Hydrological Modelling of Coastal Catchments with Acid Sulfate Soils

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Abstract: Acid sulfate soils (ASS), when disturbed, can cause serious water quality problems resulting in the destruction of marine and estuarine habitats. At present there is no general, systematic way of determining the impact of changes in land and water management strategies on the export of acidity in coastal floodplains. Instead, we rely on expensive, site specific trials, which seldom allow for the surrounding catchment hydrology and the inherent spatial and temporal variability of climate. A water quality/hydrological model has been developed to predict acid outflows in response to climate and land management decisions. The model has been used to demonstrate the impact agricultural drainage has had on the export of acid into major aquatic ecosystems. More acid is exported from ASS floodplains when a constructed drain is present. The model can be used to reduce the impact of acidification by examining the magnitude of acid outflows in response to land management changes and can also be used to examine the relationship between climate and acid events.

Keywords: Acid sulfate soils; Hydrology; Modelling; Drainage network; DEM

1. INTRODUCTION

Acid sulfate soils are sediments containing pyrite. Most were formed 10,000 years ago during the Holocene period. The oxidation of these pyritic sediments results in the production of sulfuric acid. Drainage and flood mitigation works promote oxidation and the export of sulfuric acid, dissolved aluminium and iron into streams and aquatic ecosystems. Mass mortalities of gill organisms are linked to acid drainage from acid sulfate soil landscapes [White et al.,1997]. At present there is no general, systematic way of determining the impact of changes in land and water management strategies on the export of acidity in coastal floodplains.

The hydrological-water quality model presented here helps to describe the impact of land and water management strategies on acid discharge. The model was developed using several data sets including elevation, stream network, environmental risk map data, rainfall, streamflow, and drainage map data. The model is displayed in a Geographic Information System (GIS) for viewing. Preliminary results of modelling impacts are presented in this paper.

2 STUDY SITE

The study area chosen for the development of the model is the Tweed/Cudgen catchment which is located on the north coast of New South Wales situated between $28^0 10^1$ S and $28^0 30^1$ S and longitudes $153^0 06^1$ E and $153^0 33^1$ E and has a total area of 1080 km^2. The catchment has a radial drainage pattern (Figure 1) with the Mount Warning Shield Volcano the prominent landscape feature.

The Cudgen catchment is a subcatchment of the Tweed and is a high priority area for the remediation of acid sulfate soils. Periodically, major kills of gilled organisms have been linked to acid drainage. In August 1998, a kill of an estimated 30,000 fish occurred in Cudgen Lake, a 1.5 km^2 shallow, brackish water body with restricted tidal exchange at the downstream end of a 100km^2 catchment containing 20 km^2 of acid sulfate soils. Because of its importance the model was tested on the Cudgen catchment.

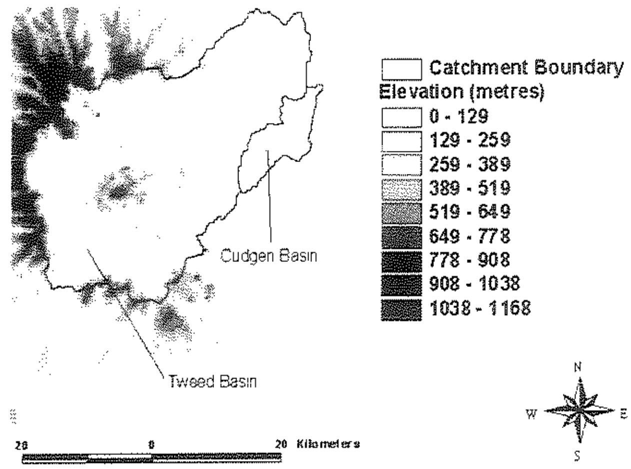

Figure 1. DEM of the Tweed/Cudgen Catchment.

3. METHODOLOGY AND RESULTS

The model was developed using a range of different software programs including ANUDEM [Hutchinson 1989], ANUCLIM [Hutchinson et al., 1991], Arc/Info®, and ArcView ®. The Modelling methodology reported here was developed from methods described by Jenson and Domingue [1988] in which the Digital Elevation Model (DEM) is based on grid cells of uniform size.

