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Journal of Alloys and Compounds 444–445 (2007) 11–18

Journal of ALLOYS AND COMPOUNDS

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Rocky Flats closure: The role of models in facilitating scientific communication with stakeholder groups

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Received 30 September 2006; received in revised form 3 February 2007; accepted 9 February 2007

Abstract

The Rocky Flats Environmental Technology Site (RFETS) was a U.S. Department of Energy (DOE) environmental cleanup site for a previous manufacturing plant that made components for the U.S. nuclear weapons arsenal. The facility was shut down in 1989 to address environmental and safety concerns, and left behind a legacy of contaminated facilities, soils, surface and ground water. In 1995, the Site contractor established the Actinide Migration Evaluation (AME) advisory group to provide advice and technical expertise on issues of actinide behavior and mobility in the air, surface water, groundwater, and soil. Through a combination of expert judgment supported by state-of-the-art scientific measurements, it was shown that under environmental conditions at Rocky Flats, plutonium and americium form insoluble oxides that adhere to small soil, organic, and mineral particles and colloids, or are colloidal materials themselves. A series of models ranging from conceptual, geostatistial, and large-scale wind and surface water erosion models were used to guide stakeholder interactions. The nature of these models, and their use in public communication is described.

Keywords: Environmental remediation; Geostatistical models; Sediment transport; Colloid

1. Introduction

The Rocky Flats Environmental Technology Site (RFETS) was a U.S. Department of Energy (DOE) environmental cleanup site located about 24 km northwest of downtown Denver. From 1952–1989, the Rocky Flats Plant fabricated components for U.S. nuclear weapons using various radioactive and hazardous materials, including plutonium and uranium. In 1989, nuclear production work was halted due to environmental and safety concerns, and the Site was added to the Environmental Protection Agency (EPA) Superfund list later that year. In 1993, the Secretary of Energy announced the end of the Rocky Flats nuclear production mission. Nearly 40 years of nuclear weapons production had created a large legacy of contaminated facilities, soils, surface and ground water at the Site.

Many areas at Rocky Flats had plutonium and americium contaminated soil and water due to the improper disposal of contaminated materials, ruptured or leaking pipes, fires, or faulty storage units. By far the largest source of plutonium and americium contamination in soils resulted from the drum storage area known as the 903 Pad. From 1958 to 1969, drums containing plutonium-contaminated lathe coolant were stored on the Pad, located on the southeastern part of the Industrial Area (Fig. 1). These drums leaked, and wind and water erosion carried plutonium and americium in a well-defined pattern to the east and southeast, beyond the eastern Site boundary in some cases. It is estimated that about 5000 gallons containing approximately 86 g (5.3 Ci) of plutonium were released into soil [1].

In March 1995 DOE estimated the cleanup for Rocky Flats would cost in excess of $37 billion and take 70 years to com-

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doi:10.1016/j.jallcom.2007.02.121

