Water Quality Impacts of the Mountain Pine Beetle Infestation in the Rocky Mountain West

John E. McCray, PhD
Lindsay A. Bearup, PhD
Nicolas Rodriquez

Hydrologic Science and Engineering Program
Civil and Environmental Engineering
Colorado School of Mines

November 2014

Completion Report No. 228

Colorado Water Institute

Colorado State University

Acknowledgements

The authors would like to thank David Clow and his team at the USGS Colorado Water Science Center for field and research support and the National Science Foundation which provided additional financial support through the WSC project entitled “Water quality and supply impacts from climate-induced insect tree mortality and resource management in the Rocky Mountain West”.

This report was financed in part by the U.S. Department of the Interior, Geological Survey, through the Colorado Water Institute. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Additional copies of this report can be obtained from the Colorado Water Institute, E102 Engineering Building, Colorado State University, Fort Collins, CO 80523-1033 970-491-6308 or email: cwi@colostate.edu, or downloaded as a PDF file from http://www.cwi.colostate.edu.

Abstract:
The Mountain Pine Beetle (MPB) is the primary cause of insect-induced mortality in pine forests in western North America where some lodgepole forests have experienced more than 90% tree mortality. The implications of MPB infestation on water resources are particularly important in the Rocky Mountains, which serve as the source-water region for more than 60 million people. Two important potential watershed impacts are changes in the hydrologic cycle and water quality. While impacts on the hydrologic cycle have received some attention, the interconnection between these changes and the impacts of the widespread infestation on water quality are not well understood. This study uses a combination of field sample analysis and modeling based in Rocky Mountain National Park to address two potential MPB-driven effects on water quality: increased metal concentrations with ecotoxicological and human health ramifications and the changes in source water contributions to streamflow with possible implications for metal and carbon transport to downstream drinking water supplies. Previous work from the research team at Colorado School of Mines identified increased potential for disinfection byproduct formation at water treatment plants receiving water from heavily MPB-killed forests. These increases exhibited surprising seasonal trends that suggest that the transport of carbon to streams, and thus the flowpaths of water, may be different in MPB-killed forests.

The first question was investigated by sequentially extracting trace metals from soils under trees with vary levels of impact, and using geochemical models to identify important process-level drivers of changes in metal mobility. Laboratory results identify redistribution of metals in soils under beetle-killed trees with greater mobilization potential for cadmium, and increases in zinc and copper, likely related to fluxes from needle leachate. Results also align with geochemical models and identify changes in organic carbon inputs as the primary driver of increased metal mobility. The second questions was addressed using a chemical hydrograph separation approach to partition streamwater into the fractions derived from groundwater, rain, and snow. Results demonstrate that fractional late-summer groundwater contributions from impacted watersheds are approximately 30 ± 15% greater after infestation and when compared with a neighboring watershed that experienced earlier and less-severe attack. Water budget analysis compared to published sap flux and remotely sensing studies reveals that this change is consistent with expected increases in groundwater from loss of transpiration across the watershed. A predictive statistical model (calibrated to observations within and around Rocky Mountain National Park) suggests that dissolved organic carbon concentrations in streams will be higher in areas where tree mortality is higher. Although, a strong statistical correlation was not found with the method used. Ultimately, this study identifies process-level hydrologic and biogeochemical changes that improve understanding of the vulnerability of Rocky Mountain water supplies to MPB outbreaks.

Keywords: Mountain Pine Beetle, Rocky Mountain National Park, Trace Metals, Water Quality, Streamflow Partitioning

Table of Contents

List of Figures & Tables

Justification of Work Performed

MPB infestations induce significant changes in forest canopy, impacting many aspects of the local water and energy cycle (Mikkelson et al. 2013, Figure 1), including canopy interception of precipitation and solar radiation (Pugh and Gordon 2013; Winkler et al. 2014; Reed et al. 2014) and evapotranspiration (Biederman et al. 2014; Vanderhoof and Williams 2015; Hubbard et al. 2013; Maness et al. 2013). As a combined result of these changes, annual water yields and peak flows have been shown to increase following insect infestation (Bethlahmy 1974; Bethlahmy 1975; Potts 1984); however, recent efforts in Colorado have not been able to adequately determine if peak flows have increased. Decreases in forest canopy may also produce offsetting changes to total evapotranspiration, by reducing soil water/groundwater uptake by plants (Hubbard et al. 2013) but increasing energy available for ablation and ground evaporation (Reed et al. 2014; Pugh and Gordon 2013), resulting in complex changes in water availability that may mask bulk changes in peak streamflow but may ultimately result in differences in water table depths and altered streamflow generation processes in infested watersheds. In addition to changes in watershed hydrology and water availability, large-scale die-off from MPB infestation has the potential to significantly alter watershed biogeochemistry and solute transport, with potential impacts on downstream water quality. MPB tree-mortality may cause (1) increased dissolved organic matter (DOM), (2) increased dissolved organic carbon (DOC), (3) increased nitrification resulting from increased tree stress and litter fall, and (4) reduced pH (as summarized in the literature review published with support from this project; see Mikkelson et al. 2013).

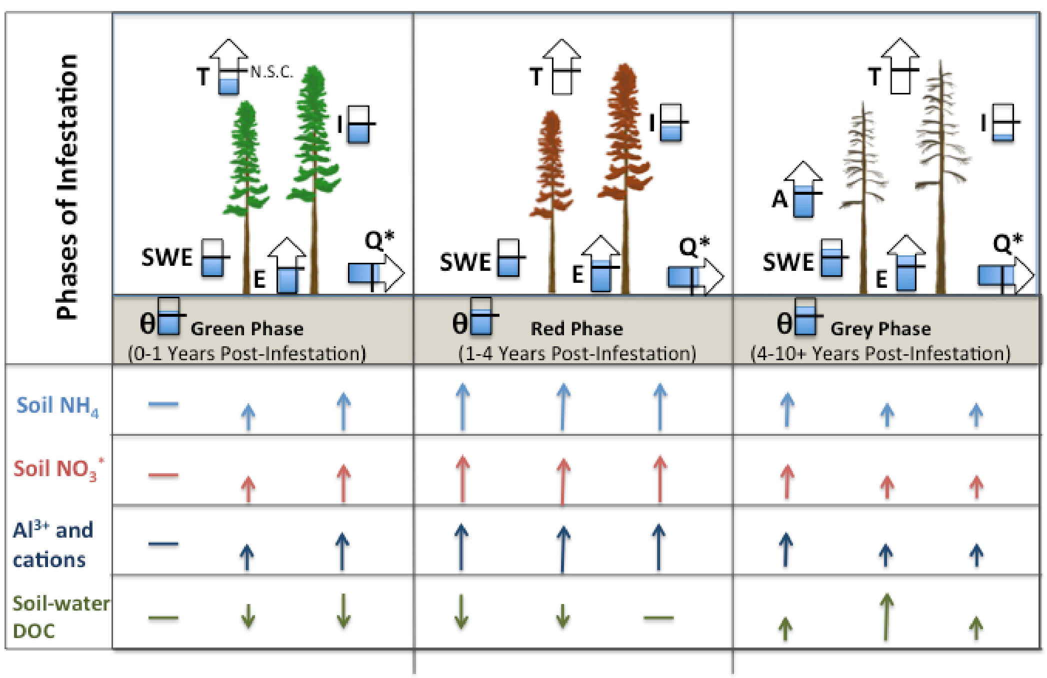


FIGURE 1. Schematic of hydrologic and biogeochemical changes resulting from MPB-induced tree death. Reproduced from (Mikkelson et al. 2013a).

