Modeling long-term contamination in river systems from historical metal mining

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ABSTRACT

Heavy-metal contamination of sediments within river systems is a major environmental problem around the world. Deposited as a by-product of metal mining, contaminated sediments are persistent and widespread, frequently affecting large areas of floodplains, which makes precise assessments of contamination levels and patterns difficult. This paper describes findings from a new, generic, catchment sediment model called TRACER, which uses historical mining records to accurately predict present-day and future levels and patterns of contamination. This model provides detailed views of the extent of contamination and demonstrates how contaminated sediments form into "hot spots," which in turn become secondary sources of pollution. The exceptional longevity of the contamination is also revealed; $>$70% of the deposited contaminants remain within the river system for $>$200 yr after mine closure. Simulations of the impact of future climate changes in northern England show that increased flood magnitudes are likely to decrease surface contamination through dilution by cleaner sediment from hillslopes unaffected by mining activity.

Keywords: contamination, model, river, climate-change, heavy metal.

INTRODUCTION

River systems in many parts of the world have become severely contaminated by the extraction and processing of metal ores. In very acidic rivers, the majority of contaminant metals are transported in dissolved form. However, in most river systems, particularly those with near-neutral to alkaline pH, metal ions become adsorbed onto sediment particles. These contaminated sediment particles are deposited within river channels and on floodplains—contaminating large areas up to several hundred kilometers from the source—where they may remain for hundreds or thousands of years (Lewin and Macklin, 1987). These stores of sediment may in turn become diffuse sources of contamination if remobilized, e.g., by bank erosion (Macklin, 1996). As ~90% of metal contaminants are transported physically in sediment-associated form (Martin and Maybeck, 1979), knowledge of long-term sediment deposition and remobilization is required to accurately assess contamination levels and dynamics.

Previous studies have shown that the dispersal of sediment-associated contaminants away from well-defined point sources can be estimated by using simple exponential decay functions (Wolfenden and Lewin, 1978), but determining the location, concentration, and availability of these secondary sources in channels and on floodplains is more difficult. This conclusion raises four key questions for managing river systems affected by metal mining: (1) How much contaminated sediment will remain within these river systems after mining has ended? (2) Where is it currently located? (3) What future environmental risks may arise from contaminated floodplains? (4) How will changes in flood magnitude and sedimentation rate caused by future climate change influence contamination levels?

Present-day contaminant levels in rivers can be assessed by geochemical analysis of surface sediment samples and floodplain cores, but detailed surveys are costly and time consuming. Numerical modeling, however, may offer a better way to predict the location of contaminated sediment in river systems and their long-term and large-scale movements. Previous workers have used linked one-dimensional flow and sediment models (Graf, 1996) and have shown that contamination is likely where stream powers are low. However, the spatial resolution of these studies is too coarse to provide sufficient resolution, and they dealt with single-point sources of contamination. Here we present a new model, called TRACER, that integrates a two-dimensional catchment-slope and fluvial model (CAESAR, see Coulthard and Macklin, 2001; Coulthard et al., 2002), which has a three-dimensional model of sediment erosion and deposition with different grain sizes and simulates floodplain evolution over individual flood events at a high spatial resolution (1–50 m).

METHODOLOGY

A detailed simulation of sediment dynamics is essential to predict the movement of sediment-associated contaminants, and such a simulation is provided by the cellular automaton evolutionary slope and river (CAESAR) model. CAESAR (for a detailed description, see Coulthard et al., 2002) is a cellular model that uses a regular mesh of grid cells to represent a river catchment. Every cell has properties for elevation, water discharge and depth, vegetation cover, bedrock depth, and grain size. The model uses an hourly rainfall record as an input for a hydrological model (based upon TOPMODEL; Beven and Kirkby, 1979), which may be altered to represent the hydrological effects of different vegetation covers. Here, a 10 yr rainfall record from a nearby gauge is used; to represent different climates, the magnitude of the rainfall record is changed linearly. The output from the hydrological model is then routed through the catchment by using a scanning multiple-flow algorithm that sweeps across the catchment in four directions (from north to south, east to west, west to east, and south to north). In each scan, flow is routed to the three downslope neighbors (as per Murray and Paola, 1994), but if the flow is greater than the subsurface flow, the excess is treated as surface runoff, and a flow depth is calculated by using an adaptation of the Manning equation. The maximum depth calculated for the cells over all four scans is then recorded, and for all cells with a flow depth, the fluvial erosion and deposition are calculated by using the Einstein-Brown equation. This equation is used because it allows the easy integration of multiple grain sizes, and here 11 size fractions (from 0.0001 to 0.256 m) are modeled, integrated within a series of active layers (Hoey and Ferguson, 1994). Importantly, this allows surface armoring to develop as well as a limited stratigraphy (see Coulthard et al., 2002), which over the course of long simulations enables previously deposited fine-grain material (for example stored on a floodplain) to become a source of sediment when eroded. Limited slope processes are also included, i.e., mass movement is modeled when a critical slope threshold is exceeded, together with soil creep. These allow fine material from slopes to be fed into the fluvial system, as well as the input from landslides (both large scale and small—e.g., bank collapse). After the fluvial erosion and deposition and the slope-process amounts are calculated, the elevations and grain-size properties of the cells are up-