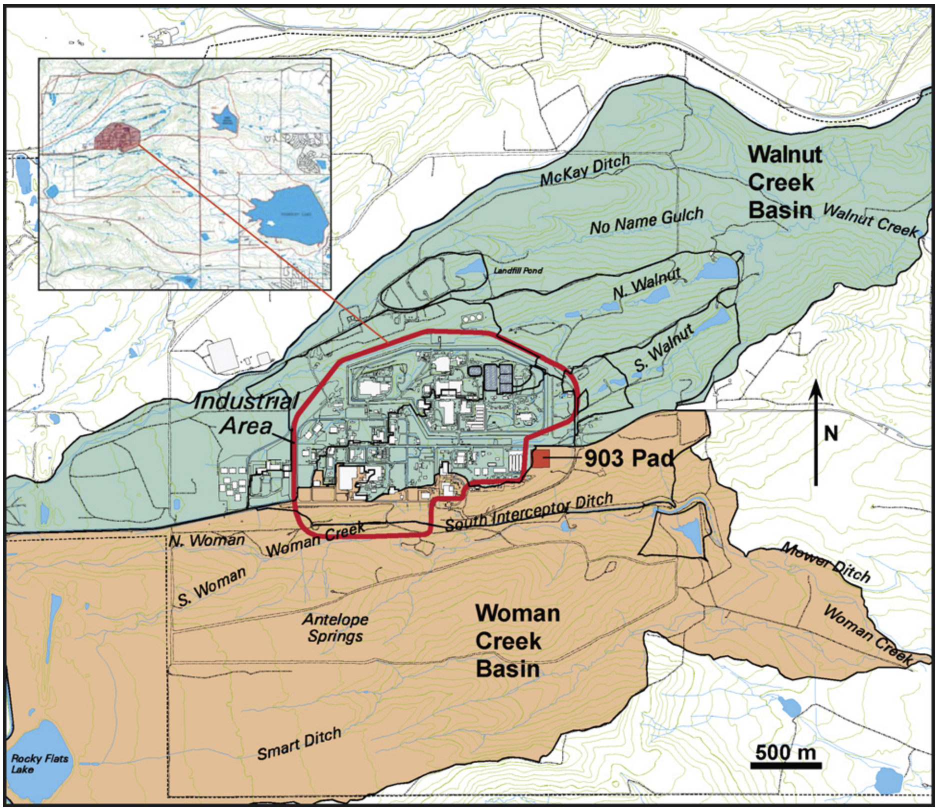

Fig. 1. The Rocky Flats Site map showing the Industrial Area, and the Walnut Creek and Woman Creek drainage basins. The inset shows the proximity of the Site to Great Western Reservoir and Standley Lake.

plete [2]. By 1996, DOE and Kaiser-Hill initiated a massive accelerated closure effort that resulted in a plan to reach closure by December 31, 2006 at a contracted cost of $7 billion. After a troubled start, Kaiser-Hill completed the task nearly a year ahead of schedule. Factors that contributed to this turnaround included the incentive-laden contract, strong support and stable funding from Congress, high-level DOE support that mobilized the entire complex to assist the cleanup, technological and operational innovation, and scientific understanding [3]. In this report we discuss the role of scientific models in communicating with stakeholder groups, and in guiding key cleanup decisions and facilitating good project management.

2. About the Site

RFETS encompasses approximately 26.7 km^2 and was similar to a small city, with its own fire department, medical offices, cafeterias, steam plant, and water- and sewage-treatment plants (Fig. 1). Over 800 structures were located within a centralized 1.6-km^2 Industrial Area surrounded by a 25.1 km^2 grassland Buffer Zone. This open space continues to serve as a buffer between Rocky Flats and the nearby, growing communities and is home to many species of animals and plants.

Water at RFETS and the surrounding area is distributed among surface water, shallow groundwater, and deep groundwater [4]. Surface water flows across RFETS primarily from west to east along North and South Walnut Creek, and Woman Creek in the Industrial Area (Fig. 1). Detention ponds had been constructed along these drainages to manage plant wastes and surface water runoff. The A- and B-series ponds are located on North and South Walnut Creeks, and the C-series ponds on Woman Creek. Past discharge of low-level contaminated wastes to the A- and B-series ponds resulted in the accumulation of plutonium and americium in the pond sediments.

Shallow groundwater refers to water within the alluvium and weathered bedrock geologic units to a depth of 30 m. Surface water and shallow groundwater are inextricably linked [5]. Water from stream channels, storm water and industrial areas infiltrates downward, recharging the shallow groundwater, which, in turn recharges the stream channels depending upon the time of the year. Beneath the alluvium is a highly impermeable bedrock layer that inhibits vertical flow. As a result, shallow groundwater flows laterally, discharging as baseflow into the streams or as hillslope springs and seeps. Approximately 200–300 m below the surface lies the Fox Hills Sandstone, where deep regional groundwater flows. Because of the intervening bedrock, this regional groundwater aquifer is hydraulically isolated from the Rocky Flats surface and shallow groundwater and actinide contaminants [6].

The climate is temperate and semiarid, characteristic of Colorado's Front Range. The average annual precipitation is approximately 36.8 cm, with about half occurring as rain from May to October and half as snow from late October through early April. Evapotranspiration averages over 40.1 cm per year, creating a water deficit in most years. Prior to the removal of the Industrial Area, much of the runoff feeding the Site's drainages occurred rapidly from the impervious Industrial Area surfaces. Winds at RFETS are predominantly from the northwest toward the southeast. The RFETS is noted for the periodic occurrence of strong, gusty winds (≥160 km/h) that are an important factor in the resuspension of soil and actinides. Air monitoring and calculations of the actinide loads showed that air transport has been a dominant actinide migration pathway.

