Stream water Acidification in Response to Anthropogenic Pollution Inputs at Forested and Cultivated Catchments in the Middle Hills, Nepal

Robert Collins, Alan Jenkins, David Boorman
Institute of Hydrology, Wallingford, Oxon, UK
Paul Whitehead
Department of Geography, University of Reading , UK

Abstract

Rainfall and stream chemistry data from the Likhu *Khola* watershed in the Middle Hills of Nepal are reported. Periodic high atmospheric inputs of acidic pollutants have been identified, probably originating from the nearby Kathmandu Valley. Wash-out of fertilizers during storm events in streams draining cultivated catchments results in increased concentrations of nitrate and sulphate, causing stream acidification. The abundance of weathering products derived from the gneissic bedrock (calcium, sodium, and bicarbonate) enable the streams to maintain a high buffering capacity and ensure that stream acidification is only transient. The continuous pH and flow record in a stream draining a forested catchment identifies a rainfall-driven acidification episode; the decrease in pH was caused by deposition of acidic oxides during the event. Predictions of long-term soil and stream acidification using MAGIC-WAND have been undertaken. The model predicts a significant decrease in soil base saturation over the next 50 years in response to the predicted increase in anthropogenic pollution.

Introduction

The sustainable use of land, water, and agricultural resources is an essential component in the future development of Asian Third World countries, especially those regions bordering the Himalayas, where population growth is rapid and predicted to continue. This population pressure results in an intensification of agriculture through the adoption of multiple annual crop rotations supported by large applications of inorganic and organic fertilizers and the expansion of cultivated land on to steeper hill slopes and previously forested areas (Schreier et al. 1994). Continued and excessive application of mineral and organic fertilizers to increase crop yieldd may, however, lead to detrimental effects in the form of soil and water acidification as well as downstream eutrophication. The problem may be exacerbated as a consequence of deposition of acidic oxides from fossil fuel burning and, in this respect, the rapid industrialisation of many Asian countries is predicted to increase pollutant emissions in the future (Arndt and Carmichael 1995).

The Land Use, Soil Conservation and Water Resource Management Project was established in 1991 by the Institute of Hydrology, UK, the Royal Geographical Society, and the Department of Soil Science, His Majesty's Government, Nepal.

The project had the objective of providing data with which to quantify the impacts of land-use change on erosion and nutrient leaching in the Himalayas. This paper draws on a small part of the data collected under this project to determine the impacts of anthropogenic pollution on surface water and soil chemistry.

The Study Sites and Sampling Methodology

The study focussed on the Likhu *Khola* watershed in the Middle Hills of Nepal (Fig. 1). The watershed is located approximately 10km north of Kathmandu, and so industrial emmisions emanating from the Kathmandu Valley provide a source of acidic deposition. In addition, terraced agricultural land throughout the watershed is treated with substantial applications of both mineral and organic fertilizers. Urea and ammonium sulphate are the main forms of mineral N fertilizer used, with approximately 140-200kg ha^{-1} applied to each of the rice crops per year (normally two). Additionally, 6-8 tons yr^{-1} of farmyard manure are applied to the rain-fed terraces.

