

Special Series

Designing tools to predict and mitigate impacts on water quality following the Australian 2019/2020 wildfires: Insights from Sydney's largest water supply catchment

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EDITOR'S NOTE:

This article is part of the special series “Ecological consequences of wildfires.” The series documents the impacts of large-scale wildfires in many areas of the globe on biodiversity and ecosystem condition in both terrestrial and aquatic ecosystems, the capacity for systems to recover, and management practices needed to prevent such destruction in future.

Abstract

The 2019/2020 Australian bushfires (or wildfires) burned the largest forested area in Australia's recorded history, with major socio-economic and environmental consequences. Among the largest fires was the 280 000 ha Green Wattle Creek Fire, which burned large forested areas of the Warragamba catchment. This protected catchment provides critical ecosystem services for Lake Burragorang, one of Australia's largest urban supply reservoirs delivering ~85% of the water used in Greater Sydney. Water New South Wales (WaterNSW) is the utility responsible for managing water quality in Lake Burragorang. Its postfire risk assessment, done in collaboration with researchers in Australia, the UK, and United States, involved (i) identifying pyrogenic contaminants in ash and soil; (ii) quantifying ash loads and contaminant concentrations across the burned area; and (iii) estimating the probability and quantity of soil, ash, and associated contaminant entrainment for different rainfall scenarios. The work included refining the capabilities of the new WEPPcloud-WATAR-AU model (Water Erosion Prediction Project cloud-Wildfire Ash Transport And Risk-Australia) for predicting sediment, ash, and contaminant transport, aided by outcomes from previous collaborative postfire research in the catchment. Approximately two weeks after the Green Wattle Creek Fire was contained, an extreme rainfall event (~276 mm in 72 h) caused extensive ash and sediment delivery into the reservoir. The risk assessment informed on-ground monitoring and operational mitigation measures (deployment of debris-catching booms and adjustment of the water supply system configuration), ensuring the continuity of safe water supply to Sydney. WEPPcloud-WATAR-AU outputs can prioritize recovery interventions for managing water quality risks by quantifying contaminants on the hillslopes, anticipating water contamination risk, and identifying areas with high susceptibility to ash and sediment transport. This collaborative interaction among scientists and water managers, aimed also at refining model capabilities and outputs to meet managers' needs, exemplifies the successful outcomes that can be achieved at the interface of industry and science. © 2021 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC).

KEYWORDS: Bushfire, Drinking water, Modeling, Water contamination risk, Wildfire ash

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INTRODUCTION

Major wildfires are common in the eucalypt-dominated forests of Eastern Australia, one of the world's most fire-prone forest ecosystems (Bradstock et al., 2012). The 2019/2020 fire season, however, was unprecedented in recorded history, burning 21% of this temperate broadleaf and mixed forest biome instead of the ~2% that typically burns in a

severe fire season (Boer et al., 2020). The fires killed 34 people and destroyed nearly 6000 buildings, leading to unprecedented challenges and costs to the economy and public health (Johnston et al., 2020; Lal et al., 2021).

The 2019/2020 bushfires also posed a major threat to key ecosystem services such as the provision of clean water. Following fire, the loss of vegetation and ground cover, as well as changes to soil physicochemical properties, can substantially increase surface runoff and soil erodibility (Robichaud et al., 2000; Shakesby, 2011; Shakesby & Doerr, 2006). In addition, ash produced by fire provides an additional layer of highly erodible material in burned areas. Wildfire ash is a mixture of pyrogenic organic and inorganic materials rich in nutrients and potential contaminants (Bodi et al., 2014). Following rainfall, eroded soil and ash pose a considerable contamination risk to water bodies, including water supply reservoirs (Smith et al., 2011). Nutrients in ash and eroded soil can promote algal blooms that release toxins and affect treatment processes; metals can generate odor, taste, and toxicity issues; and dissolved organic compounds can affect treatment capabilities and induce formation of carcinogenic by-products (Hohner et al., 2019). This risk is exacerbated by the effects of climate change, not only in the wake of increases in fire occurrence and severity, but also in the size and intensity of rainstorms that transport ash and soil into water bodies (IPCC, 2014; Martin, 2016; Nunes et al., 2018).

The 2019/2020 wildfires hit New South Wales particularly hard, burning a total 53 000 km² of the state. The burned area affected 35% of the 9050 km² Warragamba catchment that surrounds Sydney's main drinking water reservoir, Lake Burratorang. This caused major concerns about the viability of maintaining the supply of clean water to the Greater Sydney region (Hannam, 2019; Visentin et al., 2019). Collaborative work on the impacts of previous fires between the catchment managers and researchers has provided valuable insight into soil erosion processes (e.g., Shakesby et al., 2007), ash and soil chemical composition (Santín et al., 2015), and the relationship between burn severity and the amount of ash produced (Chafer et al., 2016). However, critical gaps remained in the ability to predict the transport of ash, soil, and associated contaminants in them to the lake in this vast catchment following this extensive fire. Predictive tools and procedures are needed to quantify and locate risks to water quality and, so, support managers to more effectively prepare for and mitigate water contamination. In this article, we report on the challenges and successes of collaborative efforts between local water managers and researchers in Australia, the UK, and United States to address these knowledge gaps in the first critical months after the fire and to develop strategies for responding to future fire events.

THE WARRAGAMBA CATCHMENT AND THE GREEN WATTLE CREEK FIRE

Lake Burratorang is the largest raw water supply reservoir servicing Greater Sydney (>5 million consumers). At 52 km in

length and 2027 GI capacity, it is impounded by the Warragamba Dam and collects water from its 9050 km² catchment (Figure 1). Within the Warragamba catchment lies the restricted-access Special Area, which protects approximately 2600 km² of largely undisturbed native eucalypt-dominated medium woodlands and medium open forests (NVIS Technical Working Group, 2017) adjacent to Lake Burratorang (Figure 1). The Warragamba catchment experienced intensive drought conditions from 2017 to 2019 (Bureau of Meteorology, 2020), which resulted in a drawdown of Lake Burratorang to 43% capacity by November 2019 (Supporting Information Figure S1).

Dry lightning ignited the Green Wattle Creek Fire on 27 November 2019 in the Warragamba Special Area. By 4 January, the fire had burned ~2700 km² and expanded north, south, and east to envelope the area around Lake Burratorang. Although small portions of the catchment had previously experienced wildfires in 2006 and hazard reduction burns from 2003 to 2020 (NSW National Parks and Wildlife Service, 2020), the fuel accumulated before the fire was substantial (Boer et al., 2020). By 30 January 2020, the Green Wattle Creek Fire was declared “contained” after burning most of the Special and Controlled areas of the Warragamba catchment (~2800 km²; Figure 1).

