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Critical load – A New Approach, Concept and Applications

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Deposition of S and N oxides causes acidification and eutrophication of aquatic ecosystem. Critical load is being used by most of the European countries as a tool to set goals for future acid deposition such that the environment is protected. In present communication, critical load concept, steady state mass method, which is commonly used for deriving this load and its application for aquatic ecosystem have been discussed. The method is very simple to apply but major problem lies primarily in the estimation of authentic input data. By using this approach it is possible to identify the controls on 'S' and 'N' deposition which may be required to protect the ecosystem in future thus making it as a powerful tool for planning acidification abatement policies for a region.

Key words : Critical load, Acidification, Aquatic ecosystem and Abatement policies.

Introduction :

Concern about the undesirable effects of air pollution in many areas of Northern hemisphere has led to a considerable amount of national and international research into the impact of acidic deposition on ecosystem functioning and vitality. Ecosystem may be consists of water and soil. Quality of water is affected by the dumping of industrialize effluent or waste materials in to the surface water. In addition to this deposition of S and N compounds also causes adverse impacts on water quality. Deposition of S and N compounds, which are mainly the result of urbanization, caused the acidification of surface water, ground water and soil. Due to atmospheric deposition the major change in water chemistry are increase in SO_4, NO_3 and Al concentration and decrease in pH and alkalinity values. Population of fish and other biota in water are decreasing due to high concentration of labile Al and low pH of water (Henriksen *et al.*, 1992). Apart from acidification, excess inputs of nitrogen through deposition also cause high level of NO_3 in water and change of vegetation (Boumans, 1991).

Political decisions on emission reductions require scientific determinations of those deposition levels of SO_2, NO_x and NH_3 which causes adverse environmental effects. Information's of these, so called **critical load** plays an important in the development for a given region 'acidification abatement policy' (De vires, 1993).

The most general definition of critical load is '**quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to our present knowledge**'. Another definitions is 'the maximum deposition of acidifying compounds that will not cause chemical changes leading to harmful effects on ecosystem structure and function' (Nilsson, 1988). Some aspects of these definitions are worth special attention. Firstly, the definitions focuses on chemical changes in the environment, and establish these as the link between emissions and the biological ecosystem. Secondly, the phrase long-term expresses the fact that there is a time lag between a change in emissions and a change in chemical effects in the environment. To make it possible to apply the concept of critical loads additional terms are necessary to understand, which are :

Receptor : It is the type of ecosystem, which is considered for study like surface water (lakes and streams), ground water and forest soils.

Biological indicator: is the type of organism that has been selected to represent to receptor. Typical biological indicators would be fish for surface water, trees and vegetation for forest soil and human health for ground water.

Chemical criteria: is a chemical measure affected by the acid deposition that is used to predict the risk of damage to biological indicators.

Critical limit: are the most unfavorable values that the chemical criteria may attain without large term harmful effects on ecosystem structure and function.

In deriving critical loads, a long-term (decades) perspective has to be considered, as most of the effects are results of accumulated deposition. The term critical load should not be confused with target load, which is related to political decision. The critical load is an inherent property of an ecosystem, where as the target load is less restrictive and implies other factors such as economical (cost benefit) or emotional consideration.

Why we need critical load?

The necessity of determining critical loads is to set goals for future acid deposition such that the environment is protected. Computation of critical load is an important tool for assessing acceptable levels of acid deposition throughout the region. It is also intended to represent the long-term capacity of ecosystems to absorb pollutants. It is important instrument in balancing the acidification and nutrient stress imposed on ecosystem by land use, such as forestry against acid deposition. The calculated value of critical load serves as an indicator that how much acidification can be loaded on to the system through deposition of S and N compounds that can not led harmful effects.

Methods and criteria to derive critical load :

Critical load for ecosystem can be estimated in a direct and an indirect way (Fig.1). Derivation of critical load can be estimated directly from the relationship between atmospheric deposition and effect on ‘specified sensitive elements’ within an ecosystem by correlation or experimental research while derivation by indirect way is based on dose response relationship between the chemical criteria and the ecosystem status. For instant, in surface water the pH should preferably be above 6 and certainly above 5.3 to avoid the death of various fish species (Hultberg, 1988).

It is general understanding that critical loads has worthy been derived through an indirect method because a direct assessment generally leads to over estimation, since effects on ecosystem may occurs before harmful effects are visible. In this respect critical loads are enforce to be calculated by the mathematical models such as steady state mass balance method with using some input data.

Critical chemical values

To set a critical load, an indicator organism is chosen, for which the response to different levels of acidification is known. A limit can be set for alkalinity, pH or Al depending on what the organism is sensitive to and a limit that is not to be transgressed due to impact of acid deposition and the critical load is the maximum load of acid input that will keep the system at this defined limit. An average value of chemical criteria for surface water and ground water are shown in Table 1. Although these values are set for European countries where this tool is being used for planning acidification abatement policies, whether these values can be taken as such for tropical countries is a big question mark as not much work has been done in this region.

