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TECHNICAL ARTICLE

The Environmental Impact of Coal Mining: A Case Study in Brazil's Sangão Watershed

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Abstract An algorithm was developed for quantifying and prioritizing mined areas according to their impact on watersheds. For the purpose of this case study, a pilot area of 88 km^2 was selected, which encompasses the upstream portion of the Sangão River of the Araranguá watershed in the state of Santa Catarina, Brazil. This methodology integrates information such as land use, soil types, topography, and hydrology using geoprocessing tools to quantify the relative load of pollutants derived from each. This permits one to prioritize reclamation. Using the algorithm and geoprocessing together has allowed us to identify the hot spots and where the rehabilitation process should begin. This tool can also be used to evaluate and analyze other watersheds impacted by mining and to integrate other pollution sources. Further research must still be done to calibrate and validate the model in order to determine the absolute contaminant loads.

Keywords Coal · Mine reclamation · Mining · Prioritization of environmental impacts

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Introduction

In the southern section of the state of Santa Catarina in Brazil, approximately 6,300 ha of land have been disturbed by surface mining of coal and waste dumps (Brasil 2009). According to the Brazilian Constitution, a mining company is responsible for repairing environmental damages caused by their activity. The obligation is "to reclaim the degraded environment, in accordance with the technical solution demanded by the competent public organization." As a result of this legal framework, miners are required to maintain downstream and effluent water quality within the legal limits. These requirements must be followed even after a mine is closed and abandoned. However, over 100 years of mining has heavily impacted the Santa Catarina coal basin, and extensive remediation is necessary to improve water quality (Gomes et al. 2006). In a 2007 decision, the Supreme Federal Court condemned the mining companies and the federal government (on behalf of bankrupt companies) for not reclaiming mined areas, and demanded that the federal government and the mining companies take action. The remediation costs can total $20,000–$40,000 (US) per hectare according to the extent of disturbance and proposed future use.

However, the economic resources for this reclamation project are limited, and different technologies have different anticipated costs and results. The reclamation strategies selected therefore should balance costs and benefits to reduce the load of pollutants and improve environmental quality. In 2006, a technical advisory group (TAG) was created to assist the federal court, and was given the responsibility of prioritizing reclamation actions based on environmental indicators.

At present, the reclamation activities have all been undertaken jointly by mining companies and the federal government; they include local and regional scale site characterization projects, such as studies analyzing surface and ground water, and monitoring their physical, chemical, and bacterial characteristics, as well as geological, hydrogeological, and structural mapping. In addition, 818 abandoned mines have been mapped, and other sources of pollution have been identified.

The TAG has approached the acid mine drainage (AMD) problem at the watershed level where physical interactions among pollution sources, water chemistry, and land characteristics can be modeled to develop an appropriate treatment method. The TAG has recognized that watershed characterization is a spatial problem, and has used Geographic Information Systems (GIS) software to store, retrieve, share, and analyze the data. This article presents the methodology developed for AMD modeling in watersheds and the results derived from its use. The methodology is based on several hydrologic modeling capabilities embedded in ArcView™ GIS and Spatial Analyst™ extensions for analyzing surface runoff patterns and overland flow from hydrologically corrected digital elevation models (DEM). Objectives for characterizing the Sangão Watershed for AMD reclamation in and near the Santa Catarina municipalities of Siderópolis and Criciúma are discussed.

Objectives

The main goal of this study was to provide information on how best to remediate AMD in the Sangão Watershed. A predictive tool, SAD-coal, is being used as a decision support system to quantify the severity of pollution associated with drainage from active and abandoned surface mines, to assess the impact of these discharges on surface waters, to simulate the positive impact that reclamation actions would have in the watershed, and thereby assist prioritization of reclamation activities and resource optimization. The objectives are to minimize costs and maximize environmental benefits, but this also involves decisions such as:

- Where should samples be collected to characterize water quality?
- How does water flow change seasonally in the watershed?
- Which streams are the most severely affected?
- What magnitude of pollution load come from each of the abandoned mines?
- Which sub-watersheds or tributaries contribute the most to loading of the Araranguá River?
- What effect would remediation have on downstream water quality?

The following actions were implemented to answer these questions.