3. Stakeholder interactions

Because of the close proximity of RFETS to a large metropolitan area, there was a strong public interest in the Site's remediation and closure. Multiple stakeholder organizations were involved in monitoring the site's closure progress and remediation planning, including regulatory agencies, neighboring communities, local governments, and other public interest groups. Stakeholder engagement encompassed the frequent formal and informal mechanisms of staying connected to the parties with a main interest in the remediation processes and outcome. Early on, engagement included education about the fundamental chemical and physical properties of plutonium, and our expectations for its behavior in the Rocky Flats environment. Engagement also implied understanding stakeholder views and taking them into consideration, being accountable to them in continuity of communication, and using the information assembled from them to drive innovation and Site evolution.

Stakeholder engagement spanned a continuum of interaction that reflected the degree of influence stakeholders had in decision making. At one extreme, the DOE and/or contractor simply informed stakeholders of their plans. At the other, stakeholders were deeply involved from early in the decision-making process. In between were varying degrees of consultation and participation.

At RFETS there was a well-organized consortia of neighboring communities, local governments, and public interest stakeholder groups. They played a strong role in pressuring the regulators, the contractor, and ourselves (as scientific advisors) to discuss scientific issues on plutonium transport in a public forum. Frequent public debate and gradual acceptance of the scientific understanding of actinide transport processes were significant elements in bringing these groups to a common understanding of key issues. This common understanding led, in turn, to the negotiation of long-sought agreements on cleanup.

4. The Actinide Migration Evaluation

In 1995 intense rainfall and wet spring conditions raised concerns among Site personnel and stakeholder groups about the potential for increased plutonium mobility and off-site transport. There was a hypothesis that plutonium was soluble in surface and ground water in order to account for increased plutonium concentrations at on-site surface water monitoring locations. Modeling efforts and site data at the time predicted very limited movement of plutonium. The prediction of plutonium immobility, coupled with the conflicting observation of plutonium transport at surface water monitoring stations, led to public mistrust and lack of confidence. This and other uncertainties on the behavior of different actinide elements (uranium, plutonium, americium) at different Site locations, led DOE and Kaiser-Hill to establish the Actinide Migration Evaluation (AME) advisory group to provide advice and technical expertise on issues of actinide behavior and mobility in the air, surface water, groundwater, and soil.

Through a combination of expert judgment supported by state-of-the-art scientific measurements, it was shown that under environmental conditions at Rocky Flats, plutonium and americium form insoluble oxides that adhere to small soil, organic, and mineral particles and colloids, or are colloidal materials themselves. The detailed science that led to this recognition has been described elsewhere [7–12]. These particles and colloids can migrate in the Rocky Flats environment by wind and surface water resuspension and sedimentation processes. The scientific data showed that soluble transport models dependent on soil and water distribution coefficients (K_ds) were not appropriate, and led to the development and application of erosion/sediment transport models for air- and surface-water transport [13]. The scientific understanding developed through these integrated studies provided the basis for the negotiation of plutonium and americium cleanup levels selected by the Rocky Flats Cleanup Agreement (RFCA) parties of 50 pCi/g of plutonium in surface soils.

The communication of these findings to the various stakeholder groups was facilitated through the use of models of various levels of sophistication.

5. Conceptual models

In 1998, a conceptual model for actinide (Pu, Am, U) transport was developed by the AME to provide a comprehensive overview of the possible mechanisms that impact actinide transport in the environment. It also contained the near-term, intermediate, and long-term goals of the AME project which helped to prioritize work scope. One conceptual model was developed for Pu and Am (Fig. 2), because these elements have similar dominant colloidal transport characteristics based on their similar, low solubilities and minor background concentrations in the environment. A separate conceptual model was developed for uranium, which has dominant dissolution transport mechanisms with higher background concentrations and greater solubility. The conceptual model was used by AME as a guide to communicate and assess potential transport pathways and focus stakeholder discussions and AME work scope on the dominant actinide transport pathways. It was also used to direct scientific investigations of the different actinide transport pathways and their relative importance. Both the conceptual model and the actual understanding of actinide transport at RFETS were continually being refined as new studies provided additional data to confirm and/or modify individual transport pathways. The results of the conceptual model and the associated quantification of the actinide pathway formed the basis for the Pathway Analysis Report (a summary report for the stakeholders supported by a detailed technical appendix) [4].