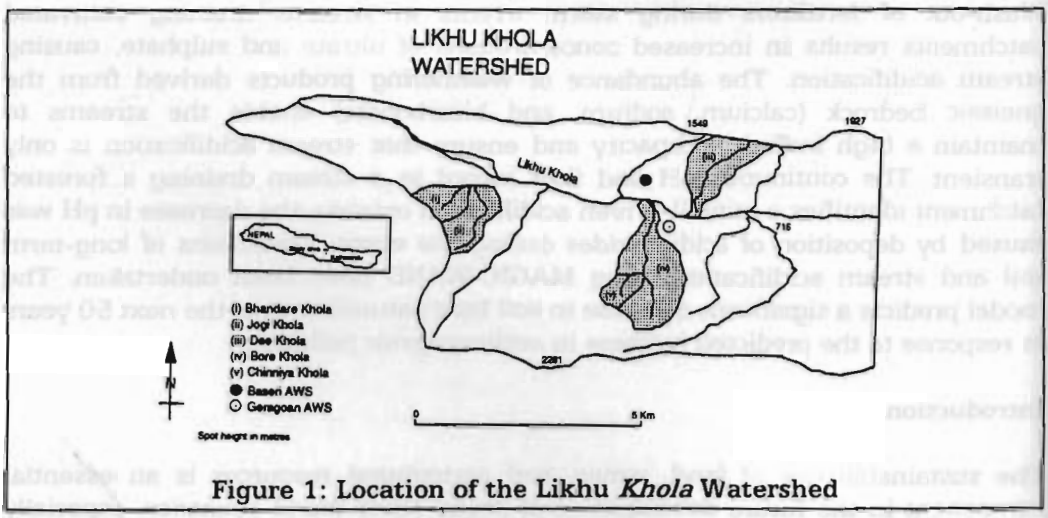

Figure 1: Location of the Likhu *Khola* Watershed

Five sub-catchments, characterised by different levels of agricultural activity and, therefore, fertilizer input, were chosen for detailed hydrochemical study (Fig. 2). Two of these sub-catchments, the Jogi and Bhandare, are intensively cultivated and provide a marked contrast to the predominantly forested Chinnya which receives minimal fertilizer application. The Bore and Dee sub-catchments, both moderately cultivated, provide an intermediate comparison. Weekly samples of stream water were collected from each catchment outflow for major ion analysis, from early June 1991 until September 1993; thus encompassing two dry seasons and three monsoon periods. In addition, bulk rainfall samples were collected at approximately weekly intervals for chemical analysis through the three monsoons from 1991-93.

Rainwater Chemistry

In general, concentrations of all major ions in bulk rainwater are low and are close to laboratory detection limits for most ionic species (Table 1). This underlines

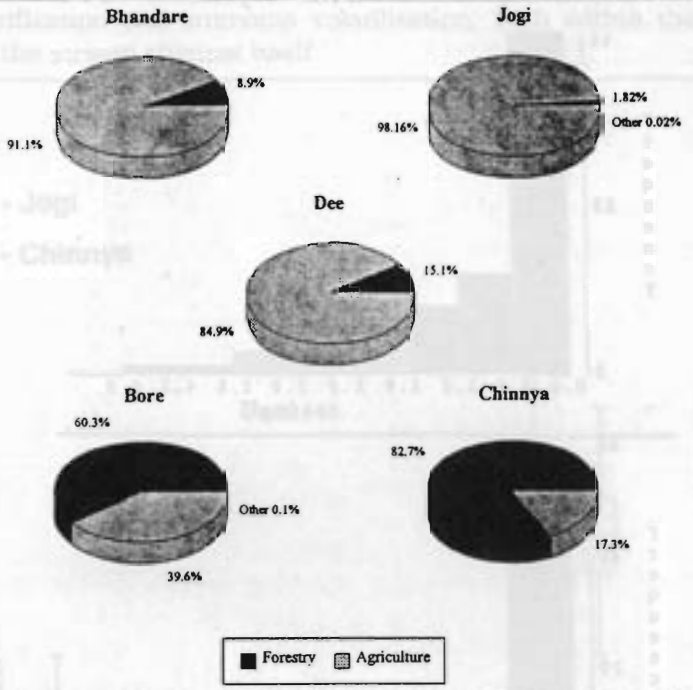

Figure 2: Sub-catchment Land Use Characteristics in the Likhu *Khola* Watershed

observations elsewhere in the Himalayas that long-range transboundary pollution is not yet a significant problem. Nevertheless, periodic extreme concentrations measured at the site (Fig. 3) indicate the potential for high atmospheric inputs of acidic pollutants. These high concentrations probably originate from local combustion or agricultural sources within the river valley, as indicated by the high concentrations of chloride relative to sodium, or from pollution sources in the heavily polluted nearby Kathmandu Valley. On the other hand, longer range atmospheric transport from sources in other countries cannot be ruled out.