The Warragamba catchment received two major rainfall events during and shortly after the Green Wattle Creek Fire. An initial six-day event between 16 and 21 January yielded 35 mm total rainfall across the catchment, and a 30-year recurrence interval rainfall event spanning three days, 7–9 February, yielded an average of 276 mm across the Warragamba forested Special Areas. These events resulted in ~800 000 ML of inflows into Burratorang Lake and doubled pre-storm storage levels (Supporting Information Figure S1). These inflows transported large amounts of ash, eroded soil, and associated contaminants that generated plumes in the lake and affected water quality (Figure 2).

CHALLENGES AFTER THE FIRE: THE CATCHMENT MANAGER'S RESPONSE

The scale of the Green Wattle Creek Fire was unprecedented in the Warragamba catchment and presented Water New South Wales (WaterNSW), the utility responsible for managing risks caused by the fire to raw water quality in Lake Burratorang, with several water quality and operational challenges. The fire damaged hydrometric gauges and smoke blanketing disrupted communications from the vertical profiler systems (VPS) aimed at monitoring water-flow rate and quality in depth at Lake Burratorang and its inflows. The in-lake system outages lasted less than 24 h; however, access to the catchment was restricted for several weeks after the fire owing to safety risks from falling trees. These restrictions delayed repairs to damaged equipment on inflowing streams and precluded on-ground inspections to assess erosion risk. This delay limited information on incoming inflows and water quality, reducing the capacity to anticipate poor water quality encroaching on the dam wall.

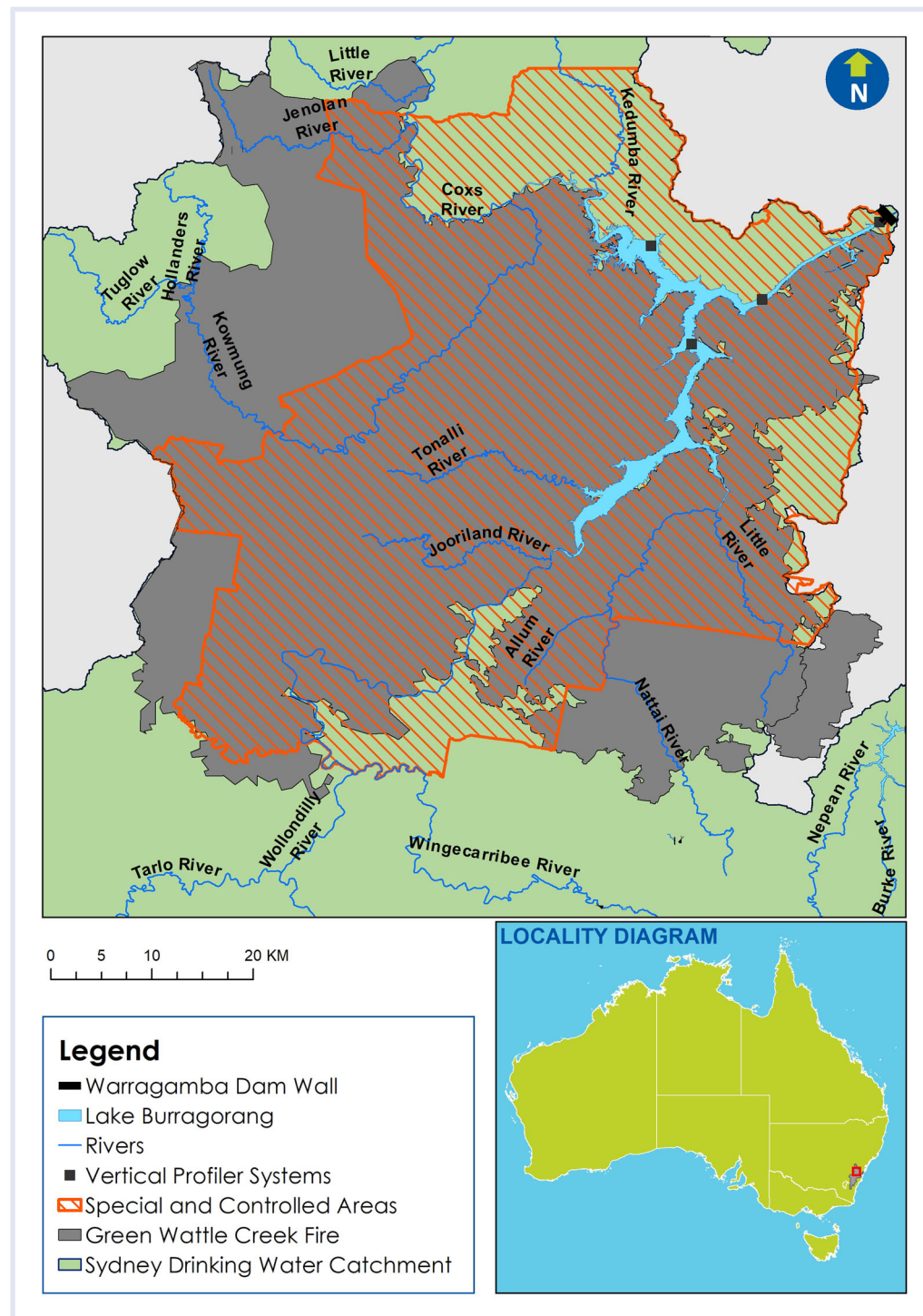


FIGURE 1 Lake Burragorang and the Warragamba Special and Controlled Areas in relation to the Green Wattle Creek Fire extent

These challenges were compounded by the extremely short (2-week) time between containment of the fire and the 30-year rainfall event. Immediately before this event, WaterNSW enacted its standard “incident response” procedure for forecasted high rainfall events, including the formation of an incident management team to closely monitor water quality during the event, coordinate operational responses, and communicate with the water

treatment customer and the state public health regulator. Restoring communications with the in-lake VPSs was prioritized, because this instrumentation was critical to tracking the inflowing sediment plume as it traveled toward water intakes. Extensive monitoring of incoming water quality, close communication with water filtration plants, and flexibility in the supply system in the form of a multilevel offtake and alternative raw water source



FIGURE 2 Example of areas burned at high (A) and low (B) severity, erosion evidences with pedestals after the 30-year rainfall event in the Warragamba catchment (276 mm in 3 days; C), ash deposition in flat areas after the torrential rain (D), view of the Burrigorang Lake after the torrential event (E), and booms containing debris after the 30-year torrential event (F). Pictures taken 45 days after the fire

selection were also essential to maintaining the raw water supply. The soil erosion model RUSLE (Renard et al., 1997) was used to identify subcatchments at high risk to surface erosion and priority areas for monitoring and inspecting soil erosion impacts (Yang et al., 2020). However, this model lacks capabilities to simulate ash and associated contaminant transport and delivery to the lake, limiting its utility in predicting water quality impacts and in supporting the design of effective mitigation measures such as stabilization treatments for hillslopes (e.g., seeding, erosion barriers, mulching) and channels (e.g., dams, grade stabilizers, debris basins, bank armoring; Robichaud et al., 2000).