Once developed, the conceptual model was continuously used to increase the general understanding of actinide transport

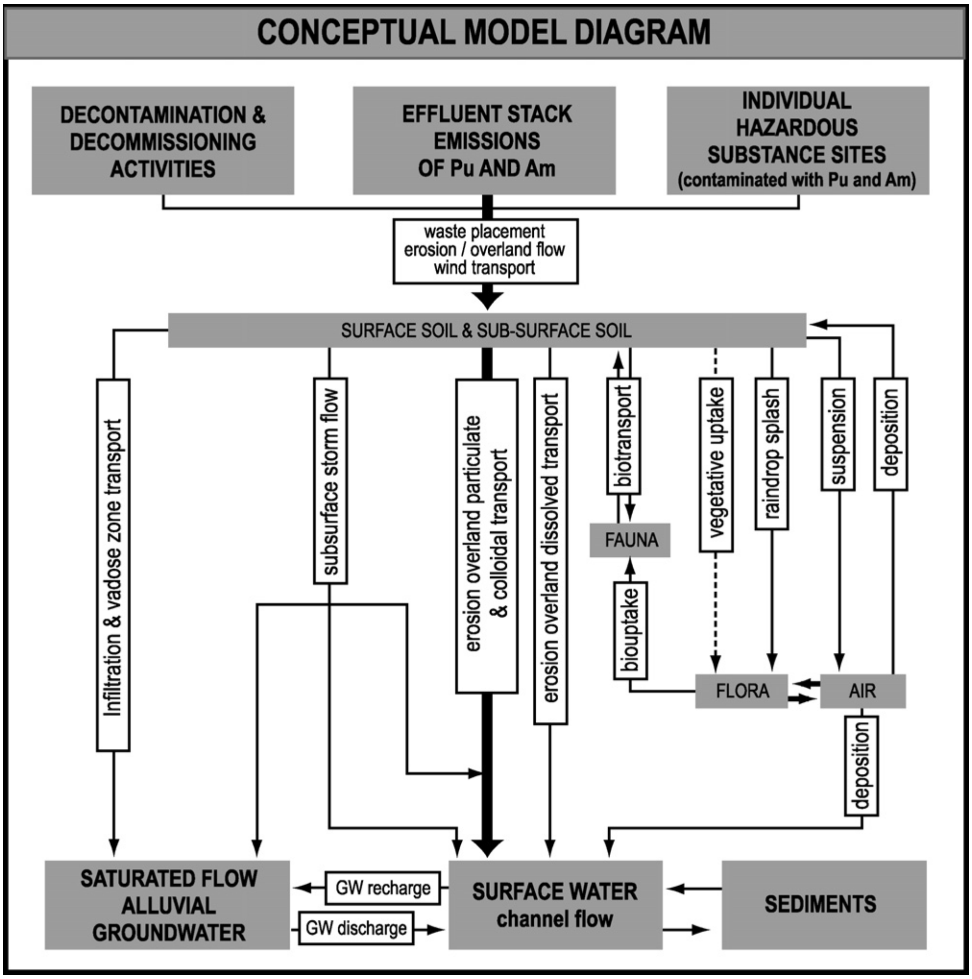

Fig. 2. To facilitate understanding and communication of potential routes for actinide transport in the RFETS environment, schematic conceptual models of potential actinide transport pathways were developed. Thicker lines denoted major pathways, while thin lines indicated minor pathways. This Conceptual model diagram qualitatively shows potential plutonium and americium transport pathways at RFETS and indicated that the dominant pathway for Pu and Am migration was expected to be through erosion of surface soils and overland particulate and colloid transport.

pathways with all the stakeholder groups, spanning interactions with regulators (DOE, EPA, CDPHE), the contractor (Kaiser-Hill managers and workers), neighboring communities, local governments, concerned citizen and concerned scientist groups.

