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Modeling the emission, transport and deposition of contaminated dust from a mine tailing site

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Abstract

Mining operations are potential sources of airborne particulate metal and metalloid contaminants through both direct smelter emissions and wind erosion of mine tailings. The warmer, drier conditions predicted for the Southwestern US by climate models may make contaminated atmospheric dust and aerosols increasingly important, due to potential deleterious effects on human health and ecology. Dust emissions and dispersion of contaminants from the Iron King Mine tailings in Dewey-Humboldt, Arizona, a Superfund site, are currently being investigated through in situ field measurements and computational fluid dynamics modeling. These tailings are significantly contaminated with lead and arsenic with an average soil concentration of 1616 and 1420 ppm, respectively. Similar levels of these contaminants have also been measured in soil samples taken from the area surrounding the mine tailings. Using a computational fluid dynamics model, we have been able to model dust transport from the mine tailings to the surrounding region. The model includes a distributed Eulerian model to simulate fine aerosol transport and a Lagrangian approach to model fate and transport of larger particles. In order to improve the accuracy of the dust transport simulations both regional topographical features and local weather patterns have been incorporated into the model simulations.

Keywords

computational fluid dynamics; contaminated dust; deposition; mine tailings

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Introduction

The US Environmental Protection Agency (EPA) regulates six air pollutants subject to the National Ambient Air Quality Standards: CO, SO₂, NO₂, lead, ozone and particulate matter with an aerodynamic diameter of 2.5 µm (PM_{2.5}) and 10 µm (PM₁₀) (NAAQS, 2013). Of these six air pollutants, particulate matter is interesting because it is the concentration of particles of a certain diameter range not the chemical composition that is regulated. It has been concluded from a review of multiple studies that elevated PM_{2.5} exposures are causal for cardiovascular disease, all-cause, cardiovascular-, and respiratory mortality (1). Additionally, elevated PM_{2.5} exposure was deemed 'likely causal' for aggravated asthma and decreased lung function, and suggestively linked to adverse reproductive and developmental outcomes and lung cancer (1). It is because of these impacts on human health that steps are taken to limit and reduce the intentional production of suspended particulate matter from anthropogenic sources

Mining operations, particularly mine tailing impoundments, are sources of particulate matter because they are comprised of fine, loose sediment. In the desert southwest the semiarid climate and lack of vegetation increases the likelihood of windblown dust. It is the combination of the semiarid climate and the easily erodible mine tailings that makes the windblown transport of particulate matter an important issue.

We utilised a 3-dimensional computational fluid dynamics (CFD) model to simulate the transport and deposition of dust from the mine tailing impoundments in the desert southwest. The specific field site we use for this research is the Iron King Mine tailings impoundment located in Dewey-Humboldt Arizona about 90 miles north of Phoenix. The abandoned mining operation has been classified as a Superfund site by the US EPA since 2008 (2). Soil samples taken from the site contained elevated concentrations of both arsenic and lead, amongst other metals (3). Recent samples taken from the tailings material has shown arsenic and lead concentrations both between 600 and 3500 ppm. Our goal is to determine how regional topography and weather affects the erosion and deposition of windblown dust.

Methodology

The area surrounding the Iron King site is semiarid with sparse vegetation, including grasslands, chaparral, and piñon/juniper woodlands (3). Figure 1 shows a Google Earth satellite image of the area and the adjacent town of Dewey-Humboldt. It is because of the potential impact on human health in the nearby residential areas that makes understanding the transport and deposition patterns of these contaminated aerosols so important.

We use FLUENT 12.0, distributed by ANSYS Corporation. The three components we use are: 1) basic fluid flow, 2) species transport, and 3) discrete phase modeling (4). It is these three models when used together that allow us to simulate the generation, transport and deposition of tailings particles eroded by the wind.

In an effort to produce realistic simulations, a model domain was created that incorporated the regional topography of the site. The model domain had a horizontal extent of about 25 km² centered on the tailings with a 1/3 arc second (10.3 m) spatial resolution (5).

The wind field was solved using a *k-ε* two equation turbulent model. A turbulent fluid flow model was needed to accurately simulate the turbulent eddies that are formed along the edges of the tailing impoundments and in the complex topography of tailings and surrounding region. The wind field was initialised with a logarithmic wind profile, a profile that is typically observed near the surface. The initialization of the wind direction and magnitude is manually controlled for each simulation and results in a recreation of steady state wind fields around the tailings.