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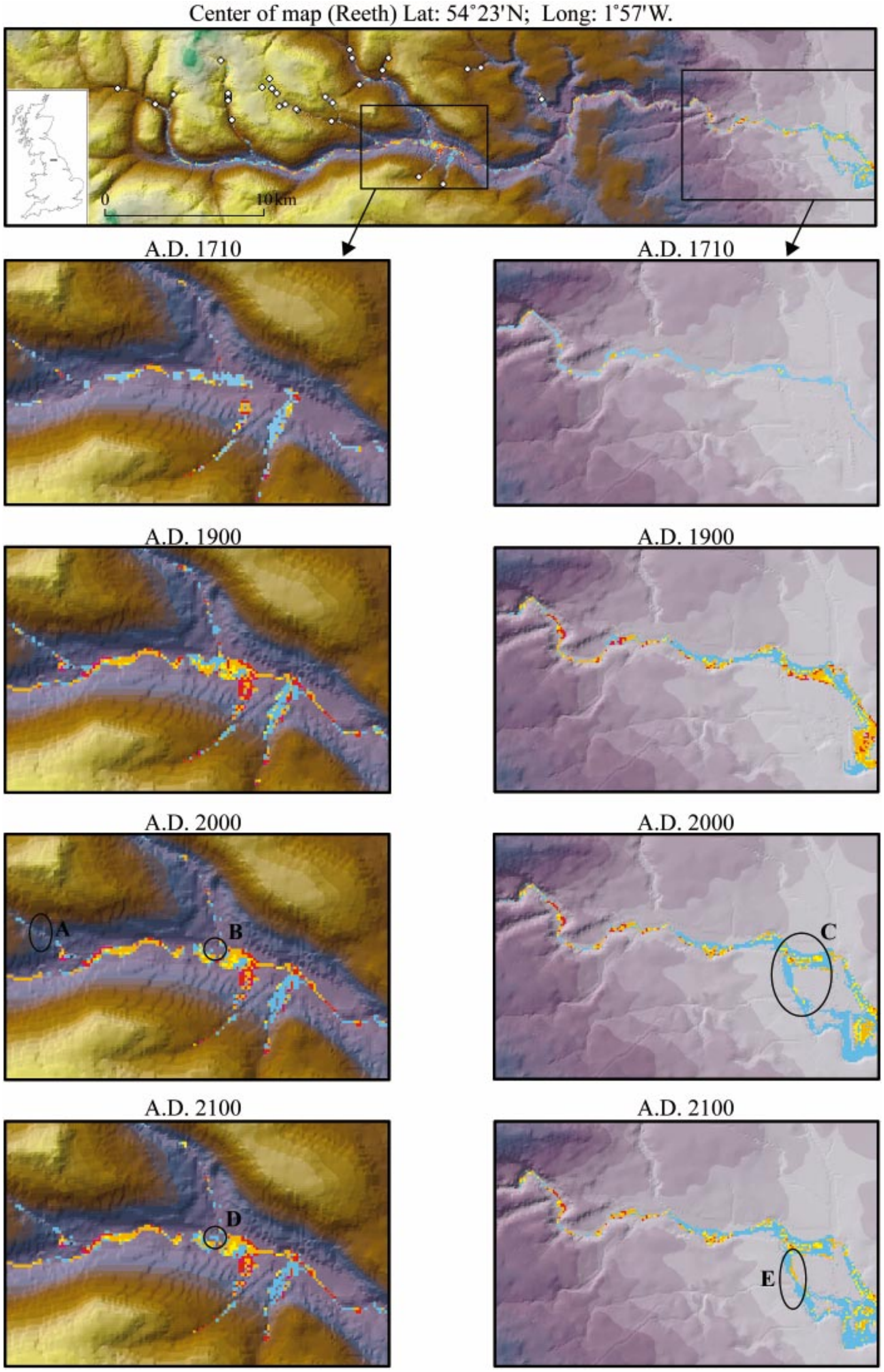