The short- and long-term effects of MPB-induced tree mortality on transport processes and water quality could be profound. Pine needles and twigs, which are relatively rich in nitrogen (N), will decay quickly (Pearson et al. 1987). Branches and trunks, which have much lower concentrations of N, but substantial carbon (C), will decay more slowly (Pearson et al. 1987). Much of the N and C released will accumulate in litter and soil, or be taken up by new forest growth (Rhoades et al. 2013). An unknown fraction of N and C will leach into soil solution or groundwater, and may subsequently be transported to surface water (Clow et al. 2011). DOM quantity and quality are important in the environment, as DOM influences metal speciation and transport and is an important precursor in the formation of organic disinfection byproducts (DBPs). An increased pulse of needle litter also occurs in infested stands as trees are killed. As a result, increased litter depth may increase DOM concentrations in leachate from the forest floor, especially during spring runoff, releasing plant and soil residues into surface waters. The focus of this study is to address the overarching research question: *Can the MPB outbreaks significantly affect water quality, resulting in increased concentrations of heavy metals, and increased potential for the formation of disinfection byproducts (DBP's)?*

Under this general goal, the project identified three more specific objectives. The hypothesis and associated achievements for each objective are as follows:

Hypothesis 1: *DBP concentrations in water treatment plant samples may be correlated with forest, hydrologic, geographic or geologic factors that represent the watershed's vulnerability (or resiliency) to MPB impacts.*

Achievements: This study addresses this goal from a transport perspective, using field studies of streamwater source allocations and integrated models of hydrologic response to insect infestation. The field study provided needed insight into how water is getting to the stream, after the findings from Objective 2 suggested that differences in sources of carbon may be influencing DBP formation. The modeling approach provided additional comparison across variables that are inherently challenging to control in the field, such as land cover change, spatial and temporal variability in climate, and geographic or geologic differences between watersheds. The field portion of this effort is published in (Bearup et al. 2014a), and the preliminary modeling results are currently under review for publication (Bearup et al. *in review*).

Rigorous geospatial statistical studies were also performed to better understand the primary variables and input parameters that are most important to include in a watershed-scale hydro-chemical model wherein carbon cycling is a primary component. These studies are the first step toward developing watershed and regional scale models that can efficiently simulate current impacts and predict future impacts of forest insect infestations on the carbon cycle in streams and groundwater, and eventually other important components of the biogeochemical cycle (i.e., N, P, O), as well as contaminants of interest (e.g., metals). In addition to an in depth literature review, a we performed a statistical comparison of different statistical methods, including ordinary kriging, universal kriging, and top-kriging, for estimation of dissolved organic carbon (DOC) in streams using MPB infestations, elevation, slope, land cover, and precipitation. This anlaysis builds toward a more complete study that identifies covariates that affect the carbon cycle in MPB affected forests in western Colorado using a simultaneous autoregressive (SAR) model, currently in progress.

Hypothesis 2: *Surface waters associated with MPB impacted lodgepole pines will see an increase in TOC and DBP formation potential that corresponds with the degree of infestation and tree mortality.*

Achievements: Mikkelson et al. (2013b) found higher TOC and DBP formation potential in source waters reaching water treatment plants from watersheds with more MPB-killed area. The authors also identified a disconnect between the timing of peak TOC and increased DBP formation. This finding generated an additional hypothesis that water was moving through these watersheds differently, resulting in altered carbon sources and transport and shifted the focus toward the hydrologic drivers and studies descrbied under Hypothesis 1. Ongoing work is looking at other watershed properties that may contribute to increased TOC fluxes and DBP formation potential.

Hypothesis 3: *Soils associated with MPB-impacted trees will have an increased potential for metal leaching (i.e., Mn, Cu, Zn) and release of humic / fulvic NOM than will soils associated with healthy lodgepole pines.*

Achievements: This objective was addressed using a field-based soil sampling campaign in Rocky Mountain National Park and lab analysis of collected samples to understand the potential for increases in metal mobility associated with MPB-induced tree death. The field analyses were also complimented by geochemical modeling analysis that identified organic matter as the soil component controlling metal mobility changes. The results of this study were published in Bearup et al. (2014b). Column studies provide additional insight into the potential for metal leaching and transport in soils under beetle-killed trees (Mikkelson et al. 2014).

Review of Methods Used

Here, we used four distinct methods to address the primary research questions of this study. These methods include a combination of field (Bearup et al. 2014a), lab (Bearup et al. 2014b), modeling (Bearup et al. *in review*), and statistical approaches and are summarized below. The following presentation of methods 1-3 is modified from the primary corresponding reference provided with each study heading. See these references for additional methodological details.

1. **Hydrological effects of forest transpiration loss in bark beetle-impacted watersheds** (Bearup et al. 2014a)

In the first portion of this work, contributions to streamflow are analyzed through time and space using an end-member mixing approach to hydrograph separation. As described in Bearup et al. 2014a), we collected rain, snow, and groundwater samples during the late summer of 2012 throughout two watersheds Rocky Mountain National Park: Big Thompson and North Inlet. These samples complement ongoing USGS stream water sampling efforts under the supervision of David Clow. Spatial comparisons between the two watersheds provide information on the response of stream contributions based on the timing and extent of outbreak. Temporally, the data collected in this study were compared with hydrograph separations performed using data from a previous study in the Big Thompson watershed in 1994, before infestation. Three-component hydrograph separation using ∂^{18}O compositions and electrical conductivity was applied to determine specific streamflow contributions. The relevant set of equations used to describe end-member contributions to streamflow is:

$$Q_s \times EC_s = Q_r \times EC_r + Q_n \times EC_n + Q_g \times EC_g$$
$$Q_s \times \partial^{18}O_s = Q_r \times \partial^{18}O_r + Q_n \times \partial^{18}O_n + Q_g \times \partial^{18}O_g$$
$$Q_s = Q_r + Q_n + Q_g$$

where Q denotes flow, EC is electrical conductivity (μScm−1), $\partial^{18}O$ is stable isotope composition (‰), and the subscripts s, r, n and g, represent stream, rain, snow and groundwater respectively. Using the mass balance based on flow, the equations can be rearranged to calculate the fraction of stream water that each end-member contributes to streamflow.

Precipitation isotope samples were collected in polycarbonate rain gauges, using mineral oil to prevent evaporation. Sampling occurred weekly to biweekly from July to October, depending on rain events. Snow isotopic compositions were obtained from a snow pit sampled near peak snow accumulation in early April 2012. Bulk snow chemistry was provided at the site through the US Geological Survey (USGS) Rocky Mountain Regional Snowpack Chemistry Monitoring. Groundwater end-members were characterized using shallow (~1 m deep) groundwater wells from a wetland and riparian monitoring study that maintained flow through the season. Samples were collected approximately biweekly from July to the end of October. Stream water isotope and chemistry samples were collected weekly to biweekly and were analyzed using standard USGS methods. Samples from the 2012 season were analyzed for ∂^{18}O at the Colorado School of Mines stable isotope laboratory. Stream and snow chemistry were analyzed at the USGS research laboratory in Boulder, Colorado. Shallow groundwater chemistry was analyzed at Colorado School of Mines in Golden, Colorado. Precipitation chemistry was available through the National Atmospheric Deposition Program and National Trends Network using weekly averaged data at the Beaver Meadows site.

