# Uncle Tony's computer: order-of-magnitude modelling as a screening tool in environmental analysis

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**This paper describes a simple, quick, non data-intensive quantitative approach for sorting certain types of environmental issues into those that are unlikely to be problems; those likely to be problems; and those requiring further, more detailed investigation. It applies to situations where the impact results from an altered input to a system, for instance of a pollutant, or an altered output, for instance a harvest. It is based on a rough (order-of-magnitude) estimation of the degree to which a proposed action is likely to perturb the throughput of a given system. If the perturbation is an order of magnitude or more smaller than the throughput, it is deemed unlikely to affect the ecology of that system in a material way. If larger than the throughput, it is very likely to have a substantial effect on the functioning of the system. If somewhere between the two limits, the problem requires further study. The method assumes a good, but not highly quantitative, knowledge of the system, and does not apply to cumulative effects.**

## Introduction

When Tony Starfield took up his position at the University of Minnesota, he wanted to stay in contact with his young nephews in South Africa. They proved poor correspondents, being embarrassed to share their everyday adventures with their learned uncle. So Tony hit on the strategem of having his computer communicate with them, secretly and via e-mail, on his behalf. 'Dear Steve, this is uncle Tony's computer speaking. Please don't tell him I am talking to you! Do you know what he did today? '. They responded unreservedly.

The idea has the simple effectiveness that characterizes so much of Tony's work. The technique described in this paper is similarly simple — mathematicians would say trivial, in the devastating way they have — that it hardly seems worthwhile documenting. But in discussions with students and professional colleagues, I am surprised to find that they do not apply a similar approach to screening the many issues that are raised during the scoping phase of environmental investigations. The use of order-of-magnitude tests to eliminate unfeasible solutions is commonplace among physicists and engineers, but apparently not among environmental scientists. I acknowledge here my indebtedness to the Department of Physics at the University of the Witwatersrand, who taught me during my first year at university the invaluable disciplines of dimensional analysis and appropriate precision.

I call the technique 'Order-of-Magnitude' (OoM). In Afrikaans, an *Oom* is an uncle, or any respected elder of the Tribe; hence the title of the paper.

## Assumptions and rules

The OoM technique applies to 'input–output' systems, where the stock of some ecosystem service is determined by the balance between the rate of production (or input) of that service and its rate of loss (output). It is assumed that in the natural state the system is close to equilibrium; that is, inputs are approximately equal to outputs. An 'ecosystem service' is any attribute of an ecosystem deemed to be important to people, either directly because they consume it (for example, fresh water or clean air) or indirectly because they value it or rely on it (such as biodiversity).

OoM, as described here, *does not* apply to situations where impacts are cumulative or synergistic. For instance, if ten separate developments each have an impact of less than one order of magnitude below the pre-development throughput (that is, under 10%; the concept of throughput is elaborated below), the combined impact is probably well within the zone of concern. Furthermore, a situation where the perturbation accumulates within the system over time (examples are persistent organic pesticides, heavy metals or radionuclides) violate the 'input–output' assumption of this approach, i.e. the system is not in steady state. Finally, there may be situations when two or more perturbations interact to have a greater combined impact than if they were to be analysed separately.

The procedure is very simple:

1. Estimate, to an accuracy of within one order of magnitude, the 'throughput' ($T$) of a particular ecosystem service. This is defined as either the production rate of that service, over a given period of time, or the loss rate. Where there are several

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production sources or loss mechanisms, it is the sum of the sources.

2. Estimate, to an accuracy of within one order of magnitude, the size of the net perturbation ($P$) resulting from the proposed action. $P$ is the difference between the change in inputs and the change in output, where the sign of the perturbation is positive for an increase in either input or output.
3. Compare the net perturbation to the throughput. If:
   a. $\boldsymbol{P \geq T}$ then the perturbation is highly likely to disrupt the supply of the ecosystem service in a meaningful way, requiring either avoidance or strong mitigation. This means that the issue is either sufficiently serious to result in the rejection of the development proposal at the 'scoping' phase of the environmental impact assessment (EIA), or else the issue needs to be specifically addressed in a full EIA process — specialist studies, mitigation option investigation, public participation and expert review.
   b. $\boldsymbol{0.1T < P < T}$ (i.e. $P$ is smaller than $T$, but greater than 10% of $T$) then it is possible that the ecosystem service will be adversely affected to an unacceptable degree. Further investigation is called for, typically involving better estimation of the parameters (i.e. fieldwork) and a dynamic systems model. If this more resolved and accurate model continues to indicate that the change in the ecosystem service is probably beyond the normal range of variation of that service, including a precautionary safety margin based on the uncertainty in estimating both the normal supply and change in supply of the service, then treat as (a) above. If not, following expert review and transparent public communication, proceed as (c).
   c. $\boldsymbol{P < 0.1T}$ then it is unlikely that the ecosystem service will be affected *by this action alone* to a degree which threatens the integrity of its future supply, or even to a degree that can be reliably measured. This issue need not be further investigated (i.e. can be terminated at the scoping phase) and does not constitute a fatal flaw ('show-stopper'). Even though the impact is small, mitigation and monitoring actions may be appropriate, and may be required by the development permit. If a full EIA proceeds, the issue and the response to it (such as mitigation or monitoring actions) need to be documented, but do not require further data collection or analysis.