A critical pH for ground water has been reported 6.0 (Sverdrup, *et al.,* 1990).Critical Al and NO_3 concentration for ground water were 0.02 and 0.8 eq ha^{-1} yr^{-1} (0.2 and 50 mg l^{-1}). For NO_3 a target value of 0.4 eq ha^{-1} yr^{-1} (25 mg l^{-1}) have been reported in literature while the surface water critical pH is 5.3 and critical Al concentration 0.003 eq ha^{-1} yr^{-1} has been reported.

Steady-state Mass Balance Method

Steady state mass balance method is useful to derive critical load of N and total acids (S and N). These methods do not include processes that influence acid production and consumption during a finite time such as cation exchange, mineralization, immobilization of NH_4, SO_4 and base cations, and absorption /desorption of NH_4 and SO_4 (Sverdrup, 1990; De vires, 1991). They include only processes that influence acid production and consumption during finite time such as weathering and net uptake, predict directly the concentration of relevant ions in soil solution (Al, NH_4, pH etc.) in a final equilibrium situation.

Critical load for Groundwater

The basic principle of the method is to identify the long-term average source of acidity and alkalinity in the system and to determine the maximum acid input that will balance the system at the biologically safe limit. Several assumptions have been made in the steady state calculations. First of all, it is assumed that ion exchange is at steady state, and that there is no net change in base saturation or no net transfer of acid neutralizing capacity (ANC) from soil solution to the ion exchange matrix. It is assumed that for nitrogen there is no net denitrification, adsorption or desorption, the nitrogen cycle is at steady state. Sulphate is also assumed to be at steady state, no sulfides oxidation, sulphate uptake, sulphate permanent fixation or sulfate reduction are considered as significant. A simple hydrology is assumed, where there is straight infiltration through the soil profile.

Fig. 2 shows watershed, which is at steady state for ground water. All the sources of acidity in the system can be put into a balance against all sources of alkalinity in the ecosystem

$$ANC_w + ANC_{ex} = AC_d + AC_u + ANC_L + AC_N$$

(where AC_d is deposition of acidity, AC_N soil generated acidity, AC_u base cation uptake acidity, ANC_w weathering rate neutralization, ANC_{ex} ion exchange neutralization, ANC_L is alkalinity leaching).

ANC_w is the weathering neutralization rate eq ha^{-1} yr^{-1}, which is assumed to be equal to the net base cation release rate:

$$ANC_w = BC_w$$

AC_u the acidity due to base cation uptake BC_u by vegetation growth (eq ha^{-1} yr^{-1})

$$BC_u = AC_u$$

AC_N is the acidity generated in the soil by ammonium uptake, nitrate uptake, nitrification and denitrification, expressed in eq ha^{-1} yr^{-1}. ANC_L is the alkalinity output from the system due to runoff or percolation in eq $ha^{-1}yr^{-1}$ and can be regarded as an objective function, defined by site characteristics and the indicator organism for the ecosystem. At steady state, when no acidification of the system is permitted, then the exchange alkalinity term must be zero ($ANC_{ex} = 0$), and this term to be balanced by the only long- term source of alkalinity, the weathering of mineral in soil. When the alkalinity/acidity balance is expressed as an equation for steady state situation, when no more acidification is allowed to occur

$$BC_w = AC_d + BC_u + ANC_L + AC_N$$

The critical acid load for the system expressed as total acidity

$$CL\ (acidity) = BC_w – BC_u – ANC_L - AC_N$$

This is the main equation for the Simple mass balance method for calculating the critical load for ground water. The acidity produced in the soil from nitrification and uptake of ammonium and nitrate can be expressed as

$$AC_N = NH_{4d} - NH_{4l} + NO_{3L} - NO_{3d}$$

(where d and L stands for deposition and leaching of respective species).