Additional measures undertaken beyond the standard response to address water quality risks from the fire included:

- Booms deployed across the main body of the lake to reduce the accumulation of debris at the dam wall near water intakes (Figure 2).
- Additional monitoring for specific pyrogenic contaminants identified by the risk assessment, including additional metals, cyanide, and polycyclic aromatic hydrocarbons (PAHs).
- Increased resolution for water quality monitoring to track and characterize inflows, extending to upper catchment regions, and conducted at daily to twice-weekly intervals.
- An assessment of contaminant release and water quality impacts from fire-related floating debris to identify ongoing risk and possible management actions.
- Sampling of benthic surface sediment cores at four regions from the upper catchment to the dam wall,

providing insight into the settled ash chemical composition, distribution, and risks of resuspension and release of potential contaminants.

The standard measures undertaken ensured that the ongoing supply of safe drinking water to Sydney was maintained throughout and after the fire event. However, this chain of extreme events, the unprecedentedly large fire in the catchment and the subsequent 30-year rainfall event, uncovered several knowledge gaps regarding current capabilities to predict, and inform on, potential impacts of contaminants in ash and eroded soil on water quality. The identification of these knowledge gaps drove a science–industry collaboration aimed at making ash and related contaminants part of the equation when evaluating water contamination risks after wildfires. The main objective of this collaboration was to refine tools to predict soil, ash, and contaminant transport so they provide useful information to water managers to design tailored response measures that complement the current standard response procedures.

SCIENCE–INDUSTRY COLLABORATION TO DEVELOP TOOLS TO PREDICT WATER CONTAMINATION RISK FROM WILDFIRE ASH

A framework for evaluating water contamination risk after wildfires

Anticipating and quantifying fire-induced risks from soil and ash erosion to water assets that support the design of effective mitigation and response actions require: (i) identifying potential pollutants in ash and soils in the catchment that can threaten water quality and (ii) understanding, and (iii) predicting how those pollutants can be transported into the water. Based on these three key components, a framework for evaluating postfire water contamination risk has recently been developed (Nunes et al., 2018), which has already been adopted by the Water Services Association of Australia (Canning et al. 2020). The framework provides a tiered solution to support water contamination risk assessments before, during, and after wildfires and, thus, assists in identifying mitigation opportunities at each of those stages and in designing effective strategies to reduce risk and protect water quality.

Previous studies in the area

Previous collaborative work between Swansea University and WaterNSW produced datasets on the contaminant content in ash and burned soil resulting from fires in this ecosystem. Contaminant data were collected following the 2013 Balmoral Fire, which affected another of the WaterNSW's catchments, and from a research burn in the Warragamba catchment in 2014 (Santín et al., 2015, 2018). This previous collaboration provided likely ash loads under different burn severities (Chafer et al., 2016). Applying these outputs to the Green Wattle Creek Fire allowed the (i) estimation of ash distribution and loads from remote sensing observation based on the differential Normalized Wildfire

Ash Index (dNWI) developed after the 2013 fire, and (ii) identification and quantification of potential pollutants in both ash and burned soils. These two outcomes informed WaterNSW of the potential impacts of ash on water quality by identifying contaminants of concern on the hillslopes while laying the foundations for the development of tools to predict water contamination risk from soil and ash.

Predicting soil, ash, and associated contaminant transport after wildfires: The WEPPcloud-WATAR tool

The WEPPcloud-WATAR tool (Water Erosion Prediction Project cloud model—Wildfire Ash Transport And Risk estimation tool) has been under development since 2017 by a research team from the UK, the United States, and Australia (Neris et al., 2017). It predicts the probability of both ash and soil, and the potential pollutants in them, to be delivered from burned hillslopes into stream channels and water bodies. The WEPPcloud-WATAR tool is powered by the well-established Water Erosion Prediction Project, WEPP, model (Lafflen et al., 1997), enhanced with the incorporation of channel hydrology and sediment routing routines (Wang et al., 2010, 2014). Its main advantage over other widely used erosion models such as USLE (Wischmeier & Smith, 1978), RUSLE (Renard et al., 1997), MMF (Morgan, 2001), SWAT (Neitsch et al., 2011), KINEROS2 (Smith et al., 1995), or PESERA (Kirkby et al., 2008) is that it can simulate transport not only of soil, but also of ash and pollutants contained in them, from the hillslopes. These enhanced capabilities provide much more comprehensive probabilistic and spatially distributed predictions of water contamination risk to water assets than other models do (Table 1; Figure 3). The model also automates the acquisition and processing of input data (climate, elevation, soil, and land management information, as well as ash composition; see previous studies in the area section) from available datasets, which substantially simplifies its application and reduces the time needed to produce simulations.

The WEPPcloud-WATAR tool has specific online interfaces for Australia (WEPPcloud-WATAR-AU), the United States (WEPPcloud-WATAR-US), and Europe (WEPPcloud-WATAR-EU; <https://wepp.cloud>). The WEPPcloud-WATAR-AU tool was deployed for the first time after the Green Wattle Creek Fire. It benefited substantially from the collaborative science–industry interaction that was already in place. The specific needs expressed by water managers in predicting water contamination risks from soil and wildfire ash supported the development of new model capabilities and outputs (presented as model upgrades in the following sections and Figure 3).