This set of rules is based on the observation that most ecosystem processes are not static over time, but exhibit variations either due to their internal dynamics or in response to external forcing. Resilience theory[1] suggests that ecosystems are robust within the range of variation that they regularly explore, or they would not persist. In the context of southern African ecosystems, most production and loss processes for ecosystem services vary on an annual to decadal timescale by well in excess of 10% of their mean value. For example, the throughput of many processes in terrestrial ecosystems is linked ultimately to rainfall, which varies inter-annually by 20% or more on the subcontinent. Furthermore, there are very few ecosystem processes that can be measured with a precision better than 10%. Even the most sophisticated and accurate flux measurement technology typically has an error of around 15%. It would be a brave or foolish ecosystem modeller indeed who claimed an absolute accuracy better than this.

## Examples of application of the method

*The Limpopo-Shashi aquifer.* In the late 1980s, the development of the diamond mine at Venetia (Limpopo province) required a supply of fresh water of about $4 \times 10^6$ m$^3$/yr. There was known to be a shallow sand aquifer immediately upstream of the confluence of the Shashi and Limpopo rivers. This aquifer also supported one of the largest patches of riparian forest in South Africa — an area 6 km long by about 100 m wide. The question was whether the abstraction of water from the aquifer would harm the riparian forest. The size of the aquifer was unknown, but it was known to be shallow, and it seemed reasonable to assume that the forest had expanded to occupy most of the area that had access to the aquifer. There is no surface water in either river for long periods.

A continuous cover of green vegetation transpires at about 80% of the rate of water loss from a large water body, $E_0$. $E_0$ can be estimated from climatic variables in a variety of ways. For data-sparse situations, the Linacre equation[2] is reasonably robust. Using the monthly maximum and minimum temperature data from Marnitz, about 50 km to the south, the annual evaporation $E_0$ was estimated at 2480 mm. The mean annual rainfall in the area is about 400 mm. In situations such as that occupied by the riparian forest, where a narrow belt of wet vegetation is surrounded by a large area of dry bush, the 'oasis effect' must also be considered. In other words, part of the energy that drives evaporation is derived from hot air drawn in from the surrounding areas, thus increasing the transpiration rate. A check of the literature suggested that the oasis effect would approximately double the transpiration rate. Therefore, expressing all the data in units of metres, the annual water use from the aquifer by the riparian forest was given by

$$\begin{aligned} E_{\text{trees}} &= (E_0 \times 80\% \times 2 - \text{rainfall}) \times 6\text{ km} \times 100\text{ m} \\ &= [(2.5 \times 0.8 \times 2) - 0.4) \times 6 \times 10^3 \times 1 \times 10^2 \\ &= 2.16 \times 10^6\text{ m}^3/\text{yr.} \end{aligned}$$

Comparing this to the amount needed for the mine indicated a real possibility that abstraction at this rate would adversely affect the riparian forest. The mine developers instituted a more detailed study of trees in the vicinity of a test well, and noted symptoms of water stress. The outcome was that an 'off-channel' storage dam was built on a dry tributary to the Limpopo, to which water could be pumped when there was excess flow in the river. This storage facility could supply the mine during periods when the riparian forest was solely dependent on the aquifer.

*Dune mining at St Lucia.* The proposal to extract titanium-containing minerals from the coastal dunes between the St Lucia estuary and the Indian Ocean raised heated debate in the early 1990s. The proposed method to separate the heavy mineral content from the dune sand was to create a large pond within the dune by pumping in water from the Umfolosi River, and extract the metals in a centrifuge on a barge floating on the pond. The pond would migrate up and down the length of the dunefield, with the dunes being reshaped and revegetated behind it. One of the key issues that had been raised was whether the quantity of water needed to create and maintain the pond in these porous sands would adversely affect the estuary, and in particular, the rare swamp forest that grows there.[3] The engineers had calculated that the pond would require 20 000 m$^3$/day of water to remain full, or $7.3 \times 10^6$ m$^3$/yr. This was very small in relation to the total water balance of the estuary, but what if it caused local flooding on the estuarine plain opposite the position of the moving pond?

The strip of land between the estuary and the sea is about 21.5 km long and 1.9 km wide. The annual rainfall in this area is about 1300 mm, and preliminary hydrological modelling indicated that drainage to the water table was about 750 mm, of which 18–22% drained towards the estuary. (It was noted that this modelling suggested an evapotranspiration rate of only

1.5 mm/day, which was somewhat lower than would be expected.) The normal supply of water from the dune cordon to the estuary, in units of cubic metres, was therefore

$$D_{\text{estuary}} = \text{Drainage} \times 20\% \times \text{length} \times \text{breadth}$$
$$= 0.75 \times 0.2 \times 21.5 \times 10^3 \times 2 \times 10^3$$
$$= 6.1 \times 10^6 \text{ m}^3\text{/yr.}$$

This was the same order of magnitude as the flow from the proposed pond, suggesting the effect could not be ignored, and a full hydrological study was launched. As a potential mitigation action, the pond was reduced in size, resulting in a fivefold decrease in water requirements. Additional three-dimensional hydrological modelling was undertaken, which confirmed that the water table would rise by several metres in a moving 'mound' around the pond, which would persist for approximately a year as the pond passed by. However, when the water-level rise in the swamp forest some distance away from the dunes was calculated, it was well within the range of variation historically encountered.