6. Geostatistical models

In order to determine the location, area, and volume of soil potentially requiring evaluation, management, or remediation, a massive Site characterization effort occurred at Rocky Flats, beginning in the late 1960s [14]. Between 1991 and 1999, nearly 2500 surface soil samples were collected and analyzed for $^{239/240}$Pu and ^{241}Am across the Site to assess the level and extent of actinide contamination [15]. As it was not practical to sample the surface soil of every square meter of the 25 km^2, therefore surface samples were collected at site locations that allowed their use to estimate concentrations of $^{239/240}$Pu and ^{241}Am over the entire site. A heterogeneous small scale concentration distribution over a large spatial area at RFETS led to the use of state-of-the-art geostatistical analyses [16], including the techniques of variograms and Kriging [17].

Variogram analysis performs the task of capturing correlation information about surface soil data by comparing sample data at different distance intervals. Generally, as the distance between samples increases, the variability also increases, with a corresponding decrease in the correlation. For Pu and Am, variogram graphs exhibited significant spatial correlation, with a structure similar to that found at other environmental sites where there is a small, concentrated contaminant source and where wind is the dominant dispersal mechanism [18].

Kriging analysis uses variogram models to estimate Pu and Am soil concentrations at locations that have not been directly sampled. Estimated spatial concentrations of $^{239/240}$Pu in surface soil at RFETS from Kriging analyses are shown in Fig. 3. Plutonium and americium generally exhibit the same spatial distribution in surface soils, with wide variations in activities occurring throughout the Site. The highest concentrations were found at the 903 Pad and areas to the east of the Pad, and display a wind-driven dispersal pattern to the east of the primary source area – the 903 Pad (Fig. 3). The plutonium and americium radioactivity in RFETS soils is highly heterogeneous, often consisting of “hot particles” [11]. Approximately 90 percent of the

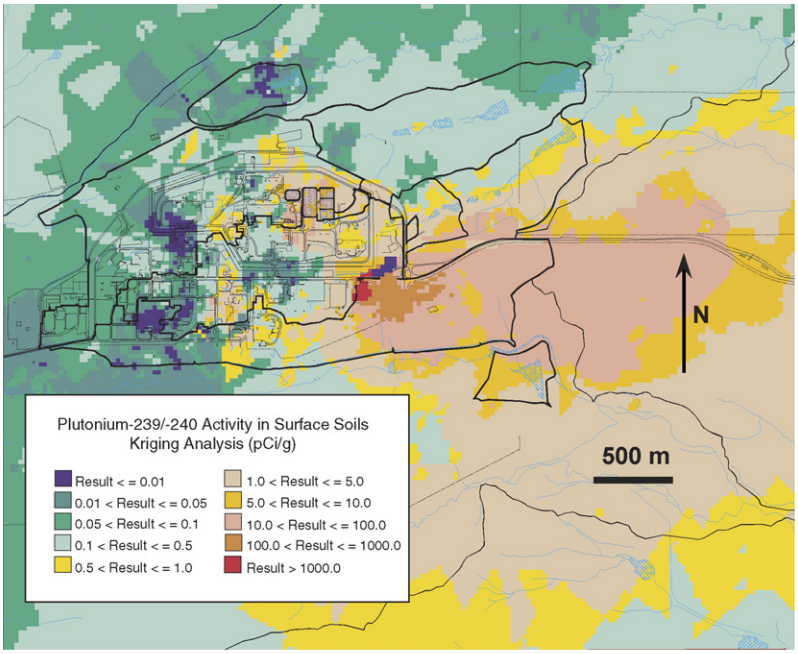

Fig. 3. Because it was not feasible to sample surface soil at every location, and geostatistical modeling technique known as Kriging was applied to the plutonium surface soil data for $^{239/240}$Pu to estimate concentrations in surface soil. The "hot spot" of $^{239/240}$Pu concentrations in excess of 1000 pCi/g at the 903 Pad is shown in red. A clear plume of $^{239/240}$Pu contamination that tracks roughly with the prevailing winds from NW to SE is evident from the data. This figure represents conditions at Rocky Flats prior to soil remediation actions.

plutonium and americium inventory was in the top 12 cm of the soil, consistent with this assessment.