Full end-member mixing analysis (EMMA) confirmed that three end-members are appropriate to describe the variability in the 2012 Big Thompson stream water chemistry. Uncertainty analysis was performed using estimates of uncertainty and variability for each tracer/endmember combination and propagating that error through the hydrograph separation equations using first-order Taylor expansion (Supplementary Section 4.3).The differences in the subsurface-derived fraction from the spatial and temporal analyses were multiplied by total streamflow measured at the time of sampling to estimate an increased groundwater flow to the stream. The change in flow was distributed over the MPB-impacted area in the Big Thompson watershed to estimate a flux. The flux was used to compare the increased groundwater contributions to traditional estimates of evapotranspiration.

2. **Hillslope response to land-cover change: an integrated model of end-member mixing (Bearup et al. *in review*)**

In this work, we develop a modeling approach and apply it to numerical experiments of a Rocky Mountain hillslope to investigate flow partitioning and transit times. Travel time is defined herein as the time taken by a particle to reach a given point in the domain or for this work, the age at the base of the hillslope. Fundamental to the utility of this modeling approach is the use of particles to track sources of outflow through the hillslope. Particle tracking allows a more direct look into complex systems by using the pressure fields from a hydrologic model to drive particle tracking simulations through both the surface and subsurface systems [*de Rooij et al.*, 2013]. Lagrangian particle tracking methods follow a parcel of water through a given pressure field. This parcel, or particle, can be initialized in a known location in the domain to identify water from different sources or tracked backward from a point in the domain to determine travel times. In this way, event and pre-event water can be separated, in the same manner that isotopes and other tracers are used to track these signals in real systems (see *Sueker et al.*, [2000] for a field example and schematic depicting the mixing of event and pre-event waters in a snow-dominated system). Ultimately, this method explicitly models traditionally field based end-member mixing analysis (EMMA), by tracing particles through the domain, rather than using point-measurements of water chemistry and isotopes to fingerprint water sources.

These experiments are designed to test two important conceptual models. The first conceptual model describes the mixed nature of water of different sources and ages in hillslope outflows, focusing on the role of groundwater. Specifically, contributions from rain and snow that infiltrate to the subsurface mix with groundwater that contains a mix of surface contributions that happened prior to the start of observation or simulation. These annual inputs, often called “new” or “event” water, would then mix with the “old” or “pre-event” groundwater and continue to cycle as this groundwater exits the system and new surface inputs replace it. Figure 1 illustrates this mixture of water from different sources using particles of different colors to represent different inputs to the hillslope. The second conceptual model describes the hydrologic response to tree death. Field-based evidence of altered contributions to streamflow with land-cover change motivates a conceptual model of altered flow paths and mixing processes resulting from the differences in land-surface processes. In particular, as trees die and transpiration ceases, the availability of water in the subsurface increases, whereas when canopy cover is lost and ground evaporation increases, the potential for infiltration and surface water flow decreases. These primary hydrologic changes with tree death result in a conceptual model that motivates hypotheses of higher water tables, resultantly shorter vadose zone travel times, and impacts to the mix of sources and age distributions in nearby streams.

The first set of experiments is run at steady state to understand bulk differences in hillslope behavior with changes in water inputs (precipitation minus evaporation), representative of living trees and beetle killed trees over longer timescales. These steady state simulations provide an initial test of the approach and conceptual models using a simple description of a hillslope that would apply if the annual forcings were the same and snowmelt contributions were instantaneous. The second set of experiments looks deeper into seasonal and complex land-cover changes using transient flow simulations that employ a coupled model of water and energy fluxes at the land surface. The transient simulations continue to test the conceptual models described above, consider long-term memory in the system, and provide a direct comparison to the seasonal field study of *Bearup et al.*, [2014]. Simulations were designed with increasing complexity including 1) simpler steady state scenarios with transient particle runs that clearly identify flow processes; 2) simplified transient flow and transport simulations that identify long-term hillslope behavior; and 3) complex transient flow and transport simulations that capture interactions between old groundwater, rain, and snow inputs that are timed with the precipitation forcings of the land surface model. Each simulation was run for both land-cover scenarios, resulting in six simulations that are summarized pictorially in Figure 1. Subsequent sections describe the simulations in further detail.

The model used for these simulations is ParFlow, a parallel, integrated hydrology model. ParFlow fully integrates variably saturated subsurface flow with overland flow. For more details on the model see Ashby and Falgout [1996], Jones and Woodward [2001], and Kollet and Maxwell [2006]. The second set of simulations also employ the Common Land Model (CLM), a land surface model that incorporates surface water and energy fluxes [*Dai et al.*, 2003; *Maxwell and Miller*, 2005]. CLM also incorporates vegetation processes, which can be altered to describe tree death. Here, tree death was modeled by reducing the leaf area index and stomatal resistance used to calculate evapotranspiration [*Kollet*, 2009; *Mikkelson et al.*, 2013], consistent with the methodology in Penn [2014]. Particle tracking was performed using the Lagrangian code SLIM-FAST, recently modified to track particles through the surface and subsurface domains [*de Rooij et al*., 2013]. Particle transfers from the two-dimensional surface domain to three-dimensional subsurface (i.e. infiltration) are determined probabilistically based on the mass balance of flow along a particle's pathline. A particle can also return to the surface from the subsurface based on the flow path in three dimensions. Consistent with the no-flow boundary conditions of the groundwater domain, particles leave the system as surface water at the bottom of the hillslope, representing the strong upward gradients observed in riparian areas. Particles were tagged based on their initial condition, regardless of how the particle reaches the hillslope outlet. Particles that start the simulation in the subsurface are thus referred to as "old" groundwater in order to distinguish it from rain- and snow-derived water that begins on the surface and may travel through the subsurface. Each particle is scaled to represent a volume using the total volume of water in that domain (either initial water in the subsurface, peak SWE, or rain event volume), as described in more detail for each simulation. SLIM-FAST has been used to model groundwater age [*Tompson et al.*, 1999; *Maxwell et al.*, 2003; *S J Kollet and Maxwell*, 2008; *Engdahl and Maxwell*, 2015] and radioisotopes [*Maxwell et al.*, 2009]; however, this is the first application that captures mixing processes of rain, snow, and groundwater specifically.

3. **Metal fate and partitioning in soils under bark beetle-killed trees** (Bearup et al. 2014b)

The final portion of this study identifies the potential mechanisms of metal mobilization and fractionation in soils collected under trees undergoing different stages of MPB-attack. Our approach builds on two-stage leaching of forest soils with a sequential extraction procedure (SEP) to identify where metals are complexed in pine forest soils and how that may change as infestation progresses. Laboratory findings are enriched through geochemical modeling to further identify controls on metal mobility and soils that may be more susceptible to metal leaching from MPB-induced tree death as well as provide generalizable results that transcend tree-scale soil heterogeneities between field samples. Collectively, this study moves toward a better understanding of metal mobilization mechanisms and changes in forest soils impacted by the MPB.