Dune mining was not permitted at St Lucia, for reasons unrelated to the dune hydrology.

*Elephant numbers in the Kruger National Park.* The elephant herd in the 1.9 million-ha Kruger National Park (KNP) was kept at approximately 8000 animals between 1970 and 1995 by removing the excess animals. It was believed that a larger number of elephants would cause undesirable changes in the vegetation and habitat for other animals. Pressure from animal-rights groups forced the discontinuation of elephant culling as an option, and since then elephant numbers have risen at about 6% per annum. Is it reasonable to expect that an increased number of elephants could alter the park's vegetation?

Two OoM approaches can be made to this problem: one based on the behaviour of elephants, and the other on their metabolic requirements. Agreement between two or more independent analyses, an approach sometimes referred to as 'triangulation', greatly increases the confidence in the conclusions.

The behavioural approach noted (unpublished research) that each elephant pushes over 1–4 trees per day, the bulls more than the cows. Thus the elephant population of the KNP uproots about

$$N_{\text{uprooted}} = 8000 \text{ elephants} \times 2 \text{ trees/day} \times 365 \text{ days/yr}$$
$$= 5.6 \times 10^4 \text{ trees/yr.}$$

Given that the mean number of mature trees per hectare in the KNP is about 300 (ref. 4), and the mean natural tree mortality is 4% (ref. 5), the number of trees that die of 'natural causes' per year in the KNP is

$$N_{\text{naural death}} = 300 \text{ trees/ha} \times 1.9 \times 10^6 \text{ ha} \times 4\%$$
$$= 2.3 \times 10^7 \text{ trees/yr.}$$

This suggests that, until the elephant population rises by at least an order of magnitude, a widespread problem of woodland transformation is not likely.

The metabolic approach is that an average elephant requires about 450 MJ/day of digestible energy.[6] Their food is about 40% digestible, and has an energy content of around 18 MJ/kg. Elephant diets are about half derived from trees, and they mostly eat the leaves of the tree. Thus elephants consume

$$C_{\text{tree leaf}} = 8000 \text{ elephants} \times 450 \text{ MJ/d} \times 365 \text{ days/18 MJ/kg/0.4 digestible} \times 50\% \text{ diet}$$
$$= 9.1 \times 10^7 \text{ kg/yr.}$$

The tree leaf production in the KNP[4,5,7] is of the order of

$$P_{\text{tree}} = 1500 \text{ kg/ha/yr} \times 1.9 \times 10^6 \text{ ha}$$
$$= 2.85 \times 10^9 \text{ kg/yr.}$$

This analysis suggests that a threefold increase in elephant numbers would result in the elephants eating 10% of the available forage. This confirms that there is no immediate problem, but does raise the possibility of conflicts with the needs of other species in about two decades' time (elephant populations increase at 6% per annum when unrestricted).

There are a few necessary *caveats* to this analysis. It is known that elephants do not feed randomly: they have a strong preference for certain tree species and landscape locations. At some times, particularly during prolonged dry periods, they survive by stripping tree bark, which leads to premature death of the tree. If elephants focused their attentions on one tenth of the landscape, and one tenth of the species in those areas, it is very likely that even at current densities they will have a transforming effect with respect to those species and locations.

The establishment of the KNP/Mozambique/Gona-re-Zhoa transfrontier park, which will more than double the size of the area that the elephants can use, was partly a strategy to postpone the problem of potential elephant overpopulation in the lowveld.

## Conclusion

The technique described in this paper is useful during the scoping phase of an environmental investigation. It permits a rapid *triage** of the typically long list of potential issues raised in such enquiries into those that will lead to a rejection of the proposed action, those which probably do not matter, and those which warrant further study. It can be applied to a wide class of problems. While it is computationally simple and relatively undemanding in terms of quantitative data, it does assume a reliable knowledge of the system: are the inputs and outputs under consideration a good representation of the main drivers? In general, sufficient data are available from the literature and local sources to reach a conclusion. Owing to the inherently conservative nature of order-of-magnitude modelling, the method is relatively robust. Consideration of cumulative impacts is specifically excluded where the other components leading to the accumulation are unknown; where they are known a similar approach could be applied to deciding at what point they become significant.


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**Triage* is a technique used by overloaded military doctors to sort battlefield casualties into those who will die regardless of their ministration, those who will survive even if they do not receive immediate attention, and those who may be saved by immediate action. The medics then focus on the third category.