1. Surface runoff from potential pollution sources was tracked to identify where the runoff enters the stream system. This information can be used to target areas for water quality sampling and analysis.
2. Water flow was estimated for all streams in the watershed. Knowing the average flow conditions in different months allows pollution loadings to be calculated. Also, modeling the flow aids in designing hydraulic structures and water treatment plants that can effectively handle the loads.
3. Water quality data was surveyed to validate the modeled in-stream watershed concentrations.
4. Sub-watersheds were delineated with respect to pollution contribution from tributaries and then ranked based on loading to the main stream, i.e. the Sangão River. This regional analysis helps to identify locations where the major problems occur in a watershed, and as a ranking tool, it guides where to start the reclamation process.
5. Choose a high-ranking sub-watershed and check the anticipated downstream effect that would result based on the mitigation technology used. Given limited financial resources, it is important to carefully consider the cost-benefit ratio when deciding where to initiate remediation or where to construct water treatment sites.

Study Area

Coal mining started in the State of Santa Catarina in the late nineteenth century (Gothe 1993), mostly in the Tubarão, Urussanga, and Araranguá River Basins (Fig. 1). Although mining has gradually become less environmentally aggressive and various old operations have been closed, the pollution processes still continue.

The mining and processing of coal has been the main source of economic activity for the approximately 500,000 residents of the 24 municipal districts in the Araranguá watershed for a long period of time. During the last two decades, industrial production has diversified; now, besides coal, industries such as ceramics and agriculture, especially irrigated rice, are economic drivers.

The 88 km^2 study area (Fig. 2) is comprised of rural and urban areas of the municipality of Criciúma and represents a portion of the Sangão watershed; the major sources of AMD are between Siderópolis and the location where the Rio Maina tributary joins the Sangão in Criciúma. This portion of the Sangão River receives AMD from waste lixiviation and from abandoned mines underground mines

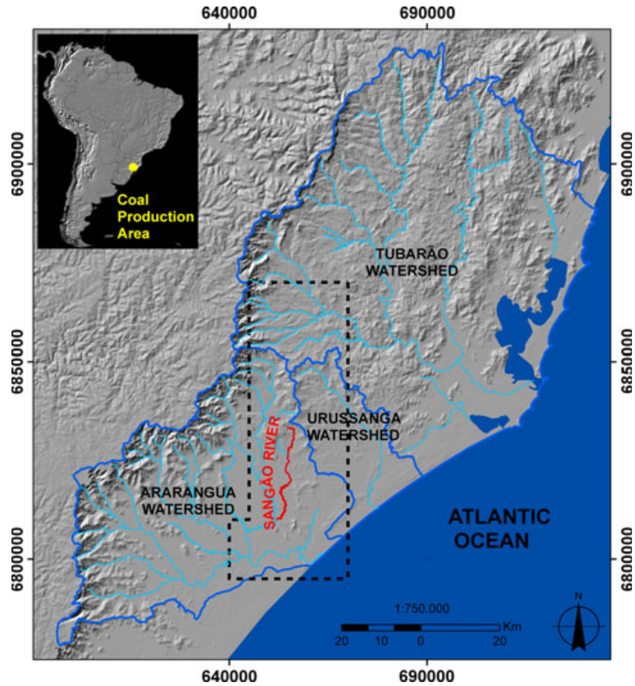

Fig. 1 Area of coal production and the main river basins

that operated in this portion of the watershed from 1917 up to 1990 on both sides of the river; surface mining was conducted further upstream. Even now, there are several waste dumps close to the Sangão River and its tributaries. In addition, the old flooded underground mines are located above the local drainage, and so release contaminated water continuously. All such mines have been located but only a few are monitored, which is why their contribution was not considered in this study; however, the impact of these mines must be the subject of further studies.

Conceptual Framework

Maidment and Djokic (2000), Olivera and Maidment (1999), and Tate et al. (2002) have discussed techniques used to estimate nonpoint pollutant loads, using hydrology and GIS tools. Basically, we used nonpoint pollution models, which incorporate the hydrologic rainfall-runoff transformation processes with some attached quality components (Rifai et al. 1993). Nonpoint sources are derived from activities on extensive units of land, originating from urban runoff, construction, hydrologic modification, mining, agriculture, irrigation return flows, solid waste disposal, atmospheric deposition, stream bank erosion, and sewage disposal (Adamus and Bergman 1995).

