

Physics-Based Simulations of the Impacts Forest Management Practices Have on Hydrologic Response

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Abstract

The impacts of logging on near-surface hydrologic response at the catchment and watershed scales were examined quantitatively using numerical simulation. The simulations were conducted with the Integrated Hydrology Model (InHM) for the North Fork of Caspar Creek Experimental Watershed, located near Fort Bragg, California. InHM is a comprehensive physics-based hydrologic-response model. The North Fork watershed (including 11 tributary catchments) is the site of an ongoing study monitoring the impacts of forest practices. InHM was parameterized and calibrated using existing data and new field measurements of soil-hydraulic properties. Continuous long-term simulations were conducted for three wet seasons: before logging, after logging, and after a period of regrowth. Simulated increases in flow and peak discharges were considerably higher after clearcut harvesting. Concept-development simulations of cumulative watershed effects (CWEs) examined potential impacts of alternative timber harvest levels and methods relative to those that occurred in the North Fork watershed. Results from these simulations show that the increases in the simulated discharge after clearcutting were significant for the catchment and watershed scales and that relatively small changes in soil-hydraulic properties produced substantial changes in hydrologic response. The simulations in this study illustrate that timber harvesting can alter the streamflow generation mechanisms and patterns within a catchment.

Key words: cumulative watershed effects, forest hydrology, hydrologic-response, InHM

Introduction

The impacts of deforestation on the amount and timing of streamflow has been a key environmental concern for centuries (see Andreassian 2004). Removal of vegetation in a forested ecosystem decreases evapotranspiration and rainfall interception, leading to increased discharge and soil-water content (see reviews by Andreassian 2004, Bosch and Hewlett 1982, Brown et al. 2005, Jones and Grant 1996, Jones and Post 2004, Jones et al. 2001). Decreased interception and evapotranspiration caused by timber harvest can lead to higher peak flows, higher stormflow discharge depths, and higher subsurface pore pressures which can cause greater suspended sediment transport, increased downstream flooding, and greater likelihood of landsliding, respectively.

Paired watershed studies to date have mostly provided empirical analysis of the impacts of timber harvest on annual water discharge, peak flows, and sediment production. The studies of Andreassian (2004), Bosch and Hewlett (1982), Bowling et al. (2000), Brown et al. (2005), Burges (2003), Jones and Grant (1996), Jones et al. (2001), and Thomas and Megahan (1998) lead to the following generalizations: (i)

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streamflow responses to deforestation and regrowth are variable and dependent upon climate; (ii) smaller catchments have much more variability in response to vegetation change; (iii) if the average response is not captured (stationary relationship), then the monitored impacts may not be interpreted correctly; and (iv) observed data records can be quite poor. The observed changes in watershed response can be examined, but only through the limited perspective of the climate that occurs during the monitoring periods before and after logging. When the largest storm events are missing from the data set, the ability to forecast the impacts from extreme events is compromised. Simulation can provide answers to some questions, especially when the observed data are poor or site monitoring is limited (Alila and Beckers 2001). For example, physics-based simulation conducted in a what-if concept-development mode can provide useful insights for land managers concerned with the impact of future timber harvest/land management scenarios (Dunne, 2001, Dunne et al. 2001, Loague et al. 2006, Loague and Ebel in press).

This study examined the impacts of alternative forest management practices on near-surface hydrologic response using comprehensive physics-based simulation. The effort reported here employed the Integrated Hydrology Model (InHM) for simulations of the North Fork of Caspar Creek Experimental Watershed, located near Fort Bragg, California. The Integrated Hydrology Model (InHM) was developed by VanderKwaak (1999) in the spirit of the Freeze and Harlan (1969) blueprint. InHM was designed to quantitatively estimate in a fully-coupled approach, 3D variably saturated flow and solute transport in porous media, 3D variably saturated flow and solute transport in macropores /fractures, and 2D flow and solute transport over the surface and in open channels. The fundamental and innovative characteristics of the deterministic-conceptual InHM, including no *a priori* assumption for a specific hydrologic-response mechanism, are discussed by Vanderkwaak (1999) and Vanderkwaak and Loague (2001). Several successful applications of InHM have been reported in the last decade (for example Ebel et al. 2007, 2008; Heppner and Loague, 2008, Heppner et al. 2007, Mirus et al. 2007, Ran et al. 2011, and VanderKwaak and Loague 2001).