3.1 Development of a Digital Elevation Model (DEM)

A 100 metre spatial resolution DEM of the Tweed Catchment was created in Arc/Info (UNIX version 8.02) using the ANUDEM program (version 5). The program uses an algorithm that interpolates the elevation data through minimising a suitably weak roughness penalty to the fitted DEM grid data. To ensure the development of a satisfactory drainage structure, necessary for hydrological analysis, ANUDEM also imposes a global drainage condition which automatically identifies and removes spurious sinks. The drainage condition eliminates the need for manual correction of elevation grid data to remove spurious drainage patterns. Streamline and contour data were derived from 1:250,000 [AUSLIG 1992] topographical map sheets. The DEM (Figure 1) was created in ASCII Grid file format and converted to an Arc/Info Grid coverage and then imported as a theme to ArcView (version 3.2).

3.2 Precipitation and Runoff Determination

The ANUCLIM program was used to produce an annual rainfall surface grid for the Tweed/Cudgen catchment. An annual Runoff coefficient was determined for the catchment based on annual stream flow results at Uki gauging station in the Tweed and from annual spatial rainfall for the Tweed catchment. The annual runoff coefficient was determined from the following:

$$Q = C \times P \tag{1}$$

Where Q is the runoff in mm/yr, C is the runoff coefficient and P is areal mean precipitation (mm/yr). The runoff coefficient is therefore:

$$C = Q/P \tag{2}$$

The spatially averaged precipitation for the catchment is:

$$P = \int P`dA/A \tag{3}$$

Where A is the drainage area and P` is the Spatially distributed mean annual or monthly precipitation. An annual runoff coefficient of 0.33 was determined for the catchment.

A runoff grid was created by using the rainfall grid developed using ANUCLIM and an avenue script [modified from Hellwege, 1996] containing the runoff coefficient.

3.3 Modelling Annual Stream Flow

An important requirement for modelling surface flow paths and for catchment delineation is the development of a surface flow direction grid in which drainage directions are assigned to individual grid cells. There are several principal methods used for determining the drainage matrix from a DEM with the D8 method being the simplest and most commonly used [O'Callaghan and Mark, 1984]. The eight direction pour model or D8 method takes the filled DEM and calculates the direction of flow for all the grid cells. Each cell drains into the neighbouring cells with the steepest decent. The ANUDEM program has the option of creating a flow direction grid when fitting the DEM. A sink was created at the outlet of Cudgen Lake where the water drains to the ocean in order to measure the total inputs into the lake.

Annual streamflow was modelled by using the runoff and the D8 flow direction grid. A weighted flow accumulation was then calculated in Arc/Info (version 8.02) using the runoff grid as the weighted grid.

3.4 Drainage Network

To assess the impact of the agriculture drainage network on acid transport, drainage lines [Atkinson et al., 2000] were incorporated into the model. A flow direction was applied to each drain throughout the drainage network resulting in the production of a new flow direction grid. A combination of different drainage densities was assessed for impact on acid transport, with a new flow direction grid created for each density. Four different drainage scenarios were used in the model. These included the natural drainage capacity, 25% of the agricultural drainage capacity, 50% drainage capacity and 100% drainage capacity (current situation).

3.5 Modelling Annual Acid Land Loads

Acid land loads were derived from acid sulfate risk map data [Naylor et al., 1998] and an estimation of annual acid loads were derived from estimations based on previous field studies [Wilson et al., 1999]. Since a majority of the surface soils have oxidised over a long time due to the installation of drains and other farming activities, the rate of acid production is regarded as constant over long time periods [Wilson et al,1999].