Table 1: Mean Rainfall Chemistry (concentrations are in mg/l)

Variable	N	Minimum	Maximum	Mean	Std Dev
pH	73	5.90	8.50	7.05	0.71
Na	73	0.04	3.60	0.29	0.56
K	73	0.02	1.30	0.19	0,28
Mg	73	0.05	1.45	0.40	0.24
Ca	73	0.40	2.40	1.15	0.56
Cl	73	1.04	5.00	3.08	0.73
SO_4	73	0.05	4.72	0.90	1.04
NO_3	73	0.01	2.75	0.26	0.42
NH_4	73	0.01	1.80	0.41	0.41
Fe	40	0.02	1.00	0.06	0.16
Al	40	0.00	0.22	0.02	0.05

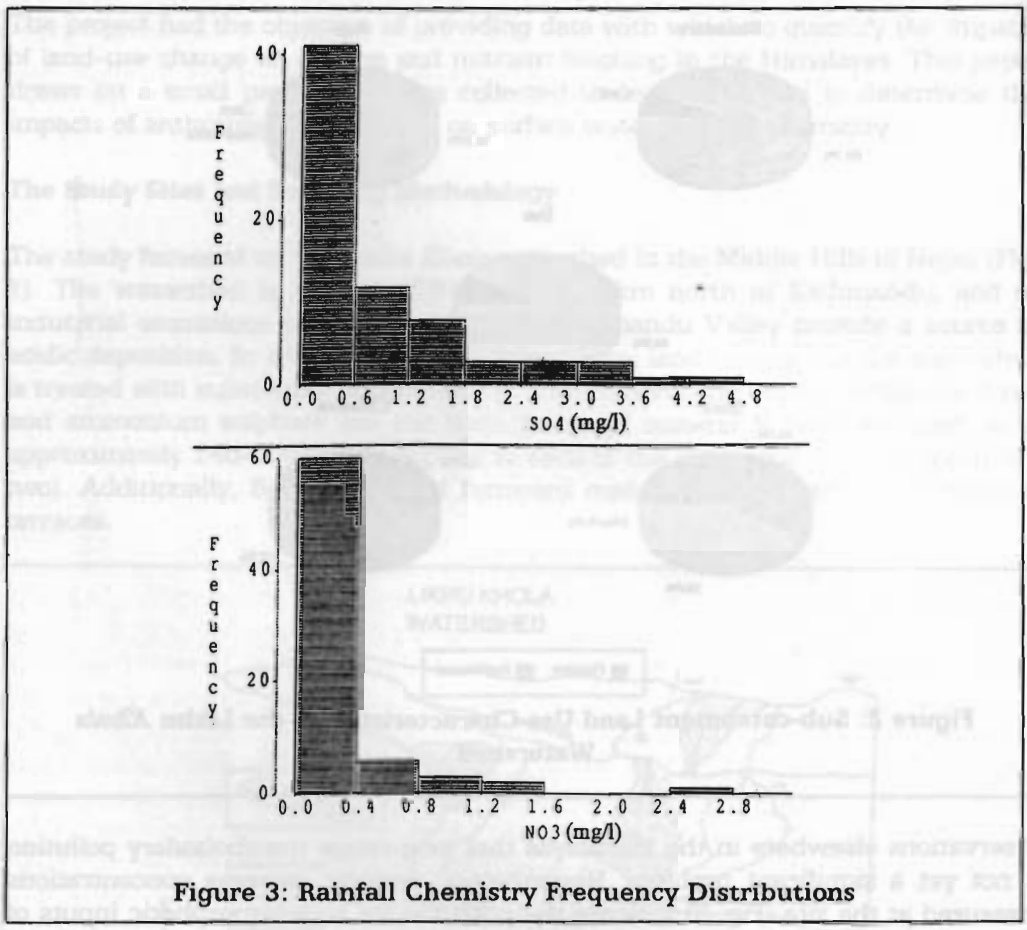

Figure 3: Rainfall Chemistry Frequency Distributions

Stream-water Chemistry - Mean Characteristics

Significant differences in the mean concentrations of major ions have been identified between catchments under different land use. Mineral fertilizers applied to terrace surfaces are washed off during rainfall, resulting in significantly higher mean concentrations of nitrate and sulphate (Fig. 4) in streams draining from the agricultural catchments than in the forested catchments. Higher mean concentrations of chloride in the streams draining cultivated catchments than in the forested catchments (Fig. 4) reflect higher water loss through greater evapotranspiration from flooded rice terraces and irrigation canals. Despite the higher mean concentrations of acid anions in the streams draining agricultural catchments, each of the streams is well buffered and remains consistently near neutral pH. Calcium, sodium, and bicarbonate ions, derived principally as weathering products from the gneissic bedrock, contribute substantially to the maintenance of a high acid buffering capacity. Tillage practices, which continually expose fresh soil to weathering and erosional processes, potentially promote higher weathering rates within the cultivated catchments. Despite high applications of fertilizer to agricultural catchments, nitrogen concentrations in drainage waters are generally low (Fig. 4). This reflects large losses of nitrogen