With the assumption that no ammonium is leached from the soil, it can shown that

$$AC_N = 2.NH_{4d} - N_{totU}$$

Depending on the amount of nitrogen compounds in the soil, the type of canopy, climate and soil type the net effect of these processes may either be a net production of alkalinity, balance or a net production of acidity. If this expression for AC_N is included in the critical load acidity the modify equation would be:

$$CL\ (acidity) = BC_w - BC_u - 2.NH_{4d} + N_{totU} - ANC_L$$

Critical load for Lakes and streams

Similar to ground water, in lakes and streams several assumptions have also been made in the steady state calculation. It is assumed that the sulphate concentration in runoff is in steady state with the atmospheric deposition of sulphate (Fig. 3). It is assumed that acid deposition related to sulphur is the only significant input of acidity, and nitrate is assumed to be completely taken up by the vegetation, ammonium deposition and subsequent nitrification is assumed to be negligible. The base cation concentration values are adjusted before calculations in order to subtract the deposition of sea salt assuming all chloride deposition is to be marine

$$Ca^* = [Ca] - 0.037\ [Cl^-]$$

$$Mg^* = [Mg] - 0.198\ [Cl^-]$$

$$Na^* = [Na] - 0.858\ [Cl^-]$$

$$K^* = [K] - 0.018\ [Cl^-]$$

$$SO_4^* = [SO_4] - 0.103\ [Cl^-]$$

Non marine base cations are expressed as

$[BC^*] = [Ca^*] + [Mg^*] + [Na^*] + [K^*]$

The definition of alkalinity or acid neutralizing capacity (ANC) as the chemical criterion for sensitive indicator organisms in surface water is defined as the difference between non-marine base cations (BC*) and strong acid anions (SO_4^{2-} and NO_3^-)

$ANC = [BC^*] – [SO_4^{2-}] + [NO_3^-]$

The base cation concentration in lake or surface water is the result of a balance between inputs from weathering deposition and removal by the vegetation and runoff. Thus, the sensitivity of a lake is related to its concentration of base cations or in other words related to the weathering rate of the soil in its catchments.

Assuming the sulphate and base cation water concentrations given are equal or close to weighted yearly average concentration of the actual components and it can be multiplied by the yearly runoff value to give the yearly flux. Then the critical load of acidity is

$CL = ([BC^*_0] – [ANC_{limit}]).\ Q – BC^*_d$

where $[BC^*_0]$ is pre acidification base concentration, which is a function of the non-marine base cation deposition, base cation uptake and soil weathering rate. ANC – concentration for the organism considered, Q is mean annual runoff and BC^*_d base cation deposition. To compute the critical load, values for BC_0^* have to be estimated from the present day water chemistry data. This calculation involve the consideration of F factor, which is:

$[BC^*0] = [BC^*_{present}] – F.\ [SO_4^{2-}{}_{present}] – [SO_4^{2-}{}_0]$

where $BC^*_{present}$ is present deposition of base cation, $SO_4^{2-}{}_{present}$ present deposition of SO_4

and $SO_4^{2-}{}_0$ is background concentration of sulphate and F is factor which is defined as the change in base cation concentration due to change in the concentration of sulphate

$F = [BC^*] / [SO_4^{2-*}]$.

Input data :

A regional determination of critical loads for ground water will generally be based on the calculation of the critical load either at a numbers of points, spread out over the land area considered or on distribution of input data derived from site specific properties. Major problem to calculate the critical load is to have the authentic input data. The require input data are:

- Base cation deposition
- Annual runoff
- Weathering rate
- Net uptake of base cation

Deposition and runoff :

Runoff and precipitation volume and rates are generally available in the concerned departments of the region. Base cation deposition figures are available as wet and dry deposition on the grid basis from the monitoring network like CPCB or it can be evaluated from the sampling of wet and dry deposition of the test region. The total (wet + dry) deposition must be derived using conversion function

$$\mathrm{Tot}_D = \mathrm{Wet}_D \left(1 + D_F \frac{\%\ \text{Forest cover}}{100}\right)$$

D_F is the dry deposition enhancement factor, derived from relating estimates of wet deposition to forest throughfall measurement.

Weathering rate :

The weathering rate is one of the key parameter for calculating the critical load and must be estimated from independent parameters. Weathering rate can determined in a number of ways; theoretically (using model) and experimentally. The PROFILE model can be used to calculate the weathering rate based on accurate mineralogy and texture data. It is a mathematical soil chemistry model, which has been computerized, it calculates the steady state chemistry through a soil profile. It has been developed at Lund Institute of technology in Sweden. To calculate weathering rate from this model mineralogy data will be needed. This data can be found in agricultural surveys and special soil characterization studies. By experimental technique, it will be determined from the correlation between observed weathering rates and total soil content of Ca and Mg as reported by Olsson and Melkerud (1990)[8]. The total Ca and Mg (XCa + XMg) will be determined by soil analysis.

Uptake

Biomass uptake of base cations is calculated from net biomass volume, base cation content and the time over which the biomass accumulated. The uptake is not the actual total uptake, but the net uptake. It can be taken from the work done by agricultural institute.