Soil samples were collected from Rocky Mountain National Park (RMNP), near Estes Park, CO (40.33° N, 105.60° W) on September 6, 2012. Soils are mapped as Isolation gravelly sandy loam and formed from alluvium, colluvium, or till derived from granite, gneiss, and schist and were observed to be shallow and poorly developed; these soils are composed of approximately 65% sand, 13% clay, and 22% silt (NRCS 2013). Samples were collected on a south-facing slope beneath three of each phase of tree (green, red, gray), resulting in 9 bulk samples for analysis. Samples were collected from the most decomposed organic layer represented under each tree. Subsamples were analyzed for soil moisture and total carbon. Sequential extraction procedures were based on Li et al. (1995) and define four operational extractable fractions: exchangeable, carbonate-bound and specifically adsorbed (acid-soluble), iron/manganese oxide-bound (reducible) and organic matter and sulfide bound (oxidizable), as summarized in Table 1.

TABLE 1. Metal Extraction Procedures. Leachate solutions and extraction methods for the sequential extraction procedures (modified from Bearup et al. 2014b)

SEP		Leachate Solution	Extraction Conditions
Exchangeable		8ml of 0.5M magnesium chloride at neutral pH	Continuous agitation at room temperature for 20 minutes
Acid Soluble		8ml of 1 M sodium acetate adjusted to pH 5 with acetic acid	Continuous agitation at room temperature for 5 hours
Reducible		20 ml of 0.04 hydroxylammonium hydrochloride in 25% (v/v) HOAc	Continuous agitation at 96˚C for 6 hours
Oxidizable	1)	3ml of 0.02M HNO_3 and 5ml of 30% H_2O_2 adjusted to pH 2.0 with HNO_3	Continuous agitation after progressively heated to 85˚C for 2 hours
	2)	3ml of 30% H_2O_2 adjusted to pH 2.0 with HNO_3	Continuous agitation at 85˚C for 3 hours
	3)	5ml of 3.2M NH_4OAC in 20% (v/v) HNO_3	Added after cooling; continuous agitation for 30 minutes

A three-site geochemical model of metal sorption in soils was used to capture important release mechanisms including ion exchange on clay surfaces, surface complexation with iron oxides, and organic complexation. The multi-surface model was populated with metal concentrations based on the results of the sequential extractions and implemented in PHREEQC (Parkhurst and Appelo 2013).

4. **Statistical model to explain DOC concentrations in streamwater**

The first step in a greater statistical analysis was to compare of different statistical methods, including ordinary kriging, universal kriging, and top-kriging, for estimation of DOC in streams using MPB infestations, elevation, slope, land cover, and precipitation. This analysis develops a relatively simple statistical model utilizing available USGS data for dissolved organic carbon (DOC) and five explanatory variables (MPB infestation extent, elevation, slope, land cover, and precipitation). The dataset was compiled for year 2007 because of a relatively large amount of DOC data available compared to other years and because of a heightened state of the MPB infestations. The dataset includes 65 locations in the Rocky Mountains in a domain ranging from -105.53° to -106.06° of longitude and 39.76° to 40.52° of latitude (68.6 km in the east/west direction by 111.3 km). More than 50 % of the locations are located within the Rocky Mountain National Park. This study compared different statistical models for spatial prediction of DOC in streams.

Discussion of Results and their Significance

In this report, we provide a brief summary of the findings of the three studies supported by this grant. For a more complete presentation of the results, discussion, and significance of these studies, see Bearup et al. (2014a, 2014b, and *in review*). The following discussion of results and significance was modified from the corresponding reference provided with each heading.

1. **Hydrological effects of forest transpiration loss in bark beetle-impacted watersheds (Bearup et al. 2014a)**

   Here, we connect climate-exacerbated insect infestation and the subsequent watershed-scale transpiration loss to late-summer streamflow generation processes. Results demonstrate that fractional late-summer groundwater contributions from impacted watersheds are 30 ± 15% greater after infestation and when compared with a neighboring watershed that experienced earlier and less-severe attack (Figure 2). Our combined approach provides spatial and temporal controls on inherently challenging field heterogeneities that may be improved only by numerical modeling of flow paths in impacted watersheds.

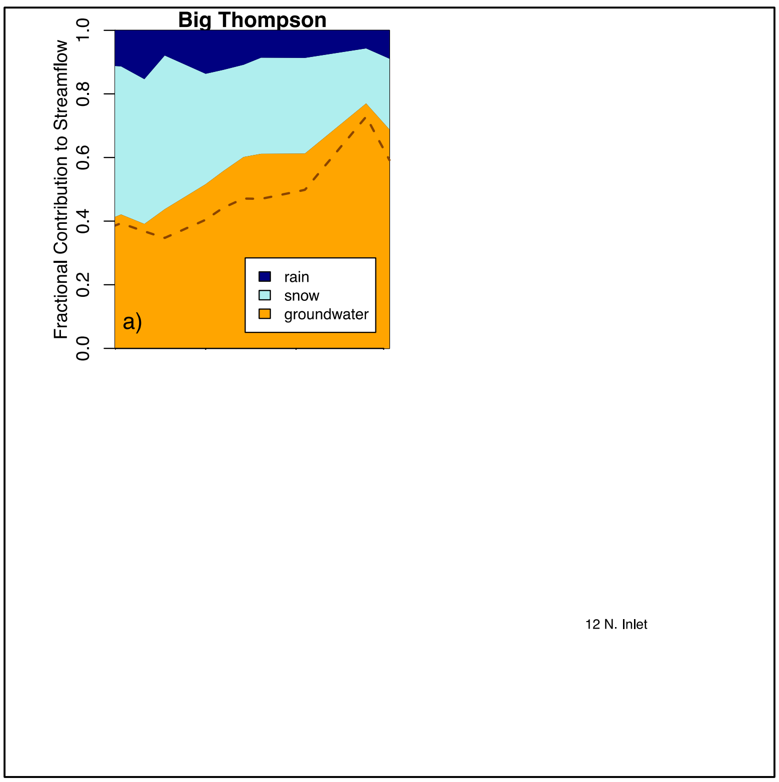


FIGURE 2. Fractional contributions of endmembers to streamflow. **a–c**, Contributions of rain (navy), snow (cyan) and groundwater (orange) to streamflow in Big Thompson, 2012 (**a**); North Inlet, 2012 (**b**); and Big Thompson, 1994 (**c**). **d**, Groundwater contributions (orange lines) with propagated uncertainty (grey shading) for each analysis. The Big Thompson 2012 groundwater fractions in **a** and **d** use the time-varying groundwater endmember and the dashed line represents the constant groundwater endmember. The 1994 methodology is consistent with the dashed line of the 2012 Big Thompson study, and the solid line is consistent with the North Inlet study. From Bearup et al. (2014a).

Uncertainty propagations through time and space are considerable, but not large enough to obscures the beetle-related differences. Water budget analysis confirms that transpiration loss resulting from beetle kill can account for the relative increase in groundwater contributions to streams, often considered the sustainable flow fraction and critical to mountain water supplies and ecosystems. In RMNP, new regeneration and continued growth of the remaining vegetation seem to offset this loss of transpiration within approximately 8 years after the onset of infestation.