through denitrification and ammonia volatilisation, both within the rice terrace system and in the stream channel itself.

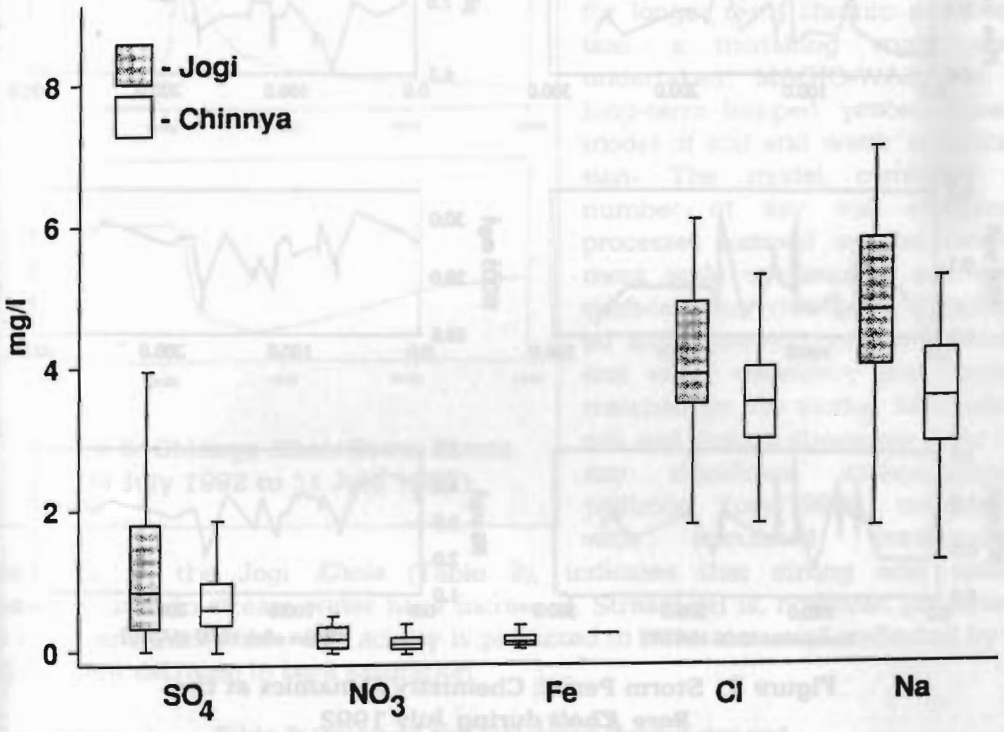

Figure 4: Differences in Stream-water Chemistry between Chinnya (forested) and Jogi (agricultural) Catchments (Horizontal lines are mean concentrations, the box shows the range of the mid 50 per cent of values and the 'whiskers' show the maximum of 1.5 x the interquartile range.)

Stream-water Chemistry - Storm Period Dynamics

Stream chemistry samples were taken at approximately hourly frequency over a period of five days, during storm events in the monsoon period of 1992, to enable examination of the potential for nutrient and acidic flushes through the catchment system during such events. The storms monitored were relatively moderate in magnitude and intensity, resulting in peak flows of only about $1 m^3 s^{-1}$. Stream chemistry response to rainfall in the Bore (Fig. 5) is characterised by a rapid decrease in base cation concentrations and bicarbonate alkalinity, since these are predominantly weathering-derived ions and so dilute with increased flow. This decrease in acid buffering capacity is accompanied by a concomitant increase in anion concentrations, predominantly fertilizer derived sulphate and nitrate, triggering a reduction in stream pH with each storm event. This acidification is transient, however, and the stream quickly recovers to its near neutral pre-storm base flow pH status. The data indicate that quick flow pathways dominate storm runoff generation in these catchments.