Figure 1. Patterns of river-channel and floodplain contamination at different time steps. (Top) Whole modeled catchment; white dots indicate location of grinding mills. Blue shows simulated Pb contaminated sediment levels <500 mg·kg^{-1}. Yellow is concentrations >500 mg·kg^{-1} (UK government limits); orange >1000 mg·kg^{-1}; red >10,000 mg·kg^{-1}. Labels A–E correspond to text in Results and Climate Change sections.

dated simultaneously. A variable time step is utilized (operating between 10^{-6} s and 10^4 s) that restricts erosion to 10% of the local slope, preventing computational instability. To date, CAESAR has been applied and validated in two river catchments (Coulthard et al., 2002; Coulthard and Macklin, 2001), but in order to simulate contaminated river systems, two new components were required.

First, to represent contaminants, different types of sediment may be added (i.e., one to represent contaminated and another uncontaminated sediment), and their progress then followed downstream. This part of the modeling is carried out by adding another array to the model code, so that for every grid cell, sediment volumes are recorded for both types of sediment. When eroded or deposited, equal proportions are moved; thus, for example, if a cell contains 0.2 m^3 of uncontaminated and 0.02 m^3 of contaminated sediment, and if half the sediment is removed, 0.1 m^3 and 0.01 m^3 are removed, respectively. The contaminated sediment can be added at any point within the modeled catchment; for example, it may be used to represent the addition of waste at a spoil heap. This mixing procedure is fully integrated within the fluvial and hillslope components of CAESAR, so contaminated material on spoil heaps can enter the fluvial system through landslides or soil creep, as well as becoming stored within floodplains and re-eroded at a later date.

Second, previous versions of CAESAR have not included models of bank erosion or channel migration, and this is an important process for remobilizing contaminated sediments stored within floodplains. However, incorporating a lateral erosion function within cellular models can be complex. Previous schemes have been developed (e.g., Howard, 1992) that base rates of bank erosion on cross-stream flow velocities that are usually considered to be a function of the radius of bend curvature. Enhancements to these processes have been made (e.g., Lancaster and Bras, 2002), but generally rates of lateral erosion increase with tightening bends (lower radius of curvature). Flow velocity and radius of curvature are relatively easy to determine if the stream is represented by (1) nodes and links, (2) linked cross sections, or (3) using a grid where the channel is only one cell wide. But, with CAESAR, the channel may be represented by one or more cells, or may be multiple (braided), making the outside stream bank and thalweg more difficult to determine. To overcome this potential problem, a simple lateral erosion method was developed for TRACER that determines the local radius of curvature on a cell by cell basis, by calculating the direction of maximum flow in and out of a cell. Then if there is a curvature in this flow, material is eroded from the cell on the outside edge of the flow and transported to the cell on the inside, depending on curvature, depth, velocity, and bank height. As it is based within a grid structure, material can only be removed from the eroding bank's cell elevation; therefore, lateral erosion occurs in steps.

APPLICATION

TRACER has been applied to the River Swale, northern England (Fig. 1), the drainage area of which has a long history of base-metal mining (dating back to the Roman occupation)

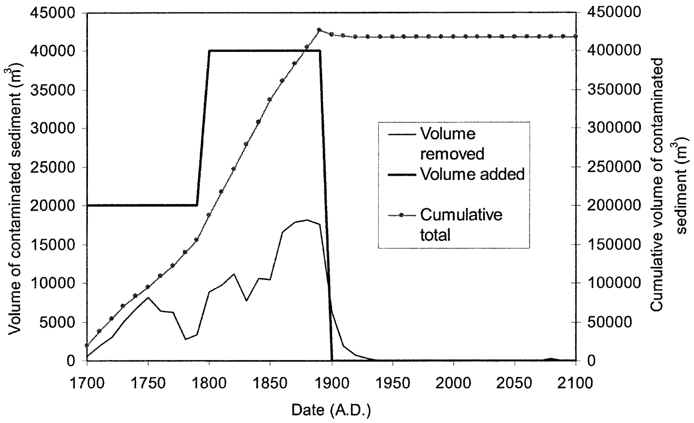

Figure 2. Volumes of mine waste added to catchment and contaminated sediment eroded from basin.