7. Erosion and Sediment Transport models

With the enhanced understanding of plutonium and americium particle transport processes, it was clear that contaminant transport models based on soluble forms of plutonium were not applicable or defensible. Therefore, alternate contaminant transport modeling approaches were sought that focused on spatially distributed contaminants in soils and sediments. Part of the capability required was the ability to predict contaminant transport under existing conditions and for a range of possible future Site remediation and management scenarios.

The state-of-the-art model selected for use in simulating hillslope erosion processes at the RFETS was the Water Erosion Prediction Project (WEPP) model [19,20]. It is a new generation process-oriented computer model incorporating improvements in erosion prediction technology based on erosion mechanics, soil physics, plant science, hydrology, infiltration theory, and stochastic weather generation. The WEPP model estimates the spatial and temporal distributions of soil erosion and sediment deposition from overland flow on hillslopes; and the erosion, sediment transport, and deposition in small channels and impoundments. It also accounts for enrichment of transported sediment in small and colloidal particles making it well-suited for contaminant transport calculations.

To estimate stream channel sediment erosion and deposition, output data from the WEPP model was routed into the U.S. Army's Hydrologic Engineering Center (HEC) sediment transport model, HEC-6T [21], that allows for up to 100 tributary inflows to the main channel, which was crucial for modeling the RFETS watersheds. Model output from WEPP and HEC-6T were combined with soil Pu and Am data (from Kriging analyses), using Geographic Information Systems (GIS) software, to develop predictions of surface water actinide concentrations in the RFETS watershed. The data on contaminant and erosion distributions were mapped separately, and used to create actinide mobility maps which indicated Site areas which would benefit from soil remediation and erosion/sedimentation control actions [13].

The soil erosion sediment transport models were used for three main purposes at RFETS. First, they were applied to the hillslopes and channel systems and compared with monitoring data to parameterize, initialize, and calibrate the models to the maximum extent. Then, storm events (runoff, soil erosion on the hillslopes, and sediment transport in the channel systems) and the ^{239,240}Pu and ^{241}Am contaminants they transported were simulated by the coupled erosion-sediment transport models to compare with monitoring data. The simulation models were found to statistically replicate the transport of contaminants by particle size fractions as measured in the field and laboratories. This provided a particle transport modeling capability at RFETS. Second, the coupled models were used with climate and distributed soil contamination data to estimate surface water yields of sediment and contaminants for the pathway analysis. Finally, the coupled models were used with climate and soil contamination data ranging from hillslopes up to major drainage channels to predict rates and routes of sediment and contaminant transport under various management scenarios proposed to reduce within- and off-site transport of contaminants. The results of these simulation modeling predictions were considered in erosion control procedures to be implemented.

Under the drastically changed reconfigured site conditions (with buildings and pavement removed), specific historical monitoring data are limited in usefulness to predict future runoff, sediment, and contaminant yields on a local to integrated landscape scale. Therefore, RFETS adopted a methodology of using historical data to calibrate simulation models and then using the simulation models to predict future runoff, sediment, and contaminant yields. The models were also used to design and evaluate temporary and smaller scale erosion control and remediation actions because they can predict the consequences of changing land management/configuration.

As part of the erosion modeling process, the predicted soil erosion (mass eroded/unit area) was coupled with soil actinide concentration data to generate a map of predicted actinide mobility for a specific storm event (Fig. 4). Actinide mobility maps and model results of plutonium and americium concentrations in surface water provided improved understanding of plutonium and americium mobility as a result of surface water erosion processes. The model results made it apparent that the largest plutonium and americium loads delivered to surface water do not necessarily originate from areas with the highest concentrations of plutonium and americium in the soil. It is the combination of soil erodibility and soil actinide concentration that dictates the quantity of actinides delivered to surface water. For example, the area east of the 903 Pad alongside the East Access Road generally has the highest levels of plutonium and americium in the soil of the Lip Area (Fig. 4). However, this area is relatively flat, with slopes of approximately 1%. As a result it experiences less soil erosion than other, steeper parts of the watershed, with a corresponding reduced amount of associated plutonium and americium transport. These modeling tools were used to evaluate alternatives considered for the 903 Lip Area remediation, and general future land configuration scenarios for the Site.