The Caspar Creek Experimental Watershed (see *fig. 1*) is the site of a long-term monitoring study of the impacts of timber harvest. In 1962 the California Department of Forestry and Fire Protection and the U.S. Department of Agriculture, Forest Service Pacific Southwest Research Station, Redwood Sciences Laboratory began a paired watershed study using two similarly sized basins within the headwaters of Caspar Creek watershed (see Ziemer 1998). The North and South Fork Basins are shown in *fig. 1*. The second phase of the Caspar Creek study, beginning in 1985, was a multiple paired-catchment study in the North Fork of Caspar Creek that evaluated the impacts of the then state-of-the art timber harvest practices (Lewis 1998). *Figure 2* shows a selection of the data collected during the study and the gaging stations on the 11 North Fork tributary catchments and on the main channel that monitored streamflow discharge from 1986 through 1995.

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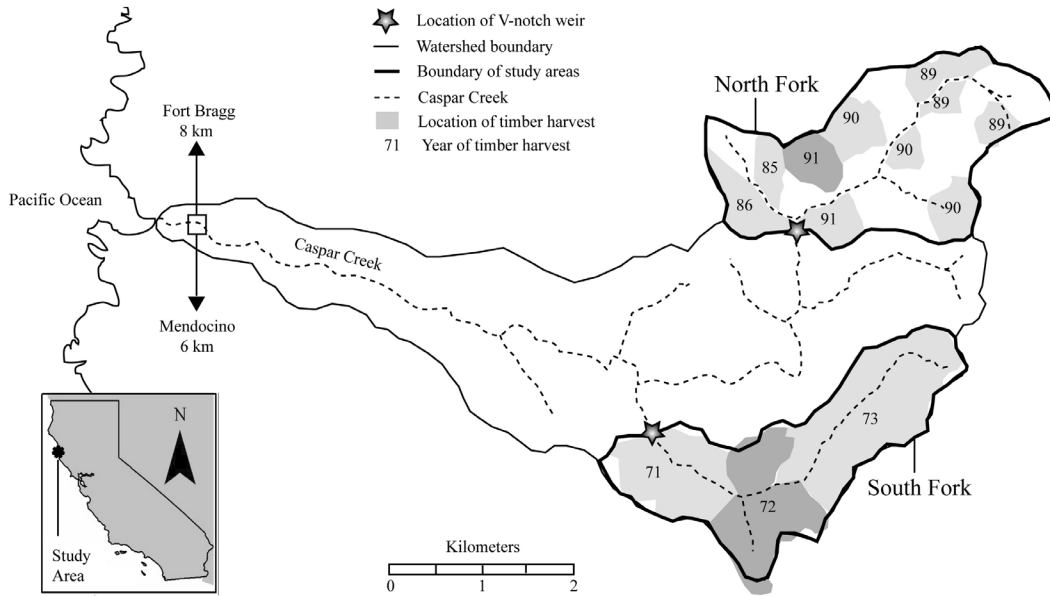


Figure 1—The Caspar Creek Experimental Watershed located within the Jackson State Demonstration Forest in coastal Mendocino County, California (after Ziemer 1998).