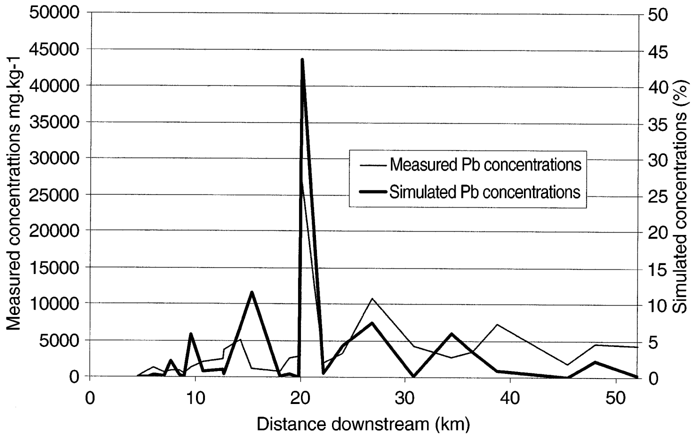

Figure 3. Comparison of measured and simulated Pb contamination levels downstream. Simulated concentrations are given as a percentage, but if we assume that the mine waste was 10% by volume contaminant (as described by Dunham and Wilson, 1985), then a 100% concentration of mine waste equals 100,000 mg·kg^{-1}.

with large-scale intensive lead mining beginning ca. A.D. 1700 and ending ca. A.D. 1900. Here, TRACER is used to simulate this period of intensive mining through to the present day and on to A.D. 2100. To simulate the inputs of contaminated sediment into the River Swale, highly detailed mine-production values dating back to A.D. 1700 were used, from which volumes of contaminated material added to the river could be estimated (Gill, 2001; Dunham and Wilson, 1985). From the period A.D. 1700–1900, 550,000 tons (0.55 Mt) of lead concentrate were produced; if we assume that 300% by volume of fine-grained waste material was generated, this tonnage equates to 600,000 m^3 of contaminated sediment discharged into the River Swale. This is a conservative estimate based on the assumption that the concentrate was 25% lead, whereas 5%–10% is a more likely value. Grinding mills (31 in total, see Fig. 1) that reduced the ore to coarse sand size (1–2 mm) were the major sources of contamination to the river system. Therefore, for this simulation the 600,000 m^3 of contaminated sediment was divided evenly between, and added to, the 1 and 2 mm grain-size fractions at these mill sites, with 33% of the total between A.D. 1700 and 1800 and 66% from A.D. 1800 to 1900. No fresh contaminated sediment was added after the cessation of mining in 1900.

MODEL RESULTS

Figure 1 shows how contaminated river sediment is dispersed and deposited downstream, and even after only 10 yr of simulated mining activity (A.D. 1710), contaminants are found throughout the modeled catchment; some areas have Pb levels above present UK government limits for agricultural soils (Ministry of Agriculture, Fisheries and Food, 1998). By A.D. 1900, immediately prior to the cessation of mining activity, there is significant contamination throughout the entire river system, with many channel and floodplain areas having simulated Pb concentrations well above 10,000 mg·kg^{-1}. The upstream section of the River Swale clearly shows how material is being moved downstream from the grinding mills located in the tributaries and deposited on an alluvial fan below the tributary, as well as in the main channel itself. This pattern is repeated below all of the mined tributaries, though overall contamination patterns are irregular with ''hot spots'' of higher levels. The downstream section, 30–50 km from the mining area, shows that large areas of floodplain are severely contaminated, some more so than the mined tributaries.

After mining ceased in A.D. 1900 we expected to see a reduction in floodplain contamination, and the simulation results at A.D. 2000 (Fig. 1) show this in the tributaries (point A) and on some alluvial fans (point B). In the lower part of the River Swale at point C, there is also significant removal of contaminated sediment caused by an avulsion that is reworking previously deposited material. Aside from these areas, however, there is relatively little change, and trunk stream channel and floodplain Pb concentrations remain very high. Two important observations can be made from this result. First, despite mining activity having ceased for $>$100 yr, 70% of the contaminated sediment remains within the river catchment (Fig. 2). Second, these contaminated sediments will pose a significant environmental hazard if river dynamics (e.g., bank erosion or avulsion) cause them to be eroded as has been previously suggested by Macklin (1996) and Miller et al. (1999).

