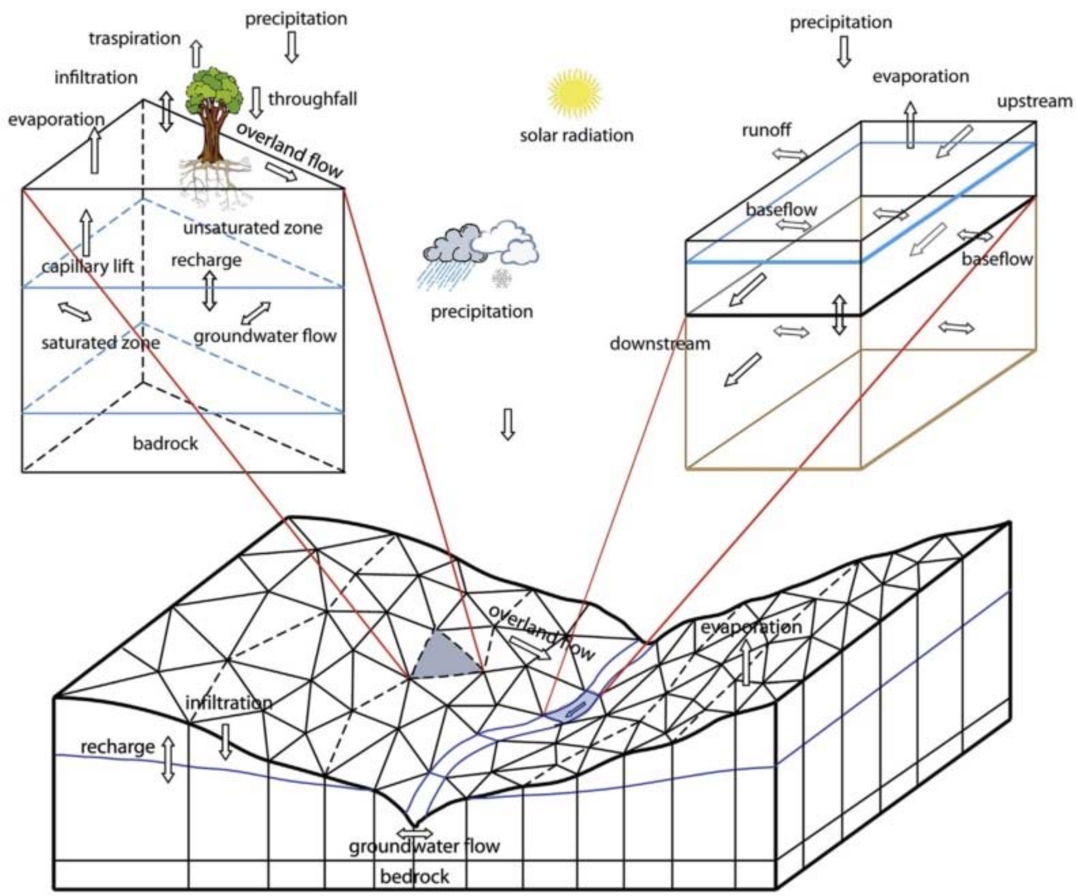

Table S1. Definition of coupling function and the lateral and vertical fluxes across the faces of a control volume. *i* and *j* are indices of neighboring control volumes and ‖ ‖ denotes conditional terms which exist only for the grids that are neighbor of a river element. Explanation of symbols is in Appendix S1. (Kumar, 2009)

Prismatic Element					
Control Volume	$\overline{\psi}$ (State)	$\vec{G}$ (Vertical Flux)	$\vec{F}$ (Horizontal Flux)	$\overline{S}_\psi$ (Source/ Sink)	$f[]$ (Coupling Flux Function)
Interception	ψ_0	$\vec{G}_3 - \vec{G}_4 - \vec{G}_5$	--	--	$\vec{G}_5 \equiv f[\psi_0]$
Snow	ψ_1	$\vec{G}_3 - \vec{G}_6$	--	--	$\vec{G}_6 \equiv f[\psi_1]$
Surface Flow	ψ_2	$\vec{G}_3 - \vec{G}_0 - \vec{G}_7 + \vec{G}_5 + \vec{G}_6$	$\vec{F}_0 + \lVert\vec{F}_1\rVert$	--	$\vec{F}_0 \equiv f[\psi_{2i}, \psi_{2j}], \vec{G}_0 \equiv f[\psi_2, \psi_3]$ $\vec{G}_5 \equiv f[\psi_0], \vec{G}_6 \equiv f[\psi_1], \lVert\vec{F}_1\rVert \equiv f[\psi_5, \psi_2]$
Unsaturated Zone	ψ_3	$\vec{G}_0 - \vec{G}_1 - \vec{G}_8 - \vec{G}_9$	--	--	$\vec{G}_0 \equiv f[\psi_2, \psi_3], \vec{G}_1 \equiv f[\psi_3, \psi_4]$ $\vec{G}_8 \equiv f[\psi_3], \vec{G}_9 \equiv f[\psi_3, \psi_0]$
Saturated Zone	ψ_4	$\vec{G}_1$	$\vec{F}_2 + \lVert\vec{F}_3\rVert + \lVert\vec{F}_4\rVert$	$-S_1$	$\vec{G}_1 \equiv f[\psi_3, \psi_4], \vec{F}_2 \equiv f[\psi_{4i}, \psi_{4j}]$ $\lVert\vec{F}_3\rVert \equiv f[\psi_5, \psi_4], \lVert\vec{F}_4\rVert \equiv f[\psi_6, \psi_4)]$
Linear Element					
Channel zone	ψ_5	$\vec{G}_3 - \vec{G}_2 - \vec{G}_7$	$\lVert\vec{F}_3\rVert + \vec{F}_5 + \lVert\vec{F}_1\rVert$	--	$\vec{G}_2 \equiv f[\psi_5, \psi_6], \vec{F}_5 \equiv f[\psi_{5i}, \psi_{5j}]$ $\lVert\vec{F}_1\rVert \equiv f[\psi_5, \psi_2], \lVert\vec{F}_3\rVert \equiv f[\psi_5, \psi_4]$
Sub-Channel Zone	ψ_6	$\vec{G}_2$	$\lVert\vec{F}_4\rVert$	--	$\lVert\vec{F}_4\rVert \equiv f[\psi_6, \psi_4], \vec{G}_2 \equiv f[\psi_5, \psi_6]$