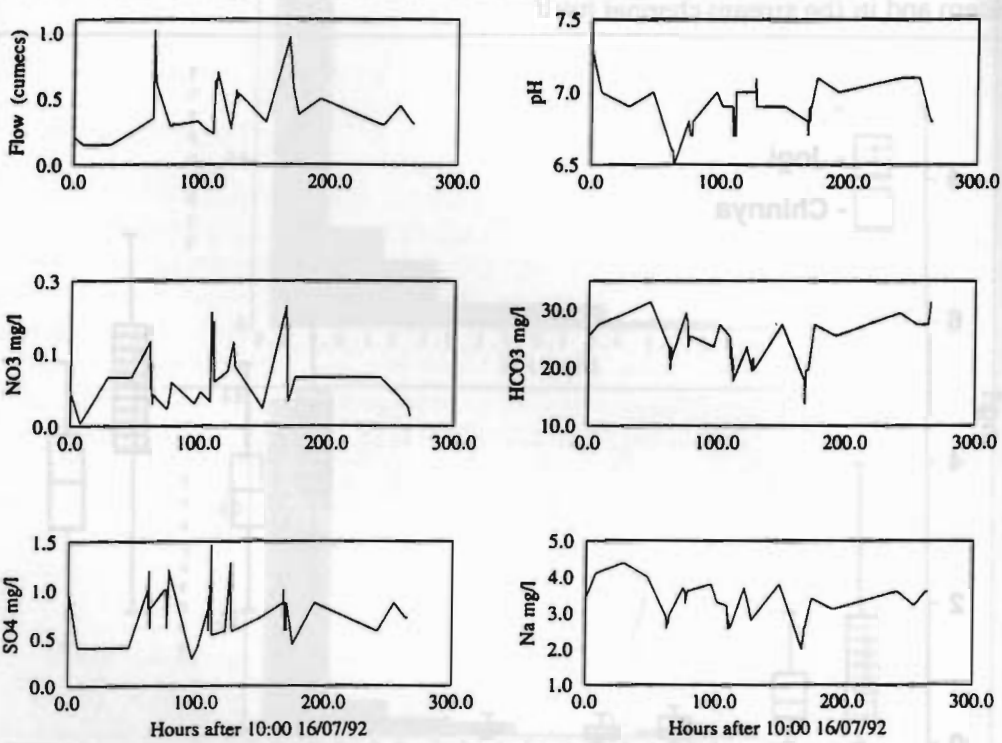

Figure 5: Storm Period Chemistry Dynamics at the Bore *Khola* during July 1992

Increases in sulphate and nitrate concentrations indicate wash-out of applied mineral fertilizers from terrace surfaces, and these are the main cause of the acidic pulses within stream waters. In this respect, ammonium sulphate fertilizer is frequently applied directly on to the flooded terrace surface after the rice crop is established and so is particularly susceptible to wash-out during monsoon storms. The dynamic response of streamflow in response to rainfall and the resulting rapid stream chemistry response, reverting quickly to pre-storm chemistry on cessation of rainfall, precludes any indication of acidic episodes from analysis of the mean chemistry as a result of low sampling frequency. Acidic episodes of this magnitude are known to be biologically damaging to aquatic biota in other environments and have been identified as a precursor to longer term chronic acidification.

In contrast to the agricultural catchments, the Chinnya, a relatively pristine forested catchment, would not be expected to demonstrate marked acidic pulses, as it receives little or no fertilizer input. However, a storm event recorded on an automatic flow and pH monitoring system in July 1992 (Fig. 6) demonstrates a severe decrease in pH in response to increased flow. The decrease is of a similar magnitude to those observed at the agricultural catchments. This event must have been driven by a high concentration of acidic anions in the rainfall, indicating an underlying vulnerability of streams draining these relatively pristine forested catchments to acidic deposition.