CLIMATE CHANGE AND LONG-TERM FLOODPLAIN CONTAMINATION

To establish whether metal contaminants could pose a future environmental risk, simulations were continued until A.D. 2100. Figure 1 indicates that although there is removal of contaminated sediment at point D, and deposition of contaminated material at point E, there is very little change overall. This result suggests that the contamination is likely to be very long-lived. Indeed, simulations show that it would take several thousand years of natural erosion at present-day rates to remove all of the contaminated material from the Swale River channel and floodplain. In the meantime, contamination will continue to affect agricultural land use and water resources. Furthermore, contaminated floodplain sediment will remain a significant pollution source for downstream areas, though TRACER predicts that relatively small amounts of this material will leave the catchment (Fig. 2). These simulations, however, assume a stable climate, yet there is considerable evidence that global warming will result in higher winter rainfall over the United Kingdom (Conway, 1998). To simulate the effects of this change on contaminant dispersal, the period A.D. 2000–2100 was modeled with a 10%, 25%, 50%, and 100% linear increase in rainfall during this period, which was represented by increasing the magnitude of the rainfall according to these rates. These runs showed little or no change with the more likely 10% and 25% rises in rainfall, but there was an unexpected reduction in surface contamination with 50% and 100% increases in rainfall, caused by the dilution of contaminants with fresh clean sediment from the uplands. Therefore, significant increases in flood magnitude resulting from climate change could actually reduce surface-contamination problems—though considerable amounts of metal contaminants may remain buried within the floodplains.

MODEL VALIDATION AND SENSITIVITY

To validate our model runs, Pb concentrations from 28 sediment samples from freshly deposited over-bank sediments adjacent to the channel, collected in 2000 (Dennis et al. 2003), were compared to surface contamination levels predicted by the TRACER model (Fig. 3). Field samples were an aggregate of 5–10 subsamples collected within a 10 m radius and their position was recorded using a global positioning system. Using a geographic information system, these were directly compared to the corresponding 50 m pixel of contamination levels generated by TRACER. Results are very similar, indicating that the model is simulating both downstream and lateral movement, as well as concentrations of contaminated sediment. Figure 3 clearly shows the input of contaminants from the mined tributaries, with substantial peaks at 14 km, 21 km, and 28 km downstream, from Gunnerside Gill, Barney Beck, and Arkle Beck, respectively. Model and field results differ at 38 km, but this peak is shortly downstream of Marske Beck where mining records were sparse, and the model may be adding insufficient amounts of mining waste. The model also tends to overestimate upstream concentrations and underpredict those downstream, which may be caused by the model only simulating movement of grain sizes down to 0.001 m. It is highly likely that in the field more material is being transported downstream in finer grain sizes. Contaminant-dilution effects may be influenced by the representation of slope processes (here only creep and mass movement), and if applied in less densely vegetated environments, surface-wash processes should be incorporated.

Nevertheless, the overall excellent relationship between model results and field data, given the uncertainties involved (e.g., mine locations, input volumes, timings of inputs, sampling errors), demonstrates that contamination patterns are strongly controlled by river-sediment transport and deposition dynamics. Further evidence of this control is provided by model sensitivity analysis in which simulations were carried out by adding both larger and smaller volumes of contaminated sediment and under different climatic conditions. Although greater volumes of mining waste increased overall sediment contamination concentrations, patterns of contamination, including the location of hot spots, remained broadly similar. Therefore, it could be noted that TRACER is possibly better at predicting patterns of contamination than precise concentrations.

CONCLUSIONS

These new model simulations have important implications for contaminant monitoring and remediation not just in northern England, but in other river basins affected by past and present-day metal mining around the world. They show that long after mine closure, contamination remains and is widespread, with floodplain deposits often more contaminated than mine sites themselves. Therefore, remediation work may be better targeted at downstream hot spots in floodplains instead of the more obvious mining sites. TRACER is a potentially useful tool for locating these hot spots, as it is generic and can be applied to any river system provided that a digital elevation model, basic geology, grain-size and rainfall information, as well as data on contaminant input volumes and locations are available. Furthermore, as mines are often located in remote regions of the world where field sampling is difficult, a modeling-based approach such as TRACER may be the only viable technique for large-scale assessment of contaminant hazard. Patterns of river-contaminant dispersal and long-term storage following catastrophic mine-tailings dam failures, such as recently occurred in Bolivia, Romania, and Spain (World Information Service on Energy, 2002), could also be forecasted with TRACER. Similarly, the model may also be used for other sediment-associated pollutants including radionuclides and microorganic pollutants.

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[1] GSA Data Repository item 2003060, source code for the TRACER contaminated sediment transport model, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.