2. **Hillslope response to land-cover change: an integrated model of end-member mixing (Bearup et al. *in review*)**

In this study, we combine a hillslope model with fully integrated processes from the subsurface through the land surface with Lagrangian particle tracking through the surface and subsurface domains. This approach explicitly simulates end-member mixing by tracking parcels of water tagged as rain, snow, and pre-event groundwater and provides a method of separating outflows from these sources. Model results are consistent with prior field analysis of changing streamflow contributions with tree mortality from widespread insect infestation in the Rocky Mountains of North America; most notably, the fraction of streamflow derived from groundwater increased in both the modeled hillslope and field study (Figure 3).

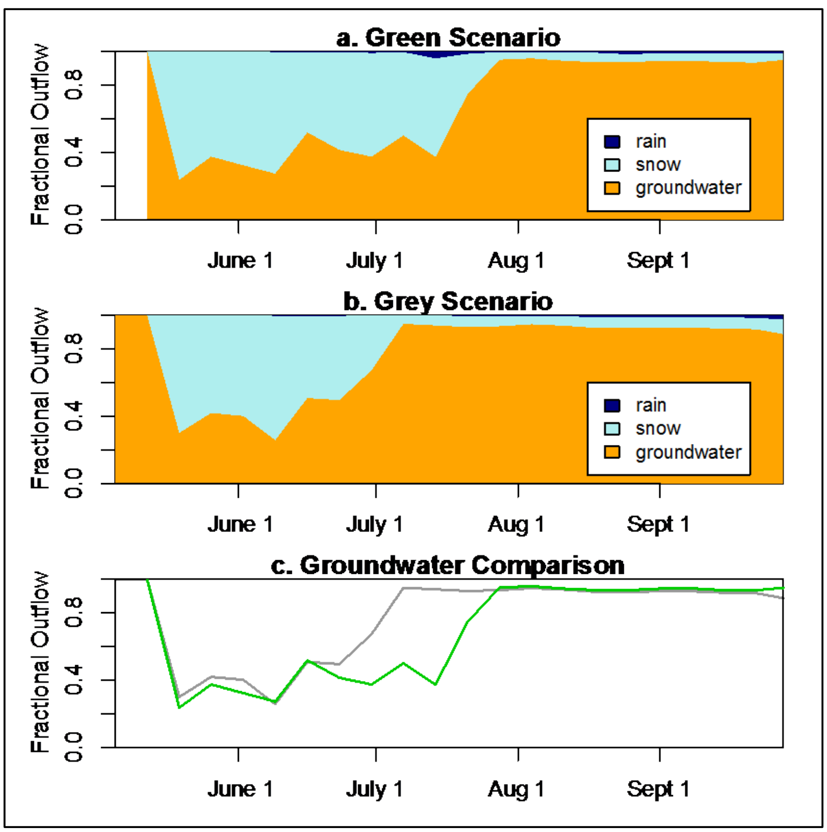


FIGURE 3. Numerical hydrograph separations of fractional outflows from rain (navy), snow (light blue), and old groundwater (orange) for green (a) and grey (b) simulations, and direct comparisons of groundwater from both land-cover scenarios (c).

Model results also provide process-level understanding that supports conceptual models of mixing within groundwater end-members and delays between annual inputs of precipitation (such as seasonal snowmelt) and the corresponding streamflow composition. Mixed hillslope outflows indicate that topography and precipitation can drive complex signatures in groundwater inputs over meaningful time periods. Modeled long-term responses to land-cover change suggest that greater water availability associated with tree death may result in shorter travel times within impacted watersheds and thus a shorter memory of disturbance. Ultimately, this work and analysis of field observations, provides insight into hillslope hydrologic processes, and can serve as a platform for more complex simulations of land-cover perturbations to travel times and streamflow source partitioning.

3. **Metal fate and partitioning in soils under bark beetle-killed trees** (Bearup et al. 2014b)

Soil moisture was significantly higher under dead trees, related to the loss of transpiration and interception. As seen in Figure 4, metal response to tree death was not consistent across metals of interest in this study. Zinc and cadmium content increased in soils under dead trees relative to living trees. Cadmium increases occurred predominantly in the exchangeable fraction, indicating increased mobilization potential. Relative increases of zinc were greatest in the organic fraction, the only fraction where increases in copper were observed. Model results reveal that increased organic complexation, not changes in pH or base cation concentrations, can explain the observed differences in metal partitioning for zinc, nickel, cadmium, and copper.

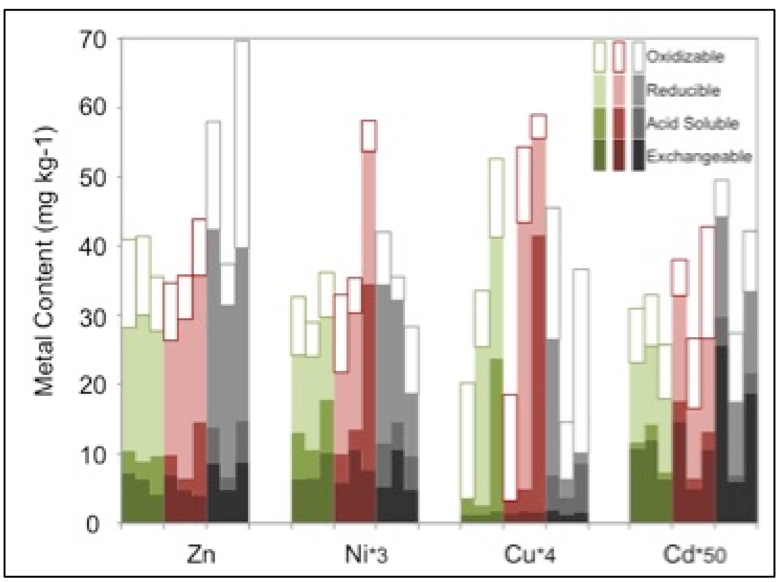


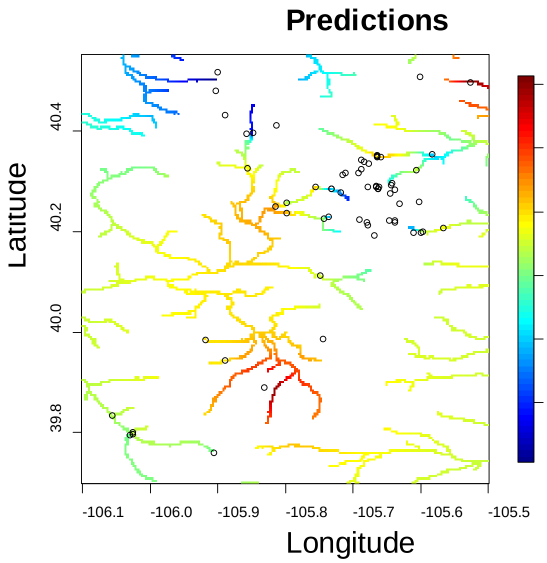
FIGURE 4. Sequentially extracted metal content from forest soils. Total metal content (bar height) divided into metal content sequentially extracted from the exchangeable, acid-soluble, reducible, and oxidizable soil fractions (segment tone) for individual trees in each phase of tree death; i.e. unimpacted (green), killed but retaining needles (red), and dead with most needles dropped (gray). Note the Ni, Cu, and Cd content are multiplied by a factor of 3, 4, and 50, respectively. From Bearup et al. (2014b).