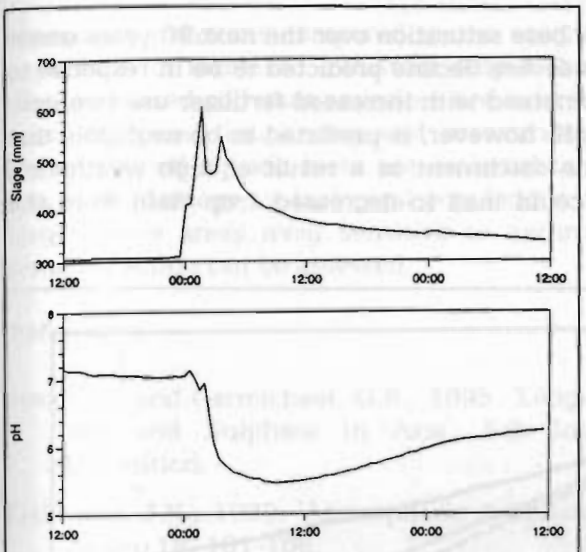

Figure 6: Chinnya *Khola* Storm Event (09 July 1992 to 11 July 1992)

Modelling Soil and Stream Acidification

In order to quantify the potential for longer term chronic acidification, a modelling study was undertaken. MAGIC-WAND is a long-term lumped, process-based model of soil and water acidification. The model combines a number of key soil chemical processes lumped on the catchment scale to simulate soil and surface water chemistry. Simulated and observed present-day soil and water chemistry are closely matched by the model. Simulated soil and stream chemistry prior to any significant anthropogenic pollution (pre-1960), compared with simulated present-day chemistry in the Jogi *Khola* (Table 2), indicates that strong acid anion concentrations in stream water have increased. Stream pH is, however, predicted to have remained stable. Soil acidity is predicted to have increased, reflected by a 20 per cent decrease in base saturation.

Table 2: Observed and Simulated Present-day and Simulated 1960 Mean Soil (% base saturation) and Water (meq m^{-3} except pH) Chemistry.

	Simulated 1960	Simulated 1994	Observed 1994
Ca	241	299	293
Mg	116	147	148
Na	216	217	212
K	25	28	31
NH_4	0	17	16
Cl	20	121	115
SO_4	4	85	85
NO_3	0	18	17
pH	7.5	7.4	7.4
% Base Sat.	50.3	43	40

The calibrated model for the Jogi *Khola* has further been used to assess the potential for future soil and water acidification under three scenarios of fertilizer application and atmospheric deposition: (i) a steady state scenario, whereby both fertilizer additions and atmospheric deposition are assumed to remain constant at present levels; (ii) a doubling in the flux of strong acid anions and ammonium from atmospheric deposition with fertilizer addition remaining constant, corresponding to a predicted increase in pollution from long-range transboundary sources (Galloway 1989) and an increase in local industrialisation; and (iii) a doubling in fertilizer application in addition to the increase in atmospheric deposition assumed under scenario (iv), reflecting the potential intensification in agricultural production in response to population increase.

The model predicts a decrease in soil base saturation over the next 50 years under all three scenarios (Fig. 7), the most severe decline predicted to be in response to increased atmospheric deposition combined with increased fertilizer use (scenario iii). The impact upon stream water pH, however, is predicted to be negligible due to the high buffering capacity of the catchment as a result of high weathering rates. This increase in soil acidity could lead to decreased crop yield from the agricultural terraces.