A GIS can combine automated cartographic features with database management. One layer, the thematic map,

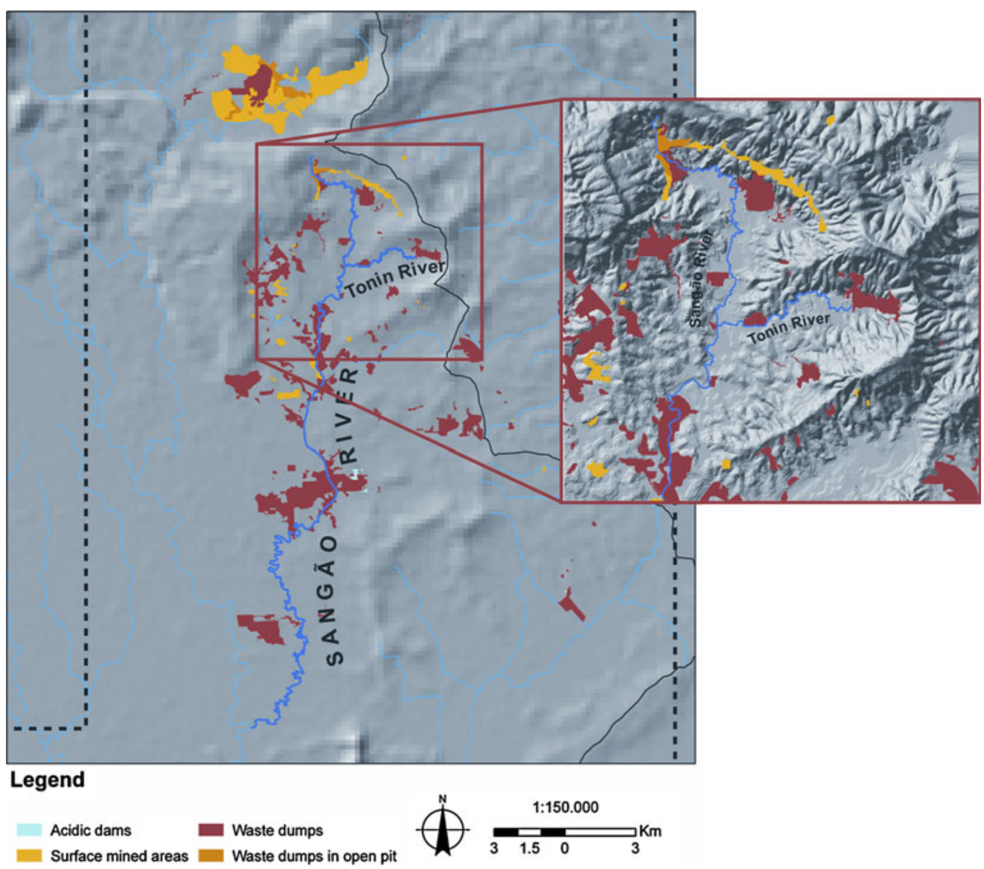

Fig. 2 The location and approximate boundaries of the study area

refers to the land use coverage, emphasizing the disturbed areas along the Sangão River Basin and the associated estimated mean concentration (EMC) values for various pollutants within those land uses. Subsequently, for a selected pollutant, an EMC grid is created and this grid is multiplied by a constant grid with the average monthly runoff in the basin. The result is the monthly loading of the constituent to each grid cell in the basin (Thomann and Mueller 1987), as shown in the formula below:

$$\text{Load (L)} = \text{Flow(Q)} \cdot \text{Concentration(C)} \quad (1)$$

where L is a unit of mass/per unit of time, Q represents the volume of liquid/per unit of time, and C is measured as mass per volumetric unit, i.e. mg/L. With the AMD load estimated at each cell (Fig. 3), a flow accumulation on the cell-based loads was derived to determine the average monthly load to Sangão River. The steps are detailed below.

Data Requirements

The input data was prepared and transformed to feed a model. A total of 21 data layers were used; six were vector data and 15 were raster grid data. The flow gauges (point shape file), rain gauges (point shape file), coalfield location (polygon shape files), drainage network (line shape files), water quality samples (point shape file), and watershed boundary (polygon shape files) data files were in vector format. The land use, soil map, DEM, and 12 monthly accumulated average precipitation data files were in raster grid formats (10 m cell size). All data were transformed into UTM zone 22 S, SAD-69 projection format.

The accumulated rain, flow, evapotranspiration, type of soils, geological background, size, locations and typologies of impacted areas, type and size of covers, and water quality data were obtained directly from field surveys. The drainage network, watershed boundaries, digital terrain model, and land uses were derived from image interpretations. Other parameters used for flow calculations were derived from other studies (Walter 2008) or were general values.