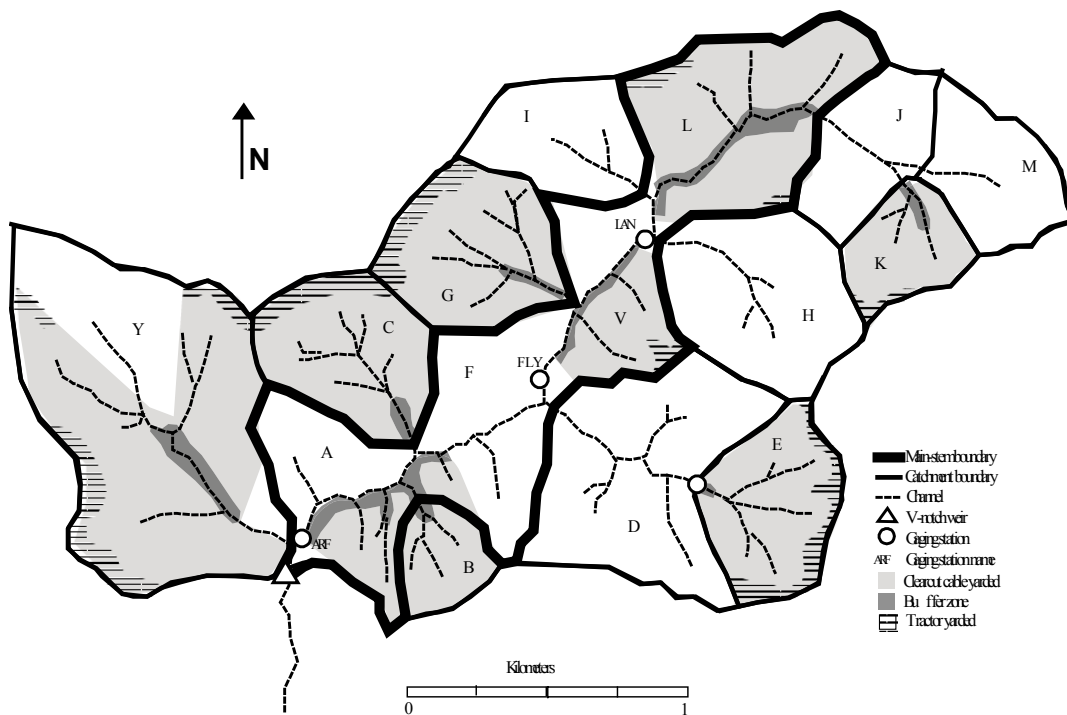


Figure 2—Outline of the main-channel boundary-value problem on a map of the North Fork of Caspar Creek. Management history, main-stem gaging stations, and North Fork catchments are identified.

Catchment- and watershed-scale simulations

Hydrologic-response simulations designed to investigate the impacts of timber harvest were conducted with InHM for the 11 North Fork Caspar Creek tributary catchments and subsequently for the entire North Fork watershed. Simulations were conducted for the wet seasons of 3 water years: (i) before logging – water year 1989 (WY89), (ii) after logging – water year 1992 (WY92), and (iii) after a period of regrowth – water year 1995 (WY95). The long-term hydrologic-response simulations were conducted for the 5 to 6 month rainy season that included the majority of the rainfall during the water year. The hydrologic response for each of the Caspar Creek catchments and the entire watershed was examined before and after logging. Changes in hydrologic response relative to forest management (for example, clearcutting) were assessed by comparison of the results from different simulation scenarios.

Boundary value problems

Thirty-three boundary-value problems (BVPs) were set up for catchment-scale simulations and three BVPs were set up for the watershed-scale simulations. Each BVP started with a 3D finite-element mesh for the area of interest. For the watershed-scale simulations, a main-channel finite-element mesh included all areas of the North Fork watershed not considered by the catchment-scale simulations. The mesh for the M catchment BVP is shown in *fig. 3*; the outline of the surface of the main-channel BVP is shown in *fig. 2*. For each BVP the bottom, upstream, and lateral catchment boundaries were impermeable. The surface boundary for each mesh was a specified flux (potential evapotranspiration and throughfall). The downstream boundaries for each BVP were a local head for the subsurface and a critical depth for the surface. The local head boundary condition is described by Heppner et al. (2007). For this study, the local head values were chosen to be water levels at downstream gaging stations for the catchment-scale simulations and the elevation of the confluence of the North Fork with the Middle Fork of Caspar Creek for the watershed-scale simulations. The x-y node spacing on the surface varied between 2 to 10 m at the channel and 24 to 60 m at the watershed boundaries with an average of 2,157 surface nodes. The surface of the main-channel mesh was made with an average x-y node spacing of 12 m for the channel and 40 to 55 m for the watershed boundaries, with a total of 3,522 surface nodes. For all meshes, the layer spacing in the vertical direction was 0.05 m for the near-surface layer, grading to 5 m at the bottom of the mesh.

Soil properties

To parameterize and calibrate InHM for the North Fork BVPs for this study, historical information was obtained and new field measurements of soil properties were made for the North Fork of the Caspar Creek watershed. The new information was needed to specify soil-hydraulic properties within the Caspar Creek flow system. The measurements made for this study included saturated hydraulic conductivity, soil texture, and soil-water retention. *Table 1* presents the range of soil hydraulic properties used in the simulations.