Predicted concentrations would be unlikely to impair human health or plant growth at these sites; however, higher ex- changeable metals under beetle-killed trees relative to healthy trees suggest a possible decline in riverine ecosystem health and water quality in areas already approaching criteria limits and drinking water standards. Impairment of water quality in important headwater streams from the increased potential for metal mobilization and storage will continue to change as beetle-killed trees decompose and forests begin to recover.

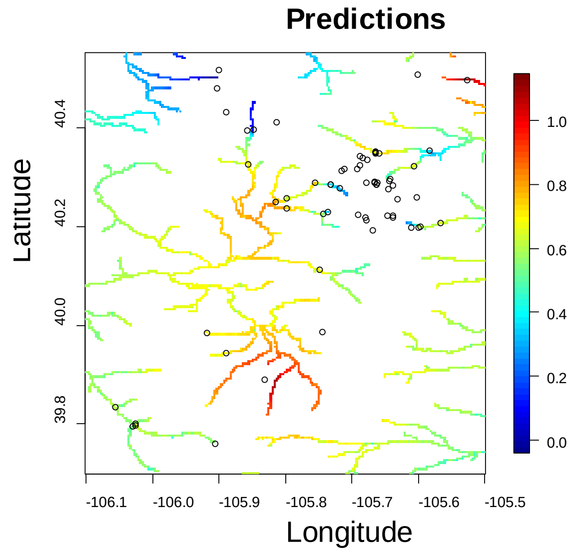
4. **Statistical model to explain DOC concentrations in streamwater** (publication in progress)

A spherical model was used and parameters were fit based on the minimization of the RMSE from an ordinary kriging cross validation process. The optimal fitted model had significant spatial dependence for distances shorter than 18.8 km. An optimal inverse distance weighted (IDW) interpolation was also performed, but its goodness of fit was worse with respect to ordinary kriging. Universal kriging cross validation was performed with iteratively re-weighted generalized least squares (IRWGLS) and with the residuals of ordinary least squares (OLS). It was found that the second approximation significantly underestimates the variance of the predictions since it does not take into account the uncertainty related to the parameters associated with the covariates. Spherical model parameters were fit based on the minimization of the RMSE from a universal kriging cross validation process. The optimal model had significant spatial dependence for distances shorter than 19 km. The OLS cross validation presented a 54% worse RMSE highlighting the importance of accounting for spatial dependence.It is important to note that the geostatistical data in stream networks logically may be more likely influenced by processes and data from locations upstream than on downstream locations that are much closer.

Top kriging is a method developed to account for this type of asymmetric dependence by modifying the estimated semivariogram. Top kriging was implemented for the DOC dataset. Nevertheless it did not present a better fit than ordinary kriging or universal kriging. Likely possible reasons include the higher importance of processes that are not bound by the watershed area such as groundwater or atmospheric processes. Another possible reason is that top kriging does not introduce a new weighting structure for the semivariogram model it simply modifies the initial semivariogram based on areal support without accounting the data asymmetry properly. Figure 4 summarizes the main results of the best two models for spatial estimation/prediction.



(a)



(b)

FIGURE 4. Comparison of universal kriging predictions (a) with respect to ordinary kriging predictions (b) The color bar represents log transformed DOC concentrations (mg/l). The grid for the predictions consist of stream cells that accumulate the runoff of 25000 or more cells. The black circles represent the locations where the data was collected. For reference the Rocky Mountain National Park extends from of 40.16°N to 40.54°N and from 105.52°W to 105.86°W

Principal Findings, Conclusions, and Recommendations

In this report, we provide a brief summary of the final principal findings, conclusions, recommendations, and identified areas for additional research. For a more complete presentation of these topics, please see Bearup et al. (2014a, 2014b, and *in review*). The following discussion is modified from the primary corresponding reference provided with each study heading.

1. **Hydrological effects of forest transpiration loss in bark beetle-impacted watersheds** (Bearup et al. 2014a)

   Both the paired watershed and temporal comparisons indicate the potential for increased groundwater contributions to streamflow after infestation. Ultimately, understanding these changes in streamflow generation provides needed insight for water resource management in MPB-infested watersheds, particularly as it relates to water quality and the transport of carbon and other constituents to water treatment facilities. For treatment plants with disinfection byproduct formation potentials that approach regulatory limits, this study suggests the need for additional awareness in the late summer, in addition to in the spring, when carbon is typically flushed from the system. This study also identifies the need for better understanding of carbon biogeochemistry along these altered flow paths and as the water reaches the streams that supply water treatment plants in beetle-affected watersheds.

2. **Hillslope response to land-cover change: an integrated model of end-member mixing (Bearup et al. *in review*)**

   Despite its simplicity, the model approach developed in this work provides insight into the complex challenges of understanding the hydrologic response to land cover at the hillslope scale and corroborates the field observations of Bearup et al. (2014a). Moving forward, adding model complexity would provide insight into additional important processes across spatial scales and years with variable weather conditions. One important future consideration is the inclusion of hydrodynamic dispersion, through the incorporation of subsurface heterogeneity or diffusion [*Jones et al.*, 2006]. Dispersion induces additional mixing and would provide additional clarity into the complex signal of a given end-member. The hillslope scale models of this work also provide a foundation for similar applications at watershed or regional scales that experience more heterogeneous tree death. By capturing the physical processes in the hydrologic system we move toward a better understanding and prediction of hydrologic response to land-cover change. This study identifies the need to better understand alterations to carbon processes as the residence time in the vadose zone and saturated zone are altered by tree death.

3. **Metal fate and partitioning in soils under bark beetle-killed trees** (Bearup et al. 2014b)

   Impacts to nutrient and biogeochemical cycles from MPB-induced tree death may ultimately lead to changes in metal partitioning in forest soils; however these increases are not expected to pose a threat to drinking water quality or plant regrowth, with the exception of watersheds that experience beetle kill and have a history of metal contamination. In these watersheds, we recommend additional monitoring for increased metal concentrations in streamwater from upslope beetle-killed area.

   Future work should move toward improved understanding of changes to the structure and type of organic compounds, including organic acids, in MPB-impacted forests. This study also identified the influence of spatial heterogeneity in distinguishing trends in soil properties from individual tree treatments, even at the stand scale. Future work should better characterize this spatial variability. Adequate understanding this variability is needed to appropriately upscale these results in watershed models and to understand long term and regional trends in metal mobility in MPB-infested forests. Ultimately, the degree of impact to the water quality in important headwater streams from the increased potential for metal mobilization and storage will continue to change as beetle-killed forests regenerate and typical forest metal and nutrient cycles are restored.

4. **Statistical model to explain DOC concentrations in streamwater**

   Universal and ordinary kriging produced similar predictions with higher DOC concentrations in MPB affected areas. However, the statistical models tended to under predict the observed data in zones where the observed locations were sparse. In general, the model predictions as well as the observed data presented lower concentrations of dissolved and total organic carbon within the Rocky Mountain National Park. This observation is consistent with the low tree mortality within the park, compared to other watersheds located in the west side of the continental divide. The results of this portion of the study reveal important requirements for further analysis that will be accounted for in forthcoming studies.