The Green Wattle Creek Fire: A test bench to improve the capabilities of the WEPPcloud-WATAR tool

Immediately after the fire, a main concern of WaterNSW managers was to determine the amount of ash and associated contaminants within the burned area. An ash load map obtained using the previously developed dNWI model (Chafer et al., 2016) and datasets on ash and soil

TABLE 1 General characteristics and native capabilities of the main models used for simulating runoff and erosion in postfire scenarios according to Lopes et al. (2020)

Model/interface	Reference	Type	Event-based?	Probabilistic outputs?	Linked to GIS?	Spatial datasets incorporated?	End-user spatial interface?	Ash transport capabilities?
USLE	Wischmeier and Smith (1978)	Empirical	No	No	Yes	No	No	No
RUSLE	Renard et al. (1997)	Empirical	No	No	Yes	No	No	No
MMF	Morgan and Duzant (2008)	Empirical	No	No	Yes	No	No	No
SWAT	Neitsch et al. (2011)	Empirical	No	No	Yes (ArcSWAT, QSWAT, AGWA)	Yes for USA (RECOVER ^b)	Yes (AGWA ^a)	No
KINEROS2	Smith et al. (1995)	Physical	Yes	No	Yes (AGWA)	Yes for USA (RECOVER ^b)	Yes (AGWA ^a)	No
PESERA	Kirkby et al. (2008)	Physical	No	No	Yes (PESERA GRID)	No	No	No
WEPP	Lafren et al. (1991)	Physical	Yes	–	–	–	–	–
WEPP Windows*	Flanagan and Livingstone (1995)	–	Yes	Yes ^h	No	No	No	No
Disturbed WEPP ^a	Elliot and Hall (2010)	–	No	Yes ^h	Yes (WEPPcloud ^f)	No	No	No
WEPP FuME ^{a,b}	Elliot et al. (2013)	–	No	Yes ⁱ	No	No	No	No
ERMIT ^c	Robichaud et al. (2014)	–	Yes	Yes ^h	No	No	No	No
GeoWEPP ^d	Renschler (2003)	–	No	Yes ^h	Yes	No Yes (RRED ^j)	Yes	No
QWEPP ^e	Miller et al. (2019)	–	No	Yes ^h	Yes	Yes (RRED ^j)	Yes	No

(Continued)

TABLE 1 (Continued)

Model/interface	Reference	Type	Event-based?	Probabilistic outputs?	Linked to GIS?	Spatial datasets incorporated?	End-user spatial interface?	Ash transport capabilities?
WEPPcloud-RRED/RHEM/PEP/EU/AU ^{a,i}	Lew et al. (2019)	–	Yes	Yes ^h	Yes	Yes	Yes	No
WEPPcloud-WATAR ^{a,g}	Neris et al. (2017, 2021)	–	Yes	Yes ^h	Yes	Yes	Yes	Yes

Note: When a specific model capability is provided by an interface/tool, its name is included in parentheses. For the WEPP model, all interfaces and tools with capabilities for modeling runoff-erosion processes in the postfire period and their capabilities are listed.

^aWEPP interfaces/tools with capabilities for postfire erosion prediction.

^bDisturbed WEPP (https://forest.moscowfsl.wsu.edu/fswpepp/).

^cWEPP FUME: WEPP Fuel Management Erosion Analysis (https://forest.moscowfsl.wsu.edu/fswpepp/).

^dERMIT: Erosion Risk Management Tool (https://forest.moscowfsl.wsu.edu/fswpepp/).

^eGeoWEPP: ESRI ArcGIS application for the WEPP Watershed Version (http://geowepp.geog.buffalo.edu/).

^fQWEPP: QGIS application for the WEPP Watershed Version (http://red.mtr.org/baer/static/RRED_user_manual_for_QGIS.pdf).

^gWEPPcloud-RRED/RHEM/PEP/EU/AU: WEPPcloud-Rapid Response Erosion Database/Rangeland Hydrology and Erosion Model/Postfire Erosion Prediction/Europe/Australia (https://wepp.cloud/weppcloud/).

^hWEPPcloud-WATAR: WEPPcloud-Wildfire Ash Transport Assessment and Risk tool (https://wepp.cloud/weppcloud/).

ⁱProbabilistic outputs based on multiyear simulations for rain events with different magnitude and yearly probabilities and recurrence intervals. Soil and ground cover remain unchanged for the multiyear simulations.

^jAGWA: Automated Geospatial Watershed Assessment tool (Miller et al. 2007) (https://www.tucson.ars.ag.gov/agwa/).

^kRECOVER: Cloud-based database. Only covers the conterminous USA (https://giscenter.isu.edu/research/Techpg/hasa_RECOVER/index.htm).

^lRRED: Rapid Response Erosion Database. Cloud-based database. Only covers the conterminous USA.

composition obtained through previous collaborative work in the same area (Santín et al., 2015, 2018; see previous studies in the area section) were incorporated into the WEPPcloud-WATAR-AU model (upgrade 1 in Figure 3). In addition, a Burned Area Reflectance Classification (BARC) map (Parsons et al., 2010) representing soil burn severity for the Green Wattle Creek Fire (the only external input required by the tool) was provided by USGS Earth Resources Observation and Science (EROS) Center (https://www.usgs.gov/centers/eros). Based on this information and as an initial step, the tool informed WaterNSW managers of the first predictions about the concentration of potential pollutants in ash and soil, and total load of ash and associated contaminants on the hillslopes. Based on the worst-case scenario, defined as the event that all of the ash and related pollutants reach the lake, the model predicted that 2.6 million tons of ash were on the hillslopes ready to be transported toward the lake by the runoff (Figure 4). These outcomes supported WaterNSW and the water treatment customer in identifying potential limitations of water treatment capabilities for this postfire scenario.

After fires, erosion, and thus enhanced risks to water quality, remains elevated until the catchment vegetation regenerates, a process that is modeled with WEPP (Lafren et al., 1997). In order to inform capacity planning and to design mitigation actions to reduce water contamination risks in the medium term, WEPPcloud-WATAR-AU produced multiyear simulations of rain events with different magnitude and yearly recurrence intervals, and predicted the probability of ash, soil, and associated contaminants reaching the lake during those events (upgrade 2 in Figure 3). The multiyear simulations consider ash depletion, and the amount of ash available for transport decrease after each transport event according to the magnitude of that event. The current version of WEPPcloud-WATAR includes sediment routing (Srivastava et al., 2018) but does not include ash transport routines in channels. Future model improvements include developing ash transport routines in channels. The current ash routing assumes, based on the well-established high mobility of ash (Bodi et al., 2014), that all of the ash and related contaminants washed off the hillslopes reach the water asset under study. This modeling exercise instigated by WaterNSW managers also uncovered a technical limitation of this and many other models that provide high-resolution spatial predictions: the difficulty of simulating runoff-erosion events in large fire-affected catchments such as Warragamba (9050 km²). To overcome this limitation, new procedures were put in place by automating catchment delineation and using GIS products to specify ash loads. Overcoming this limitation was particularly important given the increasing probability of large fires not only in SE Australia (Lindenmayer & Taylor, 2020) but also in other forested regions globally (Cattau et al., 2020). Additional challenges to modeling postfire runoff and erosion in large catchments are associated with parameterization of baseflow, lateral flow, and channel routing (Brooks et al., 2016; Srivastava et al., 2013, 2017; Wang et al. 2010),