(a) **(b)**

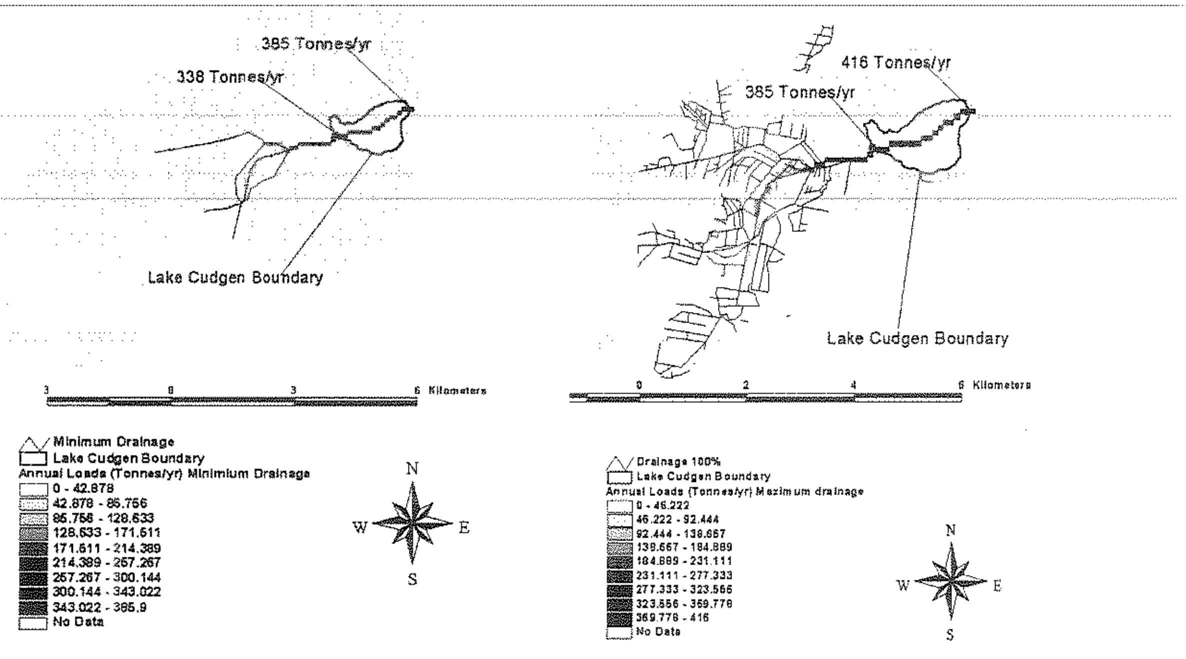

Figure 2. Annual water loads (Tonnes/Yr): **(a)** Under natural drainage density; **(b)** Under 100% drainage density.

3.6 Impact of Agricultural Drainage on Acid Water Loads and Concentrations

To assess the impact of agricultural drainage on acidification of aquatic ecosystems it was necessary to calculate the concentrations and water loadings based on both the runoff accumulation grid and the land loads grid. Total acid water loads were determined by carrying out a weighted flow accumulation on the acid land loads using the different drainage densities discussed in section 3.4. Figures 2a and 2b show the total water loads entering lake Cudgen using a combination of drainage densities.

The total acid concentration was also determined using the map calaculator functions in ArcView by dividing the runoff accumulation grid by the accumulated loads grid to give final acid concentrations in mg/l/yr. The results are shown in Figures 3a and 3b.

(a) (b)