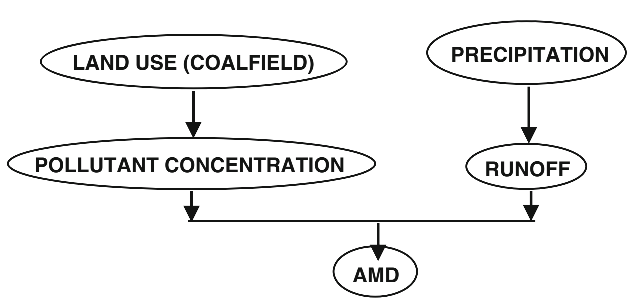

Fig. 3 AMD pollution model for surface waters

Operations with a Digital Elevation Model (DEM)

To model the flow of contaminated surface runoff from potential pollution sources across the landscape, the watershed must be properly defined with respect to the river network. The standard methodology for delineating streams and watersheds from a raster DEM is based on an eight-pour point algorithm (Jenson and Domingue 1988). This algorithm identifies the grid cells (of the eight surrounding cells) toward which water will flow if driven by gravity. This methodology consists of:

- Filling the sinks of the DEM, i.e. increasing the elevation of the points that are fictitious pits.
- Determining the flow direction, i.e. identifying the cell towards which water will flow.
- Identifying the stream cells, i.e. marking down those cells with a flow accumulation value greater than a certain user-defined threshold value.
- Labeling the links, i.e. assigning a label (number) to each reach of the stream network.
- Delineating the watershed for each link, i.e. determining the drainage area associated with each link.

The DEM of the study area used in this model was obtained from orthophotos at 1:5.000 scale with an elevation resolution of 2.5 m, derived from restitution of aerial photographs made available by Brazilian Ministry of Mines and Energy since 2002.

Once the corrected hydrologic DEM is created, it can be processed to determine the direction of water flow and therefore move pollutants from cell to cell and to determine, for each cell in the grid, the number of cells that are upstream. This methodology was implemented in ArcView™ GIS as an extension, using the Avenue™ programming language.

Estimated Flows

In watershed characterization, it is important to determine loads in kg/month or tons/year for the amount of acidity polluting a stream. By estimating and modeling the likely high, low, and average flow conditions on a monthly basis, reclamation strategies and systems can be more effectively built to match the conditions that would likely occur over the course of a year. For each cell, the flow is calculated according to the soil moisture accounting procedure (SMAP) model developed by Lopes et al. (1982). The structure of the monthly version of the SMAP model is illustrated in Fig. 4.

Here, Rsolo = reservoir in the soil (unsaturated zone), Rsub = underground reservoir (saturated zone), P = precipitation, Es = superficial flow, Er = real evapotranspiration,

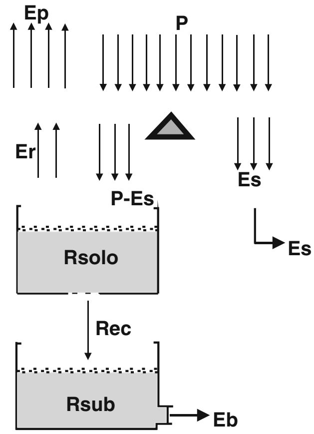

Fig. 4 Structure of the soil moisture accounting procedure (SMAP) model

Ep = potential evapotranspiration, Rec = underground recharge, and Eb = groundwater flow.

In its monthly version, the SMAP model is constituted by two mathematical reservoir models, the variables of which are continuously simulated on a monthly basis:

$$\mathrm{Rsolo}\,(i+1) = \mathrm{Rsolo}\,(i) + P - Es - Er - Rec \quad (2)$$

$$\mathrm{Rsub}\,(i+1) = \mathrm{Rsub}\,(i) + Rec - Eb \quad (3)$$

The SMAP model is composed of four transfer functions:

$$Es = P \cdot Tu^{Pes} \quad (4)$$

$$Er = Tu \cdot Ep \quad (5)$$

$$Rec = Rsolo \cdot Crec.Tu^{4} \quad (6)$$

$$Eb = (1 - Kk) \cdot Rsub \quad (7)$$

where: Tu = Rsolo/Sat; and the four parameters in the model are: Sat = saturation limit of the soil; Pes = parameter of superficial flow; Crec = recharge coefficient; and Kk = recession constant of groundwater flow.Finally, for each cell, the runoff (Q) calculation is performed using the equation:

$$Q = Es + Eb. \quad (8)$$

In this context, the SMAP model requires simple procedures, a small number of parameters, and low requirements for input data. Additionally, where data does not exist, some assumptions have to be made to provide the necessary information.