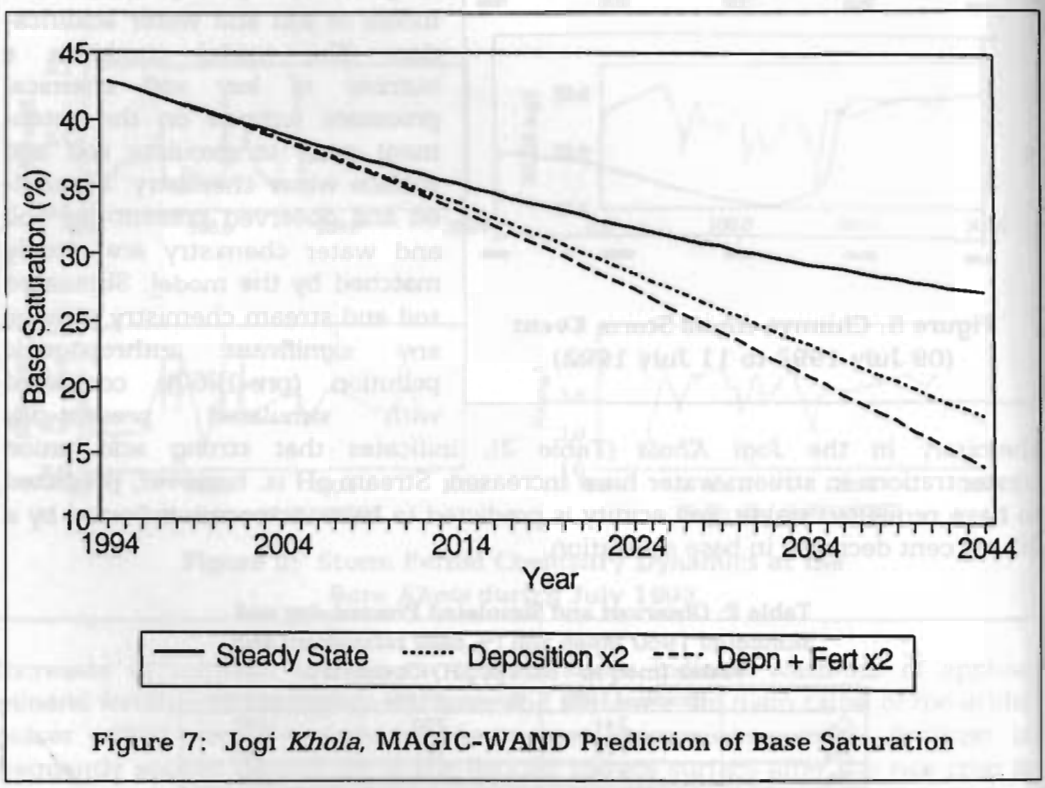

Figure 7: Jogi *Khola*, MAGIC-WAND Prediction of Base Saturation

Conclusions

Both forested and cultivated catchments in the Middle Hills are susceptible to episodic acidification. The acidic inputs driving this acidification are derived from atmospheric deposition and application of inorganic fertilizers. In the case of acidification from fertilizers, it is clear that the method of application could be changed to ameliorate the most severe effects. For pristine areas not subject to fertilizer inputs, the problem is more difficult to remedy. Similar studies in north-west Europe and North America indicate that a reduction or slowing in the rate of emission of acidic oxides would reduce the potential ecosystem impacts of atmospheric deposition. Remedial measures to reverse soil and surface water acidification in NW Europe and N America were, however, implemented too late to prevent losses of biological and economic resources, largely because the precursors to chronic acidification went unnoticed. In the Himalayas, an early warning about a potential problem has been observed and provides the opportunity for remedial measures to be adopted without long-term loss of, or damage to, natural resources. The cost implications of introducing emission

abatement measures compared to the economic and social benefits to the local population of increased industrial output, however, mean that increased rather than decreased pollutant emissions are most likely in the immediate future. In this case, continued monitoring and assessment of soil and water chemistry and terrestrial and aquatic biota are essential to provide early warnings of potential loss of, or damage to, biological populations and ecosystem diversity and to help target those areas most sensitive to anthropogenic pollution so that effective remedial action can be assessed.

References

Arndt, R. and Carmichael, G.R., 1995. 'Long-Range Transport and Deposition of SO_2 and Sulphate in Asia', 5th International Conference on Acidic Deposition.

Galloway, J.N., 1989. 'Atmospheric Acidification: Projections for the Future'. In *Ambio* 18, 161-166.

Schreier, H.; Shah, P.B.; Lavkulich, L.M.; and Brown, S., 1994. 'Maintaining Soil Fertility under Increasing Land Use Pressure in the Middle Mountains of Nepal'. In *Soil Use and Management* 10, 137-142.