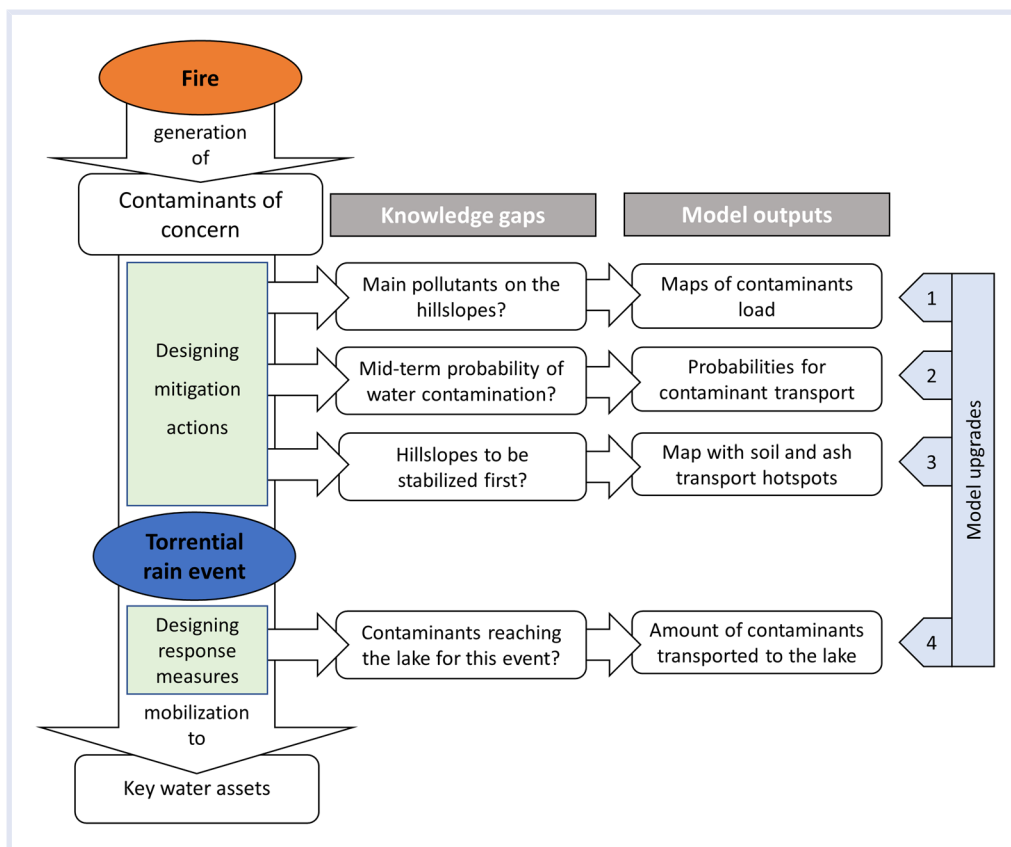


FIGURE 3 Diagram of the events after the 2019 Green Wattle Creek Fire including the knowledge gaps identified, designed model outputs, and model upgrades performed after interaction between scientists and industry end users (WaterNSW)

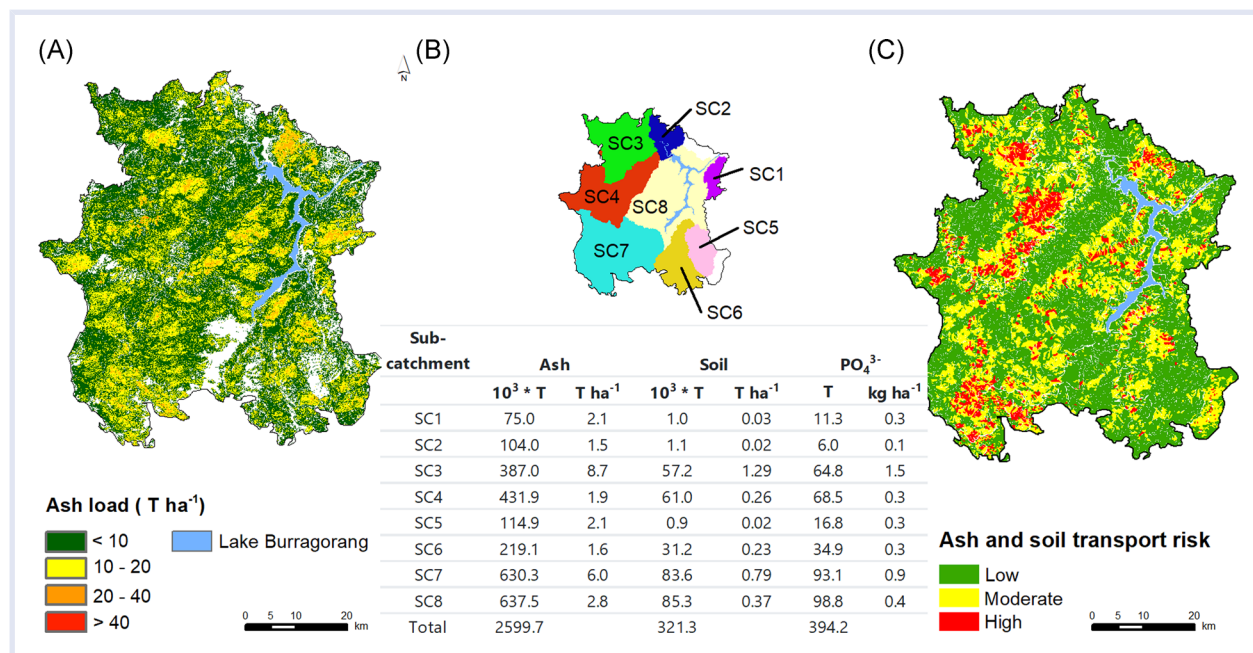


FIGURE 4 (A) Predicted ash distribution map; (B) predictions per subcatchment of eroded soil, ash, and associated contaminants (PO₄³⁻ as an example) reaching the lake as a result of the 30-year rainfall event; and (C) soil erosion and ash transport hotspots for the Warragamba catchment after the 2019 Green Wattle Creek Fire predicted by WEPPcloud-WATAR-AU (percentiles 0.33 and 0.66 were break points between risk classes for this example)

and sediment transport and routing (Srivastava et al., 2018), which increase in importance with catchment size (Kampf et al., 2020). As catchment size increases, stream processes become more dominant, and runoff-erosion models become more reliant on sediment and ash transport models. The accuracy of sediment transport models is challenging (Vanoni, 2006), ash transport models for channels do not currently exist, and spatial variability in precipitation, vegetation, and soil burn severity interactions further confound postfire large catchment modeling.