In this specific case, annual precipitation (P) and evapotranspiration (Er and Ep) data collected by the Santa Catarina agricultural service (EPAGRI) were assumed to represent regional values. The Es and Rsolo were derived using the soil conservation service curve number (SCS-CN) methodology (Mishra et al. 2003) to determine runoff and storage capacity for different situations, depending on the type and use of soils and soil coverage. These calculated values are site specific. The soil type and coverage were obtained respectively from geological and soil maps and aerial photo interpretation.

The Eb determination is more complex, and requires additional studies that are currently underway (Pazzetto et al. 2007; Souza et al. 2009) to better characterize groundwater flow from the impacted areas. Walter (2008) used the average Eb value for impacted and non-impacted areas for a sub-watershed of the Tonim River, which is in the Sangão River watershed, and this same approach was used here until better data is available. Given these boundary conditions, we then determined the flow for each individual cell forming the surface drainage system.

Estimated Mean AMD Index

The flow, pH, acidity, iron, aluminum, manganese, and sulfates were monitored and analyzed regularly. Among these parameters, the acidity parameter can be considered as a conservative pollutant in the Araranguá watershed. The soils are naturally slightly acidic (acidities up to 20 mg/L were recorded at a non-contaminated site upstream along the watershed, which was used as a benchmark), and there are no significant sources of natural alkalinity.

Mapping of impacted areas started in 2002 and has continued since then, with various missions for field validation and analysis of aerial photographs and satellite imagery. This work has been conducted using the methodology applied to the reclamation program of the Santa Catarina coal basin (Gomes et al. 2008).

The source of AMD in this region could be from four types of abandoned mine lands (Figs. 5, 6): surface mines, coal waste dumps, waste dumps in open pits, and acid dams. It was assumed that all of these contributed to AMD runoff during a precipitation event.

Fig. 5 Coal waste and an acidic pond

Fig. 6 Surface mined area and spontaneous vegetation

Since the quantity of sulfides is greater in the local coal waste than in the overburden material, more acidity is released from such waste. The estimated mean concentrations (EMC) are the typical pollutant values found in the runoff. These EMCs values were assumed to be directly related to the land use in the drainage areas and constant, independent of the duration and intensity of the rainfall events.

The exact amount of acidity released from a certain area in a rain event depends on several variables, which include the sulfur content (as sulfides), the presence of alkalinity producing minerals, the volume of wastes, the surface area, and the age of the deposit. Data availability is a limiting factor in forming an EMC table that relates the land use with the pollution potential; nevertheless, the values used represent the real situation fairly well. Further studies must be carried out to determine these parameters (Figs. 7, 8).

Mitigation procedures such as confinement, dry covers, and vegetation were found to significantly reduce the amount of pollution released from such sites. Consequently, it was decided to analyze the problem as follows: a relative AMD potential (AMDIndex) was determined as a function of the pollution typology (Pt) and degree of load reduction (R) of the coalfield treatment:

Fig. 7 Clay cover, spread soil, and vegetation

Fig. 8 Urbanized areas

$$\text{AMDIndex} = \text{Pt} \cdot (1 - \text{R}). \qquad (9)$$

The exact location and area of the disturbed land was mapped in the first phase of the reclamation project and compiled in a GIS database. All mined lands, after field inspection, were digitized and converted into grids. These grids were combined to create one grid that comprised all the potential pollution sources. The main task was to define and calculate a composite index for each 100 m^2 cell according to its pollution typology and mitigation process, if existent. The key set of weights used in Eq. 9 and the possible pollution typology expected from each area are presented in Table 1, which lists the pollution potential ranking of each coalfield.

The weighting in Table 1 is proposed by the authors as an initial approach and was based on the sulfide content from each contaminant material (remembering that virtually no alkalinity is present in the strata in this region), and on the investigators' field experience on the capacity of

Table 1 Compilation framework for AMD index ranking

Pollution typology	(Pt)	Reduction factor[a]			
		1	2	3	4
Surface mined areas	5	0.2	0.2	0.4	0.6
Waste dumps	8	0.2	0.2	0.4	0.6
Waste dumps in open pits	9	0.2	0.2	0.4	0.6
Acidic dams	8	0.0	0.0	0.0	0.0

[a] Reduction Factor → 1. Clay cover; 2. Vegetated cover; 3 = 1 + 2, and; 4. Impermeable due to urbanization

these materials to lixiviate AMD. The reduction factor applied reflects the expected attenuation of the lixiviation process due to remediation (based on observations at old mine sites with volunteer vegetation and impacted areas that have been urbanized). The main goal at this stage of the work was to propose reduction factors that would be fairly realistic and allow us to run the model. Further work must be done to verify and refine these factors. In fact, for simulation purposes, the reduction factor must be based on the reclamation design parameters and the proposed remediation technique for each site.