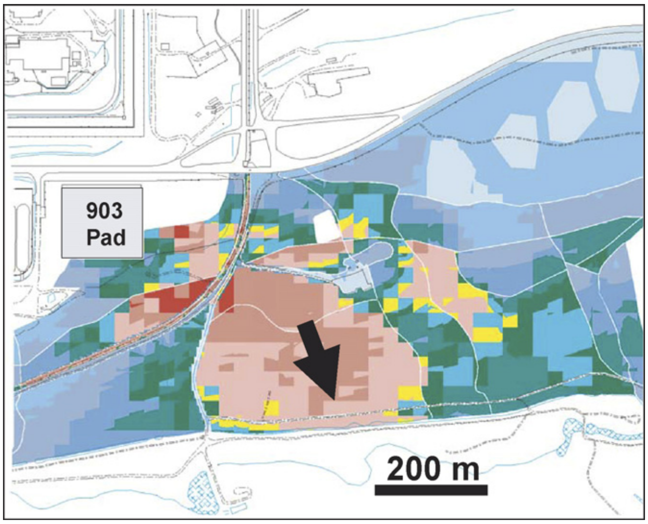

Fig. 4. Plutonium mobility map of a 100-year, 6-h storm event for the 903 Pad and Lip Area watershed. Red indicates areas with the highest plutonium mobility, blue indicates areas with the lowest plutonium mobility. The models show that up to 99% of plutonium input to surface water in the channel (South Interceptor Ditch) is from hillslope erosion. After the water, sediment, and plutonium are delivered to the channel the HEC6T model was used to route water, sediment, and plutonium downstream. The arrow indicates the general direction of sediment transport towards the South Interceptor Ditch. Model results are based on conditions prior to remediation actions being completed.

8. Impact of modeling on stakeholder communication and Site operations

The scientific understanding developed through the integrated studies and models described above provided clarity and focus on the real issues surrounding plutonium and americium migration in the RFETS environment. Once Kaiser-Hill, DOE, EPA, the State of Colorado, and the concerned citizen's groups had reached a common understanding of the technical issues surrounding plutonium and americium migration at the Site, these groups were able to reach long-sought-after agreements on how to proceed with cleanup. The common understanding that plutonium and americium were predominantly in particulate and colloidal forms led to the recognition that environmental migration occurs through sedimentation and resuspension of small particles by action of wind and surface water at the Site. This helped all parties focus remediation efforts on surface contamination and wind and surface water transport pathways that posed the greatest risk to human health and the environment. It helped guide selection of surface-specific removal technologies, and future land configuration strategies.

This new understanding led Site operators to respond with a major emphasis on erosion and the need to control it. The most poignant illustration of this shift was the Management Directive (NRT-011-04) from Kaiser-Hill President Nancy Tuor to every employee that discussed the importance of erosion control in all Site activities. The recognized need for erosion controls "close in space and close in time" helped to prevent movement of contaminants during Site remediation activities and reduced the transport of plutonium and americium to the Site's stream channels and ultimately off-site. The additional protection provided by soil erosion control measures allowed site remediation to proceed rapidly and meet or exceed project deadlines.

In 1996, the Rocky Flats Cleanup Agreement radionuclide soil action level for plutonium cleanup was 651 pCi/g, based only on dose, not its transport characteristics. In 2002, armed with improved understanding of plutonium behavior, the DOE, the Colorado Department of Public Health (CDPHE) and EPA released a series of reports that formed the basis for a new surface soil action level of 50 pCi/g that was based on risk, and resulted from unprecedented community involvement. Since plutonium contamination was generally confined to surface soils, the greatest risk to public health was from dispersal due to wind and surface water erosion processes. This new risk-based agreement focused on removal of surface soil contamination at a more aggressive 50 pCi/g standard to 91.4 cm (3 ft) below the surface, with the tradeoff that contaminated soil between 91–183 cm (3–6 ft) could remain in place at the higher concentration of 3 nCi/g, and up to 7 nCi/g at depths greater than 183 cm (e.g. within building basements and the process waste line system).