Climate and vegetation

The surface boundary conditions for the InHM simulations were estimated with BROOK90 (Federer 1995). BROOK90 is a process-based model designed to estimate evapotranspiration and soil-water movement in one dimension. BROOK90 solves the Shuttleworth and Wallace (1985) version of the Penman-Monteith equation to

Table 1—Soil-hydraulic properties for the catchment boundary-value problems for the Caspar Creek watershed.

Range of values			Base case			van Genuchten parameters	
Depth (m)	Nodal spacing (m)	Saturated hydraulic conductivity (ms ⁻¹)	Porosity (-)	Saturated hydraulic conductivity (ms ⁻¹)	Porosity (-)	α (m ⁻¹)	n (-)
0 - 0.15 ^a	0.05	3.5×10^{-2} - 1.1×10^{-1}	0.40 - 0.57	1.1×10^{-1}	0.55	30.00	1.57
0.15 - 0.3 ^b	0.05	2.2×10^{-5} - 3.0×10^{-4}	0.45 - 0.47	2.2×10^{-5}	0.45	4.24	1.82
0.3 - 1.5 ^c	0.05 - 0.10	2.6×10^{-6} - 4.0×10^{-6}	0.42	2.6×10^{-6}	0.42	8.51	1.58
3.0 - 55.0 ^d	0.5 - 5.0	2.0×10^{-7}	0.10	2.0×10^{-7}	0.10	4.30	1.20

^a soil layer 1; ^b soil layer 2; ^c soil layer 3; ^d bedrock

Table 2—Vegetation properties for the BROOK90 simulations of the Caspar Creek watershed.

Vegetation properties		Second growth WY89	Clearcut WY92	Regrowth WY95	Source
Leaf area index (-)		10	0	1	Reid and Lewis (2006)
Tree height (m)		60	0	1.5	Noss (2000)
Leaf width (m)		0.004	0	0.004	Fedderer (1995)
Maximum leaf conductance (ms ⁻¹)		0.0053	0	0.003	Korner et al. (1979), Korner (1994)
Maximum plant conductance (ms ⁻¹)		30	0	5	Fedderer (1995)
Fraction of plant resistance in xylem (%)		25	0	7	Phillips et al. (2003)
Minimum plant leaf water potential (Mpa)		-2	0	-0.5	Koch et al. (2004), Woodruff et al. (2004)
Albedo (-)		0.14	0.15	0.15	Fedderer (1995)

determine the potential evapotranspiration from a single layer canopy and the soil surface based on climate and vegetation information from Caspar Creek. BROOK90 also estimates net throughfall, after rainfall interception and evaporation using a simple water balance method. The reader is referred to Federer (1995) for a complete description of BROOK90.