Calculation of Loads

The model then applies the monthly runoff and the concentration based on the AMD Index for each cell, inside the coalfields, which results in the load for each pollutant. The loading grid is obtained by multiplying the concentration grid by the runoff grid, based on Eq. 1 and as illustrated in Fig. 9. This very simple algebraic procedure can be handled by any GIS package.

Model Stream Acidity

The next phase in characterizing river basins for AMD problems is to model the in-stream acidity. The iron, aluminum, manganese, and zinc concentrations could also be modeled using the method described for the AMD Index, but these species are more susceptible to losses due to chemical reactions or biological degradation. The use of sulfate will be subject of further investigation. Stream acidity was modeled by assuming: conservative behavior along the watershed, that the streams have the same hydrogeometric properties (stream slope, roughness, width, and depth), and; that the streams have the same ecological rate constants (re-aeration rates, pollution decay rates, and sediment oxygen demand rate).

The modeled concentrations can be considered as the maximum potential concentrations with the available data and under the stated assumptions (Thomann and Mueller 1987). In this case, the concentration is represented by the

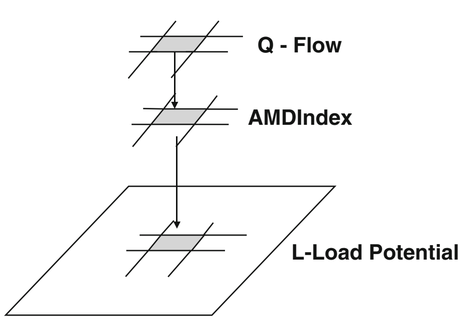

Fig. 9 Calculation of load grid

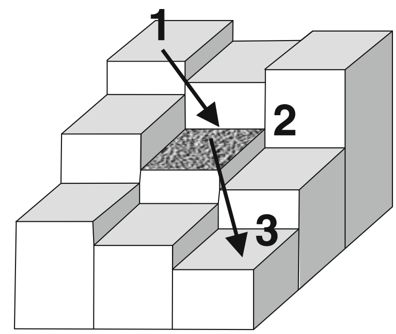

Fig. 10 Load movement across the landscape

AMD Index (Eq. 9), assuming a conservative behavior. Based on the DEM, it is possible to identify the flow network where the pollutants would move downstream.

The load movement across flow lines is illustrated in more detail in Fig. 10. Flow continuity can be calculated by recalling that a mass balance of the runoff is required:

$$Q3 = Q1 + Q2 \tag{10}$$

where Q3 is the accumulated flow in each cell. Similarly, assuming that the pollutant has a conservative behavior, the potential load (Eq. 1), produced by the flow and AMD index, is given by:

$$Q3 \cdot AMDind3 = Q1 \cdot AMDind1 + Q2 \cdot AMDind2 \tag{11}$$

where AMDind3 is the pollutant load available to be carried by the accumulated flow. As long that a given substance mass balance is conserved, i.e. there are no losses due to chemical reactions or biological degradation, all concentration changes are due to new contaminant additions, with the associated changes in flow. The upstream (cell 1) and downstream (cell 3) cells are assumed to have a negligible (background values) concentration (AMDind1 and AMDind3), whereas the central cell (Q2, AMDind2) is assumed to have the highest concentration, representing, for example, a waste pile. Thus, the downstream concentration (AMDind3) is given by:

$$AMDind3 = \frac{Q1 \cdot AMDind1 + Q2 \cdot AMDind2}{Q1 + Q2}. \tag{12}$$

In this way, the complete downstream profile can be generated. The interface of this model component with the previous modeling phases is the SAD-Coal (Mod) indicates a decision support system for coal (mod). The sub-items in the interface menu represent the above mentioned steps of the modeling process.