Future work. The work described in this section will be completed by a new PhD student at CSM that is funded by a different grant (i.e., not USGS-NIWR). First, it is necessary to extend the domain to include a dataset with a size that is statistically significant to minimize the prediction uncertainty. Second, the selection of covariates should not be based on a simple analysis of variance due to possible interdependence. Third, a new spatial analysis approximation should be implemented to account for the spatial asymmetry and the neighboring watershed concept. The plans and preliminary results for the next phase of study are described below.

Various studies have showed that the MPB infestations can affect the total organic carbon (TOC) and DOC in streams and soils, nevertheless, the effects vary considerably depending on each case. Therefore, this initiative consists of a large scale analysis of how the MPB infestations can affect TOC and DOC in streams, taking into account other variables that are likely to affect the carbon content in streams, and that can interact or have a correlation with the MPB infestations. An important variable is climate change, which is highly correlated with the MPB infestations. Therefore, it is important to work with a model that accounts for the interactions between climate change and MPB infestation in the selection of significant variables for the modeling process.

Because the actual effect or significance of the different variables in the streams' carbon content is unknown, it is difficult to select a physical based model for the study, because the ideal model would be as simple as possible in order to reduce the uncertainty of the predictions. Therefore, the initial approach of the study is to apply statistics for the selection of the most relevant variables, accounting for their possible interactions. Namely, the initial approximation consists of the identification of covariates that affect the carbon cycle in MPB affected forests on the west side of Colorado using a simultaneous autoregressive (SAR) model.

The statistical model would include spatial and temporal variation. As mentioned before, the domain would be the west side of the state of Colorado, where the Rocky Mountains and the forests are located. The timespan is primarily determined by data availability and the time extent of the MPB infestation, including a significant period before the current infestation began, *i.e.* approximately from 1990 to 2014. The time resolution is also highly dependent on data availability and is chosen to be monthly initially. The spatial resolution is expected to be determined with sensitivity analysis, by applying the model with different resolutions on a smaller sub-domain; initially, the range of variation is 100 m to 500 m.

The proposed covariates or inputs and outputs of the model are treated as regular lattices. The inputs for the model are elevation, slope, aspect, temperature, precipitation, snow cover, wastewater treatment plant (WWTP) locations, land cover, soil type, fires, MPB affected areas, spruce beetle affected areas, and areas affected by other beetles and other pine-tree diseases. There is one raster for each month and each input variable. Temperature and precipitation are obtained from the PRISM database and downscaled to the model spatial resolution. With respect to fires, all the unaffected raster cells have a value of zero and the affected cells have a value proportional to burn severity that decreases linearly with time as the forest recovers. Because there is high uncertainty on the duration of the phases that a tree experiences after dying because from MPB, each

MPB outbreak for a given point is assigned a different value depending on its age (in years). In that way, it is easier to detect lag times of response after implementing the model. The land cover is obtained from the NLCD database and because its temporal coverage is relatively sparse, the years without data will be estimated based on a spatial and temporal interpolation. The land cover input accounts for human related effects because it includes developed areas, however, it is not a representative covariate for tree mortality since it does not differentiate the different types of trees in the forests.

For carbon in streams the surrogate variables are DOC and TOC loads. The loads are calculated as the product of concentration and flow from the USGS database. Flow data and carbon data measured at the same location in the same day are used for the calculation of loads, non-coincident flow or concentration data is not included. For cases with more than one load measured in the same month for the same location, a representative weighted average is calculated giving more importance to the data points that are more distanced in time (i.e., that represent a longer time period within the month). Similarly, if two locations are included in the same cell and they have data for the same month, the loads are averaged. The model accounts for spatial dependence introducing a representative and asymmetric neighboring criteria. For each cell with data, the associated watershed is delineated based on the digital elevation model, where all the cells outside of the watershed receive a neighboring weight of zero, while the cells within the watershed receive a neighboring weight proportional to its flow accumulation value (i.e., sampling points downstream have integrate upstream flows and are more representative of that watershed as a whole). Ultimately, the purpose of the model is to determine what covariates have a significant effect on the streams’ carbon content for a posterior physical based model implementation. However, the model would also allow the statistical prediction of DOC and TOC loads in space and time, and therefore the results could be used as a benchmark model for an objective performance evaluation of physical-based hydro-chemical models.

Summary

In forests across the intermountain west, changing land cover from MPB-induced tree death has altered interrelated hydrologic and biogeochemical cycling. In this work, we used a combination of field, lab, and modeling analyses to investigate the effects of tree death on streamwater source partitioning, metal mobility, and controls on dissolved organic carbon. End-member mixing analysis revealed greater groundwater contributions to streamflow in a watershed with more area of killed trees. Field results were enhanced through integrated modeling that corroborated the importance of increased water availability in the subsurface, with implications for transport in effected watersheds. Sequential leaching of metals from soils under beetle-killed trees identified Cd and Zn as metals of interest, posing a particular threat to watersheds that are already impaired. Mechanistically, geochemical models suggest increased metal leaching is a result of increases in organic carbon from litter fall and tree decomposition. A predictive statistical model (calibrated to observations within and around Rocky Mountain National Park) suggests that dissolved organic carbon concentrations in streams will be higher in areas where tree mortality is higher. Although, a strong statistical correlation was not found with the method used. A more rigorous statistical method was proposed for future research. Ultimately, this work identifies key changes to processes at both the tree and watershed scale that can impact water resources in these important mountain headwaters.

References

Ashby S, Falgout R (1996) A Parallel Multigrid Preconditioned Conjugate Gradient Algorithm for Groundwater Flow Simulations. Nuclear Science and Engineering 124(1):145–159

Bearup LA, Maxwell RM, Clow DW, McCray JE (2014a) Hydrological Effects of Forest Transpiration Loss in Bark Beetle-Impacted Watersheds. Nature Climate Change 4(6):481–486. doi:10.1038/nclimate2198

Bearup LA, Maxwell RM, McCray JE Hillslope Response to Land-Cover Change: An Integrated Model of End-Member Mixing

Bearup LA, Mikkelson KM, Wiley JF, Navarre-Sitchler AK, Maxwell RM, Sharp JO, McCray JE (2014b) Metal Fate and Partitioning in Soils under Bark Beetle-Killed Trees. The Science of the Total Environment 496C:348–357. doi:10.1016/j.scitotenv.2014.07.052

Bethlahmy N (1974) More Streamflow after a Bark Beetle Epidemic. Journal of Hydrology 23(3-4):185–189

Bethlahmy N (1975) A Colorado Episode: Beetle Epidemic, Ghost Forests, More Streamflow. Northwest Science 49(2):95–105

Biederman JA, Harpold AA, Gochis D, Ewers BE, Reed DE, Papuga SA, Brooks PD (2014) Increased Evaporation Following Widespread Tree Mortality Limits Streamflow Response. Water Resources Research:n/a–n/a. doi:10.1002/2013WR014994

Clow DW, Rhoades C, Briggs J, Caldwell M, Lewis Jr WM (2011) Responses of Soil and Water Chemistry to Mountain Pine Beetle Induced Tree Mortality in Grand County, Colorado, USA. Applied Geochemistry 26:S174–S178