Species transport modeling allows for the tracking of multiple gaseous species in the CFD simulations. By controlling the diffusive properties of a species we can simulate the transport and diffusive growth of a dust plume. By setting the diffusive property of a species to represent a plume of 1 μm diameter aerosol particles, the simulated transport of the species is representative of a dust plume of micrometer diameter particles (Stovern MK et al. Simulation of Windblown Dust Transport from a Mine Tailings Impoundment using a Computational Fluid Dynamics Model 2014 under review). Species transport modeling works best when simulating the transport of the smallest sized particles due to their long gravitational settling times. However, for larger particles (>10 μm diameter) species transport simulations are not the ideal method and discrete phase modeling provides a better estimate of particle transport.

Discrete phase modeling (DPM) is used to determine the trajectory of particles released into a flow field. The particle diameter, injection location and release velocity are defined for the DPM simulations. The particles in the DPM simulations were released in a uniform grid with 5 m horizontal spacing from the tailing impoundments for multiple different initialised wind directions. When these particles impact the ground boundary they are trapped and their deposition location is recorded.

Results

Multiple dust plume simulations were conducted using the dominant wind directions observed on the tailings over a period of 18 months: southeasterly, southerly, southwesterly, and westerly. The wind velocity vertical profile was initialised with a 7 m/s wind speed at 10-m height. The species plume simulations used a PM2.5 emission rate that was calculated using *in situ* observations and the US EPA AP42 wind erosion model (6).

The dust plume simulations were run for a total of 900 s with 4-second time steps, which allowed for the dust plume to be fully advected through the model domain. Figure 2 shows a nadir viewing snapshot of the near surface species dust concentration for a southerly wind direction simulation 90 s after the dust plume was emitted, overlaid on a Google Earth image of the area (Stovern MK et al. Simulation of Windblown Dust Transport from a Mine Tailings Impoundment using a Computational Fluid Dynamics Model 2014 under review). The units of the colour mapping correspond to the mass fraction of the dust species. By

taking vertical profiles of mass fraction we can determine the total deposition resulting from the dust plume at any location. Deposition was calculated every 500 m downwind from the tailings for the four different wind direction simulations. Surprisingly, there was not a systematic reduction in total deposition as the plume moved away radially from the tailings downwind. In fact there were some locations that saw greater total deposition than a location that was 500 m closer to the tailings (Stovern MK et al. Simulation of Windblown Dust Transport from a Mine Tailings Impoundment using a Computational Fluid Dynamics Model 2014 under review).

Following the species plume simulations, DPM simulations were conducted to determine the fates of individual particles. For these simulations particles with a 2.5 μm diameter were uniformly released from the tailings surface. Figure 3 shows the particle trajectories after being freely released from the tailings. The particle trajectories are coloured by their elevation within the model domain. When we released these particles and tracked their deposition locations we found an interesting pattern. Particles tended to become trapped in the turbulent eddies that formed near the edges of the tailings. However, particles that traveled further than 500 m from the tailings tended to deposit on regions of topographic upslope (Stovern MK et al. Simulation of Windblown Dust Transport from a Mine Tailings Impoundment using a Computational Fluid Dynamics Model 2014 under review). Topographic upslope is a measure of the ground slope as measured along a radial direction with the origin being the centre of the mine tailings. Positively sloped areas are defined as upslope and negatively sloped areas are defined as downslope. When we calculated the slopes for the locations used to calculate deposition from the species simulations it was realised that the upslopes (i.e., small topographic ridges) coincided with regions of higher deposition. A reduction in deposition was also observed in regions of downslope. Utilising two fundamentally different aerosol transport models, DPM and species transport, we have been able to show that airborne particulate matter preferentially deposits in upslope regions.

The result of this work gives us some insight into how topography plays an important role in the transport and deposition of airborne particulate matter. The impact of topographic upslope on aerosol deposition should be integrated into all small scale regional dust transport models in order to produce the most realistic predictions of windblown dust deposition. By using these models we were better able to understand the controlling mechanisms of dust transport in the region. Currently, mitigation plans such as phytostabilisation are currently being implemented on the mine tailings to reduce the transport of the contaminated dust and the dust's impacts on human health. The CFD model used to understand the controlling mechanisms of dust deposition can be modified to simulate the impact of these proposed wind erosion mitigation efforts.

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Figure 1.

Google Earth image of the town of Dewey-Humboldt, Arizona, showing the extensive mine tailings (center-left). The figure spans 3.2 km by 3.25 km.

Figure 2.

Spread of a dust plume emitted from the mine tailings under a 7 m/s m/s (at 10-m height) southerly wind, 90 min after emission.

Values shown are particle mass fractions. Available at: <http://yosemite.epa.gov/r9/sfund/r9sfdocw.nsf/db29676ab46e80818825742600743734/316161edfc4699a5882574ab0001d1c0!OpenDocument#descr>

Figure 3.

Particle (PM2.5) trajectories as they are emitted from the tailings subject to a wind field corresponding to a 7 m/s wind speed @ 10-m height. Legend shows particle elevation (m).