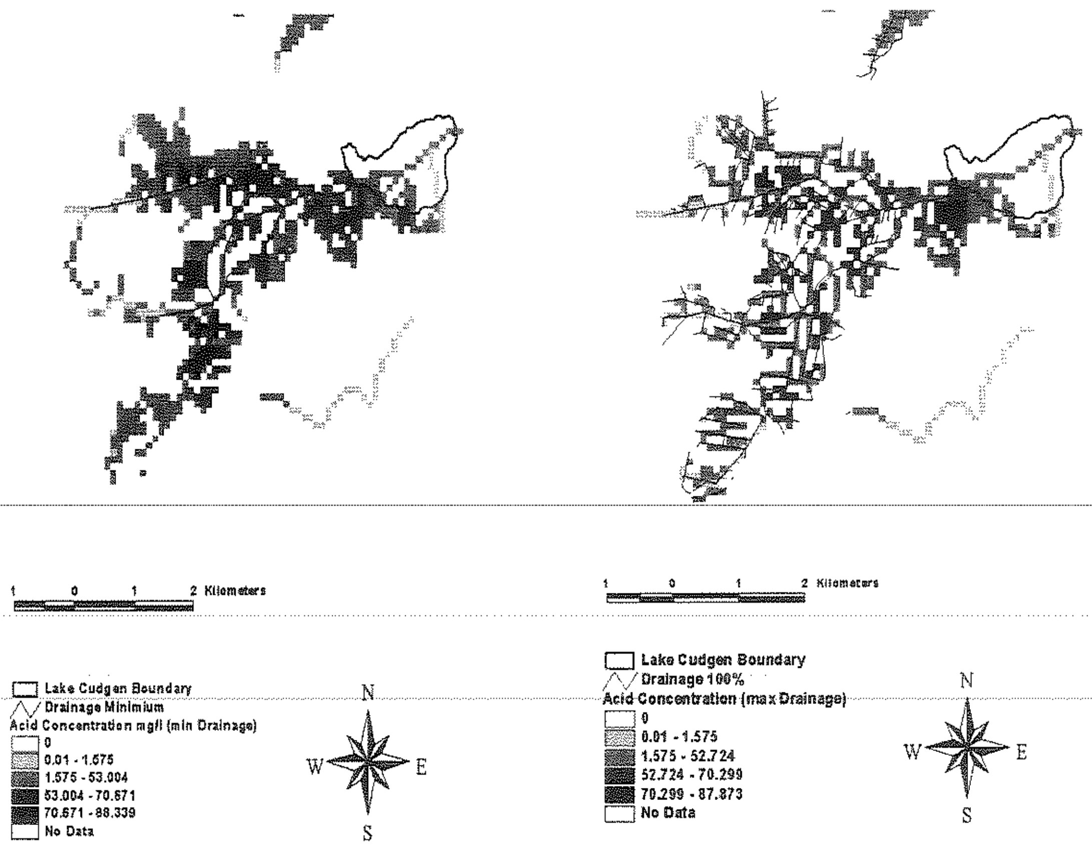

Figure 3. Annual Acid Concentrations (mg/l/yr): **(a)** Under natural drainage density; **(b)** 100% drainage density.

4. DISCUSSION AND CONCLUSIONS

The drainage system has little impact on increasing the water loads to Lake Cudgen (Figures 2a and 2b). However, the acid concentrations (Figures 3a and 3b) show that there is a significant impact on the transportation of acid from the floodplain to the drains at different drainage densities. Under the influence of maximum drainage there is significantly more acid being removed from the floodplain to the drains. Under natural drainage conditions most of the acid is contained within the floodplain.

The model also suggests that if the rate of acid evolution is constant over time and the water loads do not differ significantly under different drainage densities over long time periods, the dynamics of the system are controlled by the amount of water entering the system as runoff and leaving the system as evaporation. This is consistent with previous field interpretations which suggest that, apart from the intensity of a rainfall event, the position of the water table and the available soil pore space also has a significant impact on water quality [Wilson et al.,1999]. Some ground water modelling in conjunction with some surface water modelling as done here will provide a more comprehensive tool for predicting acid transport.

The results obtained here clearly reinforce the current belief that remediation strategies must be aimed at treating the problem at the drainage level. Based on the modelling results, the removal of some agricultural drains in combination with laser levelling of the floodplain will reduce the amount of acid transported from the floodplain to the drainage network. Upland routing of flows around the high risk acid sulfate soils areas will also ensure better water quality for Lake Cudgen.

The model developed here is flexible enough to allow for minor alterations to the input data such as changes to the runoff coefficient and land loads. The model offers land management groups a tool for assessing the impact of drainage and climate on the transportation of acid and acid products. Remediation options can be put into place to lessen the degree of acid runoff based on model predictions. The model outlined in this paper will help farmers and other stakeholders prioritise their management options.

In summary, the results obtained suggest that the flood mitigation drains play a major role in the export of acid from the floodplain. The drainage system acts as a potential reservoir for acid and is a conduit for the transportation of acid to aquatic systems such as Lake Cudgen.

5. ACKNOWLEDGEMENTS

The authors wish to thank the Acid Sulfate Soil Program (ASSPRO) and The NSW Department of Agriculture who have helped funded this project. The authors would also like to thank Ms Sue Rea and Mr Glenn Atkinson from NSW Department of Land and Water Conservation for the mapping data and Mr John Stein (CRES, ANU) for his advice and help with the ANUDEM program.

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