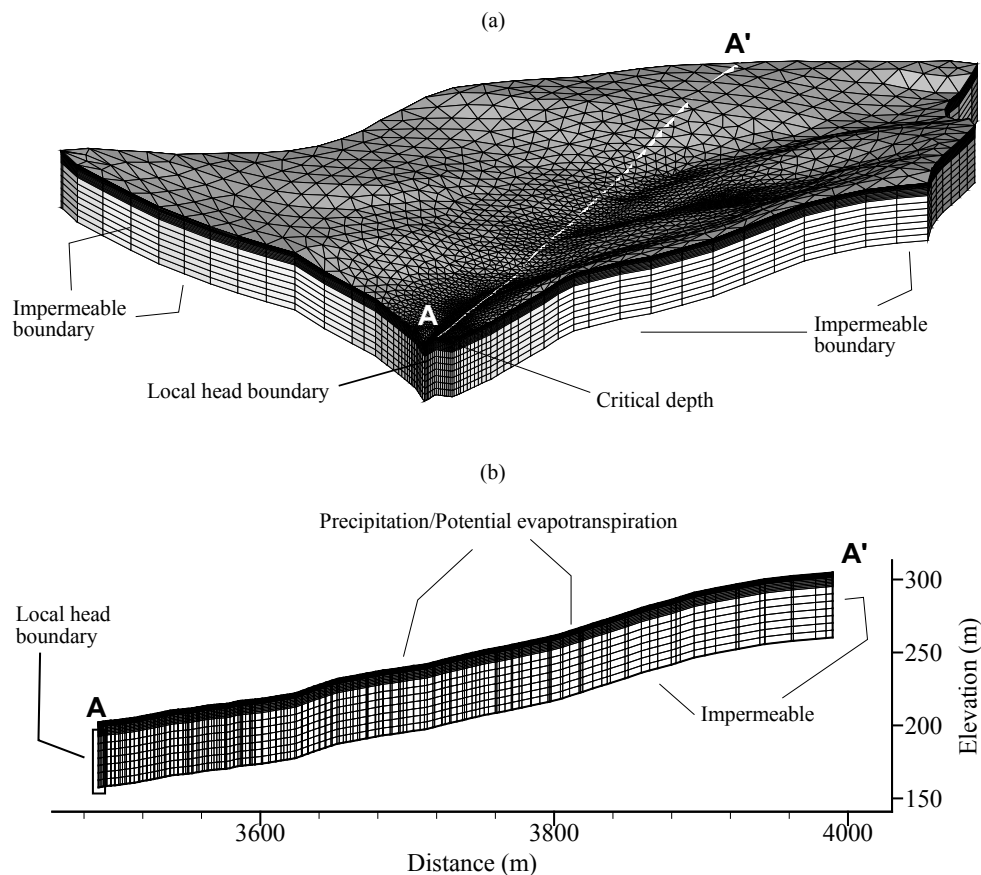


Figure 3—M catchment boundary-value problem used for simulations of hydrologic response and management impacts in the Caspar Creek watershed. (a) 3D mesh and boundary conditions. (b) Vertical cross-section taken from A-A' in (a) showing the mesh and boundary conditions with no vertical exaggeration.

The climate forcing data input to BROOK90 measured at Caspar Creek were (i) precipitation at five minute intervals, (ii) daily maximum and minimum air temperature, and (iii) daily solar radiation. Vapor pressure was approximated with BROOK90 using an algorithm developed by Murray (1967). Daily wind speed for the Caspar Creek watershed was derived from the NCEP/NCAR Reanalysis Data (Kalnay et al. 1996). Monthly average values of air temperature or solar radiation (calculated from 1986 to 1996) were substituted for missing measurements. When available, the vegetation properties were chosen based on site-specific information from Caspar Creek. *Table 2* provides the vegetation property values used in the BROOK90 simulations. Throughfall and potential evapotranspiration estimates from BROOK90, in 5 minute intervals, were used in the InHM simulations. The

interception estimates from BROOK90 were calibrated against measurements from Caspar Creek (Reid and Lewis 2007).

Simulation procedure

The long-term simulations were conducted for the 5 to 6 month rainy season that included the majority of the rainfall during the entire water year. Initial conditions for each BVP were estimated (by simulation) before each rainy season. Then there was some calibration of InHM before the final hydrologic response simulations for the Caspar Creek catchments. For the watershed-scale simulations, the results from the long-term catchment-scale simulations were applied as input to the main-channel simulations for all 3 water years. The simulated hydrologic response results for the Caspar Creek catchments and the entire North Fork watershed were compared with observed data to (i) better understand hydrologic response related to the impacts of logging and (ii) evaluate the performance of InHM.

Model calibration

The M catchment had the most complete observed discharge record for the water years focused on in this study and was, therefore, used to parameterize and calibrate InHM. The M catchment simulation was calibrated to observed discharge data. The calibration was initially done for the first large storm (event 1) of WY89 and then for the entire WY89 simulation period. The InHM-simulated hydrologic response for the M catchment reproduced the transient observed discharge record to an acceptable level. Therefore, the M catchment calibration was used to parameterize all of the other catchments for this study. No calibration was done for the main-channel watershed-scale simulation. Further details of the calibration can be found in Carr (2006).

Management impact simulations

To simulate the impacts of forest harvesting at Caspar Creek, the BROOK90 vegetation properties were changed to represent clearcutting (WY92) and regrowth (WY95). The management impact simulations represented timber harvest patterns that occurred in the North Fork of Caspar Creek before WY92 (*fig. 1*). All of the BROOK90 parameter values for the three simulation periods are shown in *table 2*. After clearcutting, the leaf area index was set to zero in the catchments that were clearcut and was set to five for the main-channel simulation that was partially cut. As a result, there was no interception in the clearcut areas; and all of the rainfall was assumed to reach the ground as throughfall. Due to lack of field information, the soil properties were unchanged in the InHM BVPs after logging. It should be pointed out, however, that the cable yarding method of timber harvest is known to be fairly non-intrusive to soils (Laffan et al. 2001, Swank and Elliot 2001), so the assumption of minimal soil disturbance is a valid one.