For modeling, instead of the absolute acidity load, it was used the relative amount of acidity released by each area or by each sector of the watershed. For instance, each individual load calculated at each pixel (100 sq m) was divided by the total load accumulated in the watershed expressing

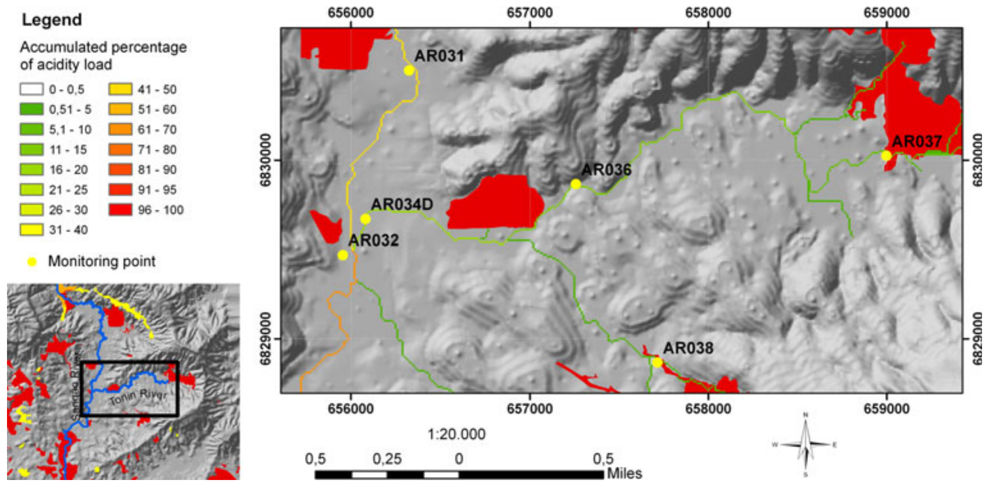

Fig. 11 Flow line calculated by the digital elevation model; the colors indicate, from *green* to *red*, the accumulated load of acidity downstream as percentage of the total load of the sub-watershed being considered

the percentage from the total load accumulated at each point of the watershed modeled. This made possible to identify the relative contribution of each area to the total load (Fig. 11).

Although it is important that simulations produce distributions of pollutant loads that are similar to those measured in the field, we are still in the process of collecting in-stream samples. The acidity (AMD Index) was modeled by first identifying all sampling locations that have a recorded acidity level. Subsequently, these points, which may be in-stream samples, were used to delineate sub-watersheds for their locations. The sub-watersheds were then assigned the value of the acidity from the sampling point. Thus, areas were essentially obtained that were known to contribute to the amount of acidity defined by the sampling location. Subsequently, the observed and calculated proportional loads were compared at these control points (Table 2). The results of this preliminary validation indicate a close match between the measured data and the results obtained, since 2002, from points of collection named AR 31, AR 32, and AR 38. It is noticeable that point AR 37 is affected by AMD contribution from abandoned mines, which significantly increase the acidity load, and also by domestic sewage that adds some alkalinity, which was not taken into account during this first run of the model. The validation procedures and model calibration will be subject of further studies, where such external contributions of acidity and/or alkalinity will be quantified and included.

Model Limitations

The proposed relationship between reduction factors and pollution typology can vary and must be adjusted for each specific site. The reduction factors chosen must be further investigated and should be defined for each specific cover and site combination. Clay and vegetative covers performance are influenced by the climate and thickness, which affect the storage and release properties of the cover.

The model only considers cumulative rain events. Thus, this model cannot be used to simulate the detailed dynamics of a single rain event since the response to such events depends on factors not considered in the present model.

The accuracy of corrected hydrologic DEM plays an important role as, after processing, it determines the direction of water flow and therefore the movement of pollutants from cell to cell in the model. Differences among digital terrain models and actual terrain can lead to differences between calculated values and measurements in the field.

Table 2 Preliminary model validation

Monitoring Point	% Load of acidity (mean values)	% Load of acidity (modeled)	Variation(%)	Observations
AR 31	45.84	43.16	−6	Close match
AR 32	70.01	64.46	−8	Close match
AR 34 D	26.44	19.47	−26	Donwstream from AR37
AR 36	17.58	12.98	−26	Donwstream from AR37
AR 37	17.07	7.82	−54	Receives AMD from abandoned mines and sewage from urban areas nearby
AR 38	2.74	2.82	3	Close match

The acidity or alkalinity background concentrations must be determined to feed the model and must be different from zero; otherwise, the load for each neutral cell will not be calculated, masking dilution processes.

The pollutant load must have a conservative behavior, where all changes are due to new contaminant loads or dilution with no significant losses due to chemical reactions or biological degradation. In the case of acidity, alkaline contributions must be considered and potential neutralization has to be taken into account.