Driven by the managers' need to know the amount of soil, ash, and associated contaminants that could have reached the lake from the 30-year rainfall event that followed the fire, capabilities to obtain predictions for actual single rain events were added (upgrade 4 in Figure 3). This update provided, for the first time, modeling capabilities to produce such near real-time predictions (Figure 4). The model produced this type of information for each subcatchment that flows into the lake, allowing for rapid response measures such as deployment of containment booms in identified critical inflowing streams (Figure 2). The simulations for this event confirmed the worst-case scenario predicted in the initial step where 2.6 million tons of ash together with 0.3 million tons of soil with their associated contaminants were washed off the hillslopes and potentially reached the lake (Figure 4). An exploratory field survey after the torrential rain event confirmed that most of the ash had indeed been washed off the hillslopes and major soil erosion had occurred (Figure 2). The estimated average sediment yield obtained for the whole catchment for the 30-year rainfall event was 102 T/km^2 . This prediction was similar in magnitude to the sediment yield estimated by Blake et al. (2009) for a series of rainstorms of slightly less intensity (230 mm in 15 d with a 63 mm in 24 h event) that occurred after the Christmas 2001 bushfire that burned parts of the Warragamba catchment ($58 \pm 25 \text{ T/km}^2$). It has not, however, been possible to validate model outputs for this event regarding soil, ash, and related contaminant delivery to the lake owing to the lack of independent monitoring data from rivers and lakes caused by the damage to the hydrometric monitoring systems previously described. An erosion monitoring program using erosion plots (hillslope scale) and flow and water quality measurement (catchment scale) in the burned area and after future fuel reduction burns has been initiated by WaterNSW in order to build a new dataset to calibrate and validate the tool for this ecosystem.

In addition to this numerical quantification of risk to water quality, WaterNSW highlighted the need for spatial predictions on which of the hillslopes could be the main sources of ash, soil, and associated contaminants in the catchment (i.e., hotspots). Although WEPPcloud is capable of providing high-resolution spatial predictions of soil erosion, the new tool (WEPPcloud-WATAR) incorporates predictions of ash and related contaminant transport that allow the identification of soil erosion, ash, and contaminant transport hotspots (upgrade 3 in Figure 3). This information was key to

effectively prioritizing critical areas and excluding stable hillslopes when planning resource allocation for undertaking assessment of priority areas for hillslope stabilization treatments. Additionally, these spatial predictions were used to guide the placement of installations for the recently initiated erosion monitoring program.

CONCLUSIONS

The Green Wattle Creek Fire 2019, together with the subsequent 30-year rainfall event in the Warragamba catchment, had the potential to threaten the freshwater supply for more than 5 million people in the Greater Sydney region. Although the standard response activated by water managers from WaterNSW effectively protected water quality and ensured the supply of safe drinking water, the sequence of events also uncovered several gaps in the ability to quantify potential impacts of ash and associated contaminants on water quality. The fire event and subsequent interaction between scientists and water managers was a test bench to improve the capabilities of an end-user tool currently under development, WEPPcloud-WATAR, the first model that predicts soil, ash, and contaminant delivery to water bodies after fires. This new tool automates the acquisition and processing of data, reducing the input data and knowledge required from the end user, simplifying its application, and reducing the response time. The modeling exercises conducted in collaboration with WaterNSW after the Green Wattle Creek Fire promoted user-driven refinement of model capabilities and the applicability of the outputs by water managers. Building on previous work and upgraded capabilities driven by managers' needs, the model is now able to provide water managers with: (i) load and spatial distribution of ash and related contaminants throughout the burned area; (ii) load of soil, ash, and potential contaminants reaching water assets as a results of a single real rainstorm and probabilities of water contamination by different pollutants and recurrence intervals; and (iii) location of hotspots for soil erosion, and ash and contaminant transport. These model capabilities can now be used by land and water quality managers to identify limitations in the water treatment capacity to manage the potential impacts of the identified contaminants in both ash and soil, and to design tailored mitigation and response measures to reduce immediate and longer-term risks to water quality. The addition of WEPPcloud-WATAR to WaterNSW's response for future fire events increases managers' preparedness for fire-induced risks to water quality. Future model-development needs include, for example, calibration and validation of the model using data collected in erosion monitoring programs after this and future fires in the same region and other fire-prone areas, developing ash transport routines in channels to simulate entrainment, transport, and deposition processes, and calculating precipitation needed to trigger the defined worst-case scenario of ash and associated contaminant transport. The upgraded version of the WEPPcloud-WATAR tool is currently being tested while supporting water managers after the extensive 2020 wildfires in Oregon (USA).

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

DATA AVAILABILITY STATEMENT

WEPPcloud-WATAR-AU is available via: <https://weppcloud.cloud/weppcloud/>.

Soil Burn Severity and Ash load maps were obtained from Sentinel2 images available online: <https://eos.com/landviewer/> according to Parsons et al. (2010) and Chafer et al. (2016), respectively.

SUPPORTING INFORMATION

FIGURE S1. Precipitation depth and capacity of Lake Burragarang before and after the Green Wattle Creek Fire including the 30-year rainfall event (7–9 February 2020).

FIGURE S2. Example of the WEPPcloud-WATAR-AU probabilistic output for one of the Lake Burragarang subcatchments. Probabilities of occurrence and recurrence intervals for rain events with different magnitude and predicted sediments and contaminants reaching the lake during those events. Values provided are simulations not validated (see The Green Wattle Creek Fire: A test bench to improve the capabilities of WEPPcloud-WATER tool section).