Results

Model performance

Simulated streamflow was compared with observations for nine of the 11 catchments and for the watershed-scale results. Streamflow data are available in ten-minute intervals for all catchments, providing a good data set to compare to simulation results. However, upon close inspection one finds that much of this data was interpolated from sparse measurements. In some cases, actual streamflow

measurements were much more infrequent than the ten-minute interval. In the early years, the data resolution was acceptable during most large storms but was sparse or absent during low-flow periods. The data quality improved in later years. Model performance was often poor during periods of poor data resolution. InHM performed best during the wetter periods for this study. Specifically, the model performed better for big storms and best for large events with high antecedent moisture content. It should be noted that WY89, WY92, and WY95 had average, below average, and above average annual rainfall. The performance of InHM was best for WY95, the wettest year and the year with the most complete observed data. A full discussion of model performance for this study can be found in Carr (2006).

Management impacts on hydrologic response

The increases in throughfall and decreases in potential evapotranspiration caused by timber harvesting had significant impacts on the simulated hydrologic response for the Caspar Creek watershed. Downstream measurement points captured the response in watersheds with a portion of the upstream area clearcut (partial clearcut) and the entire area clearcut (full clearcut). There was a large increase in simulated discharge depths during WY92 and WY95 after partial and full clearcut harvesting of the drainage area. The simulated increases in discharge depth after logging for WY92 and WY95, compared to the second growth response are shown in *table 3*. The most significant factor impacting the discharge of the catchments after logging was the increase in throughfall. Increases in throughfall result from reduced interception and the loss of evaporation from intercepted water.

Table 3—Percent increases in simulated discharge depth when compared to the second growth response.

	WY92		WY95	
	Catchment	Watershed	Catchment	Watershed
Partial clearcut	127	121	51	54
Full clearcut	204	NA	105	NA

Cumulative watershed effects simulations

The what-if concept-development simulations performed for this study examined the potential impacts of alternate timber harvest levels and methods relative to those that occurred between 1989 and 1991 at the North Fork of Caspar Creek watershed. Both the catchment- and watershed-scale hydrologic responses to different methods and magnitudes of timber harvesting were considered.

The CWEs simulations were carried out in three parts: (i) the hydrologic response changes resulting from a clearcut vegetation scenario were examined for the unharvested Caspar Creek catchments; (ii) the impacts of 100 percent clearcut timber harvest were examined for the entire North Fork watershed; and (iii) the impacts of soil compaction due to logging with skidders on seasonal hydrologic response and on the hydrologic response to a large rainfall event were examined for the nested catchment group K, M, and J. Using the same catchment and the same climate, the changes in hydrologic response as a result of forest clearing and alternate forest practices were directly evaluated against the hydrologic response with a second growth vegetation scenario.

The simulated peak discharges for the largest storms increased approximately 40 percent at both the catchment and watershed scales as a result of 100 percent clearcut timber harvesting. In addition to the change in the water balance caused by a decrease in interception and evapotranspiration after logging, soil compaction directly impacted the overall hydrologic response. The simulated peak discharges for the largest storm increased an average of 63 percent for the K, M and J catchments (with changed soil hydraulic properties), illustrating this impact. The significant increases in simulated discharge in this study could cause considerable increases in the sediment carrying capacity.

This research represents a first step towards using comprehensive physics-based simulation to investigate the impacts of timber harvest. The work conducted for this study sets the stage for unraveling the complex processes that lead to hydrologically-driven cumulative watershed effects (CWEs) such as flooding, slope-stability, sediment transport, and their impacts on, for example, salmon habitat health. Changes in watershed function will most certainly accompany logging activities, but thresholds for adverse significant changes should, ideally, be decided upon before management actions so that adverse impacts can be prevented. By defining thresholds of, for example, maximum peak discharges, significant adverse CWEs can be avoided by proper management. The simulation-based approach presented here could/should be extended and employed to identify strategies for preventing/reducing adverse CWEs.

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