Uncertainties in critical load calculation

The uncertainties involved in the average critical load calculation can be divided in to three major source of origin which are:

- Critical chemical limit
- Input data uncertainty due to
  - Spatial variability in the field
  - Accuracy of parameter estimation
- Validity of model assumption

Uncertainty in critical chemical values for a given receptor partly reflect lack of knowledge regarding the effect of acid deposition and are partly due to a natural range in sensitivity. This uncertainty can be very large, especially for critical acid loads in forest since the range in Al toxicity appears to be very large for different tree species. For ground water the uncertainty in acceptable alkalinity leaching is less since the range of critical chemical levels for alkalinity is lower.

Uncertainties in input data are due to lack of knowledge, including measurements errors and spatial variability. The values that have been used for deposition, weathering, uptake and precipitation surplus are long-term averages.

The uncertainty for the critical load at a specific location may be in the order of 50% due to spatial variability in these data. Especially for deep groundwater the uncertainty in critical load can be substantial due to uncertainties about the occurrence and rate of denitrification and weathering in saturated zone. Use of the values derived for groundwater might be a substantial underestimate of critical loads that are relevant at the depth of groundwater extraction.

Unlike the uncertainty in critical chemical value and data, it is nearly impossible to quantify the uncertainty due to modeling assumption. It is important to note that the use of one layer model will most likely cause as unprediction of critical loads. In model the large source of the uncertainty occur due to the occurrence of the nitrogen fixation, dentrification or a complex hydrology including seepage or surface runoff.

Conclusion :

Though critical loads are extensively used as scientific underpinning for pollution control policies in Europe, it is yet to be established as a major tool in Asian countries. Asia, which is a land of varied environmental conditions and ecosystems, a considerable effort, is needed in the calculation of the critical loads. The Asian ecosystem encompasses tropical rain forest to near desert conditions and mangroves to areas of taiga, therefore extensive validation procedures are required to improve the assessment of risk of damage on local scales. More monitoring and impacts data are required to improve the scientific basis for defining and mapping critical load.

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Table 1: Critical value for pH, Al concentration, and NO_3 concentration in ground water and surface water.

Criteria	Groundwater (eq ha^{-1} yr^{-1})	Surface water (eq ha^{-1} yr^{-1})
pH	6.0	5.3
Al	0.02	0.003
[NO_3]	0.8	-

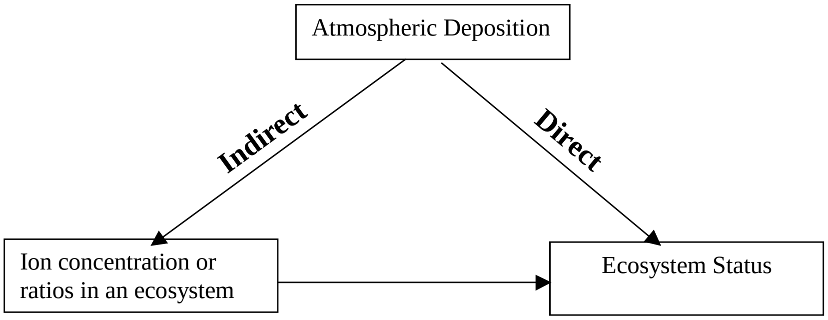

Fig. 1 : Research methods to derive critical loads for N and S.

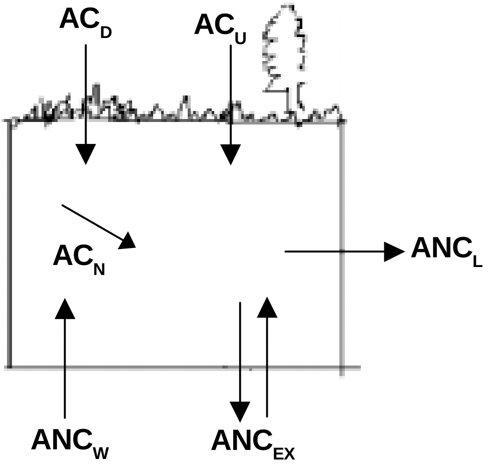

Fig. 2 : Schematic presentation of how the system boundaries are drawn when the critical load is calculated for groundwater.

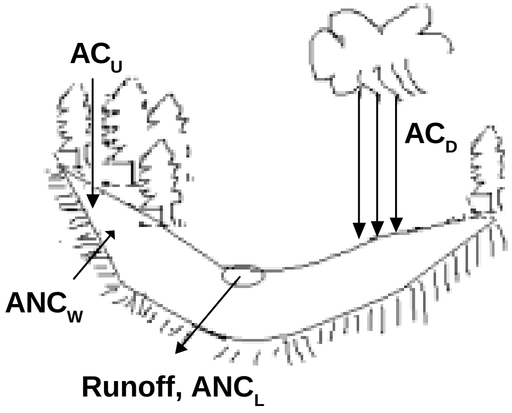

Fig. 3 : Schematic presentation of how the system boundaries are drawn when the critical load is calculated for Lakes and Streams.

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