The estimated mean AMD Index is based solely in acidity concentration, as this is the only pollutant considered conservative in this watershed. Sulfate load may work better in many watersheds, but while virtually no natural source of alkalinity exists in this watershed, probably the extent of sulfate reduction in this area is relatively high. Other monitored parameters, such as pH, iron, aluminum, zinc, and manganese are also affected by chemical and biological processes along the rivers. These parameters can only be included in the model once we have a better understanding of all of the processes affecting their concentration.

The calibration procedures and model validation are an ongoing part of the SAD-Coal research.

Proposed Analyses of Management Scenarios

Programmatic, budget, and operational decisions are often made under time constraints and changing situations that limit the use of inputs from expansive models and technical analyses. The costs and environmental risks are often key factors in these decisions. The computer-based tool (SAD-Coal) can quickly develop quantitative, accurate, verifiable, and reproducible projections of cost and environmental impacts from various options, and can improve decision making by reducing the potential for error and uncertainty. This tool is thus especially valuable if it is flexible enough for use in applications beyond those for which it has been designed. In the following section, two management scenarios are proposed.

Sub-watershed AMD Load Analysis and Ranking

The acid load (L) from each stream into the mainstream of the Sangão River can be calculated using the modeled stream acidity (AMD Index) and estimated flow (Q). The loading should be considered as the potential maximum because of the assumptions mentioned earlier. The sampling data were collected at delineated sub-watersheds for the mouths of tributaries.

The display of sub-watersheds in a region ranked by acid load provides a visual recognition of problem areas and acid load contribution to the Sangão River mainstream. It was found that the results target the most severely impacted watersheds very efficiently. While this watershed ranking is only based on acid load, other sub-watershed level characteristics can be included to further define the rankings. By simulation and the use of this tool, the benefits of different reclamation techniques can be compared and pollution sources can be ranked across the sub-watersheds to better select and identify which area should be addressed first.

Select Treatment Sites and Model Water Quality Improvement

The sub-watersheds that most contribute to the acid load of the mainstream Sangão River can be identified using the results from the previous phase. By selecting one of the sub-watersheds from the list, one can then test different treatment scenarios for AMD reclamation. The scenarios tested include determining how much acid reduction is needed and determining the effect of remediation strategies on the AMD problem.

The place for treatment can be found by querying any stream location for the amount of acid load present. Remediation strategies can be tested by digitizing a location for a constructed wetland or a limestone channel (recognizing that any limestone will have to be imported into the area) and attributing to it the appropriate amount of acid reduction. The digitized remediation strategy can then be used as a weighted grid in the flow accumulation function to test the effects of treatment. Subsequently, the location and expected acid reduction can all be altered to determine the scenario that would work best. This would provide valuable information to the reclamation specialist working towards a reclamation plan.

Conclusions and Further Research

The main advantage of the methodology discussed is that it provides information that can be used to make better decisions for addressing the AMD problems faced in the reclamation of the Santa Catarina coal basin. A detailed framework was presented for determining where to sample water quality, estimate flow from runoff grids, calculate the transport of pollutant concentrations in streams, delineate and rank sub-watersheds based on loadings to the mainstream, and provide the means to test treatment scenarios for downstream water quality improvements.

It assumes that the literature-based expected mean runoff concentrations are directly related to land use in the watershed and do not vary from event to event or between different land use subcategories. However, pollutant concentrations in runoffs are known to vary within single rain events, depending on factors not considered in the present model. Hence, this modeling approach should not be used to simulate detailed dynamics on a short time scale.

The modeling tools available in ArcView™ provided the tools for extracting the topographic structure from the digital elevation data to characterize the Sangão river basin for its AMD pollution sources. A hydrologically corrected DEM was used, which made it possible to improve the accuracy of runoff directions, watershed delineation, and the transport of pollutants within the streams.

Future directions of this study include acquiring additional acidity data in the drainage network in order to validate the model. Discharges of contaminated drainage from abandoned underground mines are a major environmental problem in this area and influence the surface and groundwater resources in and around the mines, and these effects propagate downstream. In this context, there is a need to couple the surface and ground water models for water resource development study as well as for proper management.

An integrated and comprehensive approach for satisfying the demands of all water users (e.g. coal industry, domestic, agriculture) with due regard to the quantitative and qualitative aspects of water demand should be adopted. This will require quantifying other sources of pollutants. For this purpose, a river basin or watershed should be strictly treated as the unit. The development and management of water should thus be based on a participatory approach involving users, planners, water managers, and policy makers at all levels, wherein the modeling tool presented in this study could be applied.

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