$\vec{F}_0$: Lateral surface flux exchange (LT^{-1})

$\lVert\vec{F}_1\rVert$: Lateral surface flux exchange between overland flow and channel (LT^{-1})

$\vec{F}_2$: Lateral groundwater flux exchange (LT^{-1})

$\lVert\vec{F}_3\rVert$: Lateral flux exchange between channel and groundwater (LT^{-1})

$\lVert\vec{F}_4\rVert$: Lateral groundwater flux exchange between sub-channel and triangular watershed element (LT^{-1})

$\vec{F}_5$: Flux exchange between river reaches (LT^{-1})

$\vec{G}_0$: Infiltration/Exfiltration rate (LT^{-1})

$\vec{G}_1$: Recharge flux between unsaturated zone and groundwater (LT^{-1})

$\vec{G}_2$: Vertical flux exchange between channel bed and groundwater (LT^{-1})

$\vec{G}_3$: Net precipitation flux to the canopy/ground/river (LT^{-1})

$\vec{G}_4$: Evaporation from canopy (LT^{-1})

$\vec{G}_5$: Throughfall drainage (LT^{-1})

$\vec{G}_6$: Snowmelt (LT^{-1})

$\vec{G}_7$: Evaporation from overland flow(LT^{-1})

$\vec{G}_8$: Evaporation from upper soil layer (LT^{-1})

$\vec{G}_9$: Transpiration (LT^{-1})

S_1 : Sink flux from groundwater (LT^{-1})

Table S2. Summary of data requirements in each triangular mesh element in PIHM (Bhatt et al., 2014)

Data requirements	
Interception	**State variables**: initial interception storage **Fluxes**: precipitation, evaporation, throughfall **Physical parameters**: leaf area index (LAI), vegetation fraction, interception storage capacity
Snow melt	**State variables**: initial snow depth, snow density, snow cover temperature, snow water equivalent, soil temperature **Fluxes**: precipitation, melt rate **Physical parameters**: short wave radiation, long wave radiation, net solar radiation, air temperature, wind velocity, vapor pressure, melt factor
Infiltration/ Exfiltration	**State variables**: surface water, soil moisture, groundwater storage **Fluxes**: precipitation, net precipitation **Physical parameters**: soil hydraulic conductivity, macropore hydraulic conductivity, macropore area fraction, maximum infiltration capacity, soil porosity, infiltration depth
Evapotranspiration	**State variables**: interception storage, snow storage on canopy and ground, soil moisture, soil temperature, groundwater storage **Fluxes**: precipitation, throughfall, net precipitation, infiltration **Physical parameters**: net solar radiation, air temperature, air density, wind velocity, relative humidity, vapor pressure, LAI, vegetation fraction, displacement height, resistance length, albedo, rooting depth
Surface flow	**State variables**: initial storage, surface water head in land and river mesh elements, boundary conditions **Fluxes**: net precipitation, evaporation, infiltration/exfiltration **Physical parameters**: nodal elevations, roughness coefficient, discharge coefficient, vegetation fraction
Unsaturated	**State variables**: initial soil moisture, groundwater storage, boundary conditions **Fluxes**: infiltration, evaporation, transpiration, recharge **Physical parameters**: soil hydraulic conductivity, macropore hydraulic conductivity, macropore area fraction, van Genuchten soil hydraulic parameters, soil porosity
Groundwater	**State variables**: initial groundwater storage, groundwater head in the neighboring triangular mesh elements, boundary conditions **Fluxes**: recharge, evaporation, transpiration **Physical parameters**: hydrologic conductivity, porosity, nodal elevations, regolith thickness, van Genuchten hydraulic parameters, LAI, vegetation fraction
Streamflow	**State variables**: initial stream water storage, stream water storage upstream and downstream, surface and groundwater storage in neighboring triangular mesh elements, boundary conditions **Fluxes**: inflows from upstream segments, outflow to downstream segment, surface runoff from banks, baseflow from adjacent aquifers, seepage through stream bed. **Physical parameters**: elevation of the river nodes, depth and width of channel, roughness, hydraulic conductivity

Table S3. Autocorrelation table for annual precipitation and December to January precipitation.

Variable	Autocorrelation	*p*-value
Annual precipitation	-0.04	0.77
Dec. to Jan.	0.21	0.11

Both variables do not show significant autocorrelation.

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