Dai Y, Zeng X, Dickinson RE, Baker I, Bonan GB, Bosilovich MG, Denning AS, et al. (2003) The Common Land Model. Bulletin of the American Meteorological Society 84(8):1013–1023. doi:10.1175/BAMS-84-8-1013

De Rooij R, Graham W, Maxwell RM (2013) A Particle-Tracking Scheme for Simulating Pathlines in Coupled Surface-Subsurface Flows. Advances in Water Resources 52:7–18. doi:10.1016/j.advwatres.2012.07.022

Engdahl NB, Maxwell RM (2015) Quantifying Changes in Age Distributions and the Hydrologic Balance of a High-Mountain Watershed from Climate Induced Variations in Recharge. Journal of Hydrology 522:152–162. doi:10.1016/j.jhydrol.2014.12.032

Hubbard RM, Rhoades CC, Elder K, Negron J (2013) Changes in Transpiration and Foliage Growth in Lodgepole Pine Trees Following Mountain Pine Beetle Attack and Mechanical Girdling. Forest Ecology and Management 289:312–317

Jones JE, Woodward CS (2001) Newton–Krylov-Multigrid Solvers for Large-Scale, Highly Heterogeneous, Variably Saturated Flow Problems. Advances in Water Resources 24(7):763–774. doi:10.1016/S0309-1708(00)00075-0

Jones JP, Sudicky EA, Brookfield AE, Park YJ (2006) An Assessment of the Tracer-Based Approach to Quantifying Groundwater Contributions to Streamflow. Water Resources Research 42(2):W02407

Kollet SJ (2009) Influence of Soil Heterogeneity on Evapotranspiration under Shallow Water Table Conditions: Transient, Stochastic Simulations. Environmental Research Letters 4(3):035007. doi:10.1088/1748-9326/4/3/035007

Kollet SJ, Maxwell RM (2006) Integrated Surface–groundwater Flow Modeling: A Free-Surface Overland Flow Boundary Condition in a Parallel Groundwater Flow Model. Advances in Water Resources 29(7):945–958. doi:10.1016/j.advwatres.2005.08.006

Kollet SJ, Maxwell RM (2008) Demonstrating Fractal Scaling of Baseflow Residence Time Distributions Using a Fully-Coupled Groundwater and Land Surface Model. Geophysical Research Letters 35(7)

Li X, Coles BJ, Ramsey MH, Thornton I (1995) Sequential Extraction of Soils for Multielement Analysis by ICP-AES. Chemical Geology 124(1-2):109–123

Maness H, Kushner PJ, Fung I (2013) Summertime Climate Response to Mountain Pine Beetle Disturbance in British Columbia. Nature Geoscience 6(1):65–70. doi:10.1038/ngeo1642

Maxwell RM, Miller NL (2005) Development of a Coupled Land Surface and Groundwater Model. Journal of Hydrometeorology 6(3):233–247. doi:10.1175/JHM422.1

Maxwell RM, Tompson AFB, Kollet S (2009) A Serendipitous, Long-Term Infiltration Experiment: Water and Tritium Circulation beneath the CAMBRIC Trench at the Nevada Test Site. Journal of Contaminant Hydrology 108(1-2):12–28. doi:10.1016/j.jconhyd.2009.05.002

Maxwell RM, Welty C, Tompson AFB (2003) Streamline-Based Simulation of Virus Transport Resulting from Long Term Artificial Recharge in a Heterogeneous Aquifer. Advances in Water Resources 26(10):1075–1096

Mikkelson K, Bearup L, Navarre-Sitchler A, McCray J, Sharp J (2014) Changes in Metal Mobility Associated with Bark Beetle-Induced Tree Mortality. Environmental Science: Processes and Impacts 16(6):1318–27. doi:10.1039/C3EM00632H

Mikkelson KM, Bearup LA, Maxwell RM, Stednick JD, McCray JE, Sharp JO (2013a) Bark Beetle Infestation Impacts on Nutrient Cycling, Water Quality and Interdependent Hydrological Effects. Biogeochemistry 115:1–21. doi:10.1007/s10533-013-9875-8

Mikkelson KM, Dickenson ER V., Maxwell RM, McCray JE, Sharp JO (2013b) Water-Quality Impacts from Climate-Induced Forest Die-Off. Nature Climate Change 3(3):218–222. doi:10.1038/nclimate1724

NRCS (2013) Natural Resources Conservation Service, U.S. Department of Agriculture. Web Soil Survey. http://websoilsurvey.nrcs.usda.gov Accessed 3 Dec. 2013

Parkhurst DL, Appelo CAJ (2013) Description of Input and Examples for PHREEQC Version 3-A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations. In Techniques and Methods 6-A43, 497. U.S. Geological Survey, Denver, CO

Pearson JA, Knight DH, Fahey TJ (1987) Biomass and Nutrient Accumulation During Stand Development in Wyoming Lodgepole Pine Forests. America 68(6):1966–1973

Penn CA (2014) Green to Grey: Modeling Hydrological Responses to Mountain Pine Beetle Tree Mortality in Heterogeneous Terrain. MS Thesis, Hydrology Program, Colorado School of Mines.

Potts DF (1984) Hydrologic Impacts of a Large-Scale Mountain Pine Beetle (dendroctonus Ponderosae Hopkins) Epidemic. JAWRA Journal of the American Water Resources Association 20(3):373–377

Pugh E, Gordon E (2013) A Conceptual Model of Water Yield Effects from Beetle-Induced Tree Death in Snow-Dominated Lodgepole Pine Forests. Hydrological Processes 27(14):2048–2060. doi:10.1002/hyp.9312

Reed DE, Ewers BE, Pendall E (2014) Impact of Mountain Pine Beetle Induced Mortality on Forest Carbon and Water Fluxes. Environmental Research Letters 9(10):105004. doi:10.1088/1748-9326/9/10/105004

Rhoades CC, McCutchan JH, Cooper LA, Clow D, Detmer TM, Briggs JS, Stednick JD, et al. (2013) Biogeochemistry of Beetle-Killed Forests: Explaining a Weak Nitrate Response. Proceedings of the National Academy of Sciences of the United States of America 110(5):1756–60. doi:10.1073/pnas.1221029110

Sueker JK, Ryan JN, Kendall C, Jarrett RD (2000) Determination of Hydrologic Pathways during Snowmelt for Alpine/subalpine Basins, Rocky Mountain National Park, Colorado. Water Resources Research 36(1):63–75

Tompson AFB, Carle SF, Rosenberg ND, Maxwell RM (1999) Analysis of Groundwater Migration from Artificial Recharge in a Large Urban Aquifer: A Simulation Perspective. Water Resources Research 35(10):2981–2998

Vanderhoof MK, Williams CA (2015) Persistence of MODIS Evapotranspiration Impacts from Mountain Pine Beetle Outbreaks in Lodgepole Pine Forests, South-Central Rocky

Mountains. Agricultural and Forest Meteorology 200:78–91. doi:10.1016/j.agrformet.2014.09.015

Winkler R, Boon S, Zimonick B, Spittlehouse D (2014) Snow Accumulation and Ablation Response to Changes in Forest Structure and Snow Surface Albedo after Attack by Mountain Pine Beetle. Hydrological Processes 28(2):197–209