REFERENCES

- Blake, W. H., Wallbrink, P. J., Wilkinson, S. N., Humphreys, G. S., Doerr, S. H., Shakesby, R. A., & Tomkins, K. M. (2009). Deriving hillslope sediment budgets in wildfire-affected forests using fallout radionuclide tracers. *Geomorphology*, 104(3–4), 105–116.
- Bodi, M. B., Martin, D. A., Balfour, V. N., Santin, C., Doerr, S. H., Pereira, P., Cerdà, A., & Mataix-Solera, J. (2014). Wildland fire ash: Production, composition and eco-hydro-geomorphic effects. *Earth-Science Review*, 130, 103–127. [English].
- Boer, M. M., Resco de Dios, V., & Bradstock, R. A. (2020). Unprecedented burn area of Australian mega forest fires. *Nature Climate Change*, 10(3), 171–172.
- Bradstock, R. A., Cary, G. J., Davies, I., Lindenmayer, D. B., Price, O. F., & Williams, R. J. (2012). Wildfires, fuel treatment and risk mitigation in Australian eucalypt forests: Insights from landscape-scale simulation. *Journal of Environmental Management*, 105, 66–75.
- Brooks, E. S., Dobre, M., Elliot, W. J., Wu, J. Q., & Boll, J. (2016). Watershed-scale evaluation of the Water Erosion Prediction Project (WEPP) model in the Lake Tahoe Basin. *Journal of Hydrology*, 533, 389–402.
- Bureau of Meteorology. (2020). Drought knowledge centre: Previous droughts. <http://www.bom.gov.au/climate/drought/knowledge-centre/previous-droughts.shtml>
- Canning, A., & Ryan, G. et al. (2020). *National good practice operational guidelines for bushfire management for the Australian water industry*. Water Services Association of Australia.
- Cattau, M. E., Wessman, C., Mahood, A., & Balch, J. K. (2020). Anthropogenic and lightning-started fires are becoming larger and more frequent over a longer season length in the U.S.A. *Global Ecology and Biogeography*, 29(4), 668–681.
- Chafer, C. J., Santin, C., & Doerr, S. H. (2016). Modelling and quantifying the spatial distribution of post-wildfire ash loads. *International Journal of Wildland Fire*, 25(2), 249–255.
- Elliot, W. J., & Hall, D. (2010). Disturbed WEPP Model 2.0. Ver. 2014.04.14. Moscow, ID: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
- Elliot, W. J., Robichaud, P. R., Hall, D. E., & Velasquez, E. (2013). WEPP FuME input interface v. 2013.03.01. Moscow, ID: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
- Flanagan, D. C., & Livingston, S. J. (Eds.). (1995). USDA-ARS-MWA NSERL, editor. WEPP User Summary. NSERL Report NO. 11. Vol. NSERL Report NO. 11. West Lafayette, IN: National Soil Erosion Research Laboratory USDA-ARS-MWA. (USDA- Water Erosion Prediction Project; NSERL Report NO. 11).
- Hannam, P. (2019, December 13). Sydney's water supply faces contamination if heavy rainfall arrives. *The Sydney Morning Herald*. <https://www.smh.com.au/national/nsw/sydney-s-water-supply-faces-contamination-if-heavy-rainfall-arrives-20191213-p53jkv.html>
- Hohner, A. K., Rhoades, C. C., Wilkerson, P., & Rosario-Ortiz, F. L. (2019). Wildfires alter forest watersheds and threaten drinking water quality. *Accounts of Chemical Research*, 52(5), 1234–1244.
- IPCC. (2014). *Climate Change 2014: Synthesis Report* (Contribution of working groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change). IPCC.
- Johnston, F. H., Borchers-Arriagada, N., Morgan, G. G., Jalaludin, B., Palmer, A. J., Williamson, G. J., & Bowman, D. M. J. S. (2020). Unprecedented health costs of smoke-related PM2.5 from the 2019–20 Australian megafires. *Nature Sustainability*, 4(1), 42–47.
- Kampf, S. K., Gannon, B. M., Wilson, C., Saavedra, F., Miller, M. E., Heldmyer, A., Livneh, B., Nelson, P., & MacDonald, L. (2020). PEMIP: Post-fire erosion model inter-comparison project. *Journal of Environmental Management*, 268, 13.
- Kirkby, M. J., Irvine, B. J., Jones, R. J. A., & Govers, G. (2008). The PESERA coarse scale erosion model for Europe. I.—Model rationale and implementation. *European Journal of Soil Science*, 59(6), 1293–1306.
- Laflen, J. M., Elliot, W., Simanton, J. R., Holzhey, C. S., & Kohl, K. D. (1991). WEPP: Soil erodibility experiments for rangeland and cropland soils. *Journal of Soil and Water Conservation*, 46.
- Laflen, J. M., Elliot, W. J., Flanagan, D. C., Meyer, C. R., & Nearing, M. A. (1997). WEPP-predicting water erosion using a process-based model. *Journal of Soil and Water Conservation*, 52(2), 96–102. [English].
- Lal, A., Patel, M., Hunter, A., & Phillips, C. (2021). Towards resilient health systems for increasing climate extremes: Insights from the 2019–20 Australian bushfire season. *International Journal of Wildland Fire*, 30(1), 1–5.
- Lew, R., Dobre, M., Elliot, W. J., Robichaud, P. R., Brooks, E., Srivastava, A., & Frakenberger, J. R. (2019). WEPPcloud. West Lafayette, IN: USDA-ARS NSERL.
- Lindenmayer, D. B., & Taylor, C. (2020). New spatial analyses of Australian wildfires highlight the need for new fire, resource, and conservation policies. *Proceedings of the National Academy of Science USA*, 117(22), 12481–12485.
- Lopes, A., Girona-García, A., Corticeiro, S., Martins, R., Keizer, J., & Vieira, D. (2020). What is wrong with post-fire soil erosion modelling? A meta-analysis on current approaches, research gaps, and future directions. *Earth Surface Processes and Landforms*.
- Martin, D. A. (2016). At the nexus of fire, water and society. *Philosophical Transactions of Royal Society B*, 371, 1–9.
- Miller, M. E., Billmire, M., Elliot, W., Robichaud, P., & Miller, S. (2019). NASA RRED user manual for running QWEPP. https://rred.mtri.org/baer/static/RRED_user_manual_for_QGIS.pdf
- Morgan, R. P. C. (2001). A simple approach to soil loss prediction: A revised Morgan-Morgan-Finney model. *Catena*, 44(4), 305–322.
- Morgan, R. P. C., & Duzant, J. H. (2008). Modified MMF (Morgan-Morgan-Finney) model for evaluating effects of crops and vegetation cover on soil erosion. *Earth Surface Processes and Landforms*, 33(1), 90–106. [English].
- Neitsch, S., Arnold, J., Kiniry, J., & Williams, J. (2011). *Soil and Water Assessment Tool Theoretical Documentation Version 2009*. Texas Water Resources Institute. <http://hdl.handle.net/1969.1/128050>