The Site's Storm Water Pollution Prevention Plan (SWPPP) encouraged minimum soil disturbance, which resulted in control

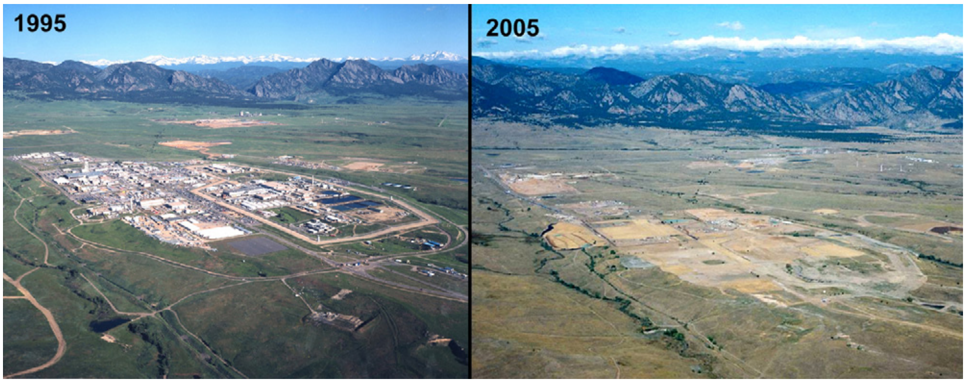

Fig. 5. A comparison of aerial photos of the Rocky Flats Site taken in 1995 (left) and the remediated Rocky Flats Site, taken in October 2005 (right).

and minimization of erosion and sedimentation, maximization of well developed vegetative cover, and minimization of runoff across the site. Each project was reviewed for impacts to surface water with a specifically designed control system. Erosion control measures included straw bales and wattles, straw crimping, silt fences, mats, hydromulch and Flexterra^{TM}, and rip-rap lining of drainage channels. In addition, some new wetland areas were installed. Several of these measures have expected useful lifetimes of a few months to a few years, and require regular maintenance until the landscape is stabilized and vegetation well established.

In actual decontamination, demolition, and remediation work, the Site employed a combination of tents, comprehensive dust and erosion control measures, and general environmental protection during cleanup activities. As a result, surface water and air monitoring stations at the Site boundary showed little change in actinide migration as a result of the site cleanup activities. In fact, there has been far less runoff than predicted by the Site-Wide Water Balance – this in turn has led to increases in uranium in groundwater which is believed to be dominated by high natural uranium. So there has really been a shift in the actinide of interest following closure.

9. Conclusions

Making the case for particle transport mechanisms as the basis of plutonium and americium mobility, rather than aqueous sorption–desorption processes, established a successful scientific basis for the dominance of physical transport processes by wind and water [7]. Conceptual models played a pivotal role and served as the platform for communicating the scientific understanding to stakeholder groups. Geostatistical models were used to develop maps of the soil contamination and assist in evaluating the spatial extent of soil contamination. Simple contamination maps (Fig. 2) were used to communicate the findings to stakeholder groups. Soil erosion and sediment transport models were used to predict plutonium and americium transport, which led to design and application of site-wide soil erosion control technology to help control downstream concentrations of plutonium and americium in stream flow. Finally, good scientific understanding in the public interest helped bring clarity and focus to real issues of actinide migration at RFETS. This in turn helped to develop a more defined scope with a clearer endpoint that allowed the most extensive cleanup in the history of Superfund legislation to finish a year ahead of schedule, ultimately resulting in billions of dollars in taxpayer savings and removing a $600-plus million annual liability from the DOE budget (Fig. 5).

Acknowledgements

The authors acknowledge the dedicated efforts of all members of the AME Advisory group over the past 10 years. We are grateful to Kaiser-Hill LLC and DOE for their support of AME studies, and we acknowledge the Office of Basic Energy Sciences, and the Office of Biological and Environmental Research at the U.S. Department of Energy for their support of actinide and synchrotron radiation science that assisted RFETS cleanup activities.

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