- Neris, J., Elliot, W. J., Doerr, S. H., & Robichaud, P. R. (2017). Development of a model to predict ash transport and water pollution risk in fire-affected environments. *Geophysical Research Abstracts*, EGU General Assembly 2017. 19:EGU2017-18845.
- Neris, J., Santin, C., Lew, R., Robichaud, P. R., Elliot, W. J., Lewis, S. A., Sheridan, G., Rohlf, A. M., Ollivier, Q., Oliveira, L., & Doerr, S. H. (2021). Designing tools to predict and mitigate impacts on water quality following the Australian 2019/2020 wildfires: Insights from Sydney's largest water supply catchment. *Integrated Environmental Assessment and Management*. <https://doi.org/10.1002/ieam.4406>
- NSW National Parks and Wildlife Service. (2020). *The 2019/20 fire season: Context and impacts*. [https://www.parliament.nsw.gov.au/lcdocs/other/13406/Presentation%20-%20National%20Parks%20and%20Wildlife%20Service%20\(NPWS\)%20-%2030%20June%202020.pdf](https://www.parliament.nsw.gov.au/lcdocs/other/13406/Presentation%20-%20National%20Parks%20and%20Wildlife%20Service%20(NPWS)%20-%2030%20June%202020.pdf)
- Nunes, J. P., Doerr, S. H., Sheridan, G., Neris, J., Santin, C., Emelko, M. B., Silins, U., Robichaud, P. R., Elliot, W. J., & Keizer, J. (2018). Assessing water contamination risk from vegetation fires: Challenges, opportunities and a framework for progress. *Hydrological Processes*, 32(5), 687–694.
- NVIS Technical Working Group. (2017). *Australian Vegetation Attribute Manual: National Vegetation Information System, Version 7.0*. Department of the Environment and Energy.
- Parsons, A., Robichaud, P. R., Lewis, S. A., Napper, C., & Clark, J. T. (2010). *Field guide for mapping post-fire soil burn severity* (Gen. Tech. Rep. RMRS-GTR-243). Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
- Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D. K., & Yoder, D. C. (1997). *Predicting soil erosion by water: A Guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE)*. Vol. 703. Washington, D.C.: U.S. Gov. Print. Office. USDA-ARS Agriculture Handbook.
- Renschler, C. S. (2003). Designing geo-spatial interfaces to scale process models: The GeoWEPP approach. *Hydrological Processes*, 17(5), 1005–1017. (English).
- Robichaud, P. R., Beyers, J. L., & Neary, D. G. (2000). *Evaluating the effectiveness of postfire rehabilitation treatments*. EEUU, USDA Forest Service, Rocky Mountain Research Station, p. 63.
- Robichaud, P. R., Elliot, W. J., Pierson, F. B., Hall, D. E., & Moffet, C. A. (2014). *Erosion risk management tool (ERMiT)*. Moscow, ID: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.
- Santin, C., Doerr, S. H., Otero, X. L., & Chafer, C. J. (2015). Quantity, composition and water contamination potential of ash produced under different wildfire severities. *Environmental Research*, 142, 297–308.
- Santin, C., Otero, X. L., Doerr, S. H., & Chafer, C. J. (2018). Impact of a moderate/high-severity prescribed eucalypt forest fire on soil phosphorous stocks and partitioning. *Science of the Total Environment*, 621, 1103–1114.
- Shakesby, R. A. (2011). Post-wildfire soil erosion in the Mediterranean: Review and future research directions. *Earth Science Review*, 105(3–4), 71–100.
- Shakesby, R. A., & Doerr, S. H. (2006). Wildfire as a hydrological and geomorphological agent. *Earth Science Review*, 74(3–4), 269–307.
- Shakesby, R. A., Wallbrink, P. J., Doerr, S. H., English, P. M., Chafer, C. J., Humphreys, G. S., Blake, W. H., & Tomkins, K. M. (2007). Distinctiveness of wildfire effects on soil erosion in south-east Australian eucalypt forests assessed in a global context. *Forest Ecology and Management*, 238(1–3), 347–364.
- Smith, H. G., Sheridan, G. J., Lane, P. N. J., Nyman, P., & Haydon, S. (2011). Wildfire effects on water quality in forest catchments: A review with implications for water supply. *Journal of Hydrology*, 396(1–2), 170–192.
- Smith, R. E., Goodrich, D. C., & Quinton, J. N. (1995). Dynamic, distributed simulation of watershed erosion: The KINEROS2 and EUROSEM models. *Journal of Soil and Water Conservation*, 50(5), 517–520.
- Srivastava, A., Dobre, M., Wu, J. Q., Elliot, W. J., Bruner, E. A., Dun, S., Brooks, E. S., & Miller, I. S. (2013). Modifying WEPP to improve stream-flow simulation in a Pacific northwest watershed. *Transactions of the ASABE*, 56(2), 603–611.
- Srivastava, A., Wu, J. Q., Elliot, W. J., Brooks, E. S., & Flanagan, D. C. (2017). Modeling Streamflow in a snow-dominated forest watershed using the Water Erosion Prediction Project (WEPP) Model. *Transactions of the ASABE*, 60(4), 1171–1187.
- Srivastava, A., Wu, J. Q., Elliot, W. J., Brooks, E. S., & Flanagan, D. C. (2018). A simulation study to estimate effects of wildfire and forest management on hydrology and sediment in a forested watershed, northwestern U.S. *Transactions of the ASABE*, 61(5), 1579–1601.
- Vanoni, V. A. (2006). *Sedimentation engineering*. Virginia, USA: American Society of Civil Engineers. (Manuals and reports on engineering practice; np 54).
- Visentin, L., Clun, R., & Power, J. (2019, December 27). *Bushfires threaten Sydney's drinking water supply*. The Sydney Morning Herald. <https://www.smh.com.au/politics/nsw/nsw-water-agencies-working-around-the-clock-20191223-p53mhc.html>
- Wang, L., Wu, J., Elliott, W., Dun, S., Lapin, S., Fiedler, F., & Flanagan, D. (2010). *Implementation of channel-routing routines in the Water Erosion Prediction Project (WEPP) model*. 2009 SIAM Conference on “Mathematics for Industry” The Art of “Mathematics for Industry”, San Francisco, CA.
- Wang, L., Wu, J. Q., Elliot, W. J., Fiedler, F. R., & Lapin, S. (2014). Linear diffusion-wave channel routing using a discrete Hayami convolution method. *Journal of Hydrology*, 509, 282–294.
- Wischmeier, W., & Smith, D. (1978). *Predicting rainfall-erosion losses—A guide to conservation planning*. Agriculture Handbook No. 537. USDA.
- Yang, X., Zhang, M., Oliveira, L., Ollivier, Q. R., Faulkner, S., & Roff, A. (2020). Rapid assessment of hillslope erosion risk after the 2019–2020 wildfires and storm events in Sydney drinking water catchment. *Remote Sensing*, 12, 3805. <https://doi.org/10.3390/rs12223805>