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Sustainability Criteria for Water Resource Systems

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IRREVERSIBILITY AND SUSTAINABILITY IN WATER RESOURCES SYSTEMS

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Abstract

One of the main characteristics of the sustainability concept is in the long-term evaluation of the possible set of outputs from any decision. Due to the fact that water resources projects have an extremely long physical lifetime and quite broad and diverse impacts, ranging from social, to environmental and economic outputs, the impact evaluation procedure is subjected to a substantial degree of uncertainty. Another approach is seen in the identification of actions which are as far as possible reversible to be able to cope with unexpected and disadvantageous outputs. It is the objective of this a paper to analyse the usefulness of measures such as reversibility to characterise sustainability. Two examples are investigated from which one is based on utilities which are time dependent while in the other example a physical approach is emphasised. Both examples refer to water and environmental management.

1. Introduction

Water management structures have an extremely long life time. Several reservoirs in the middle east are being continuously operated since centuries and irrigation schemes are dating back over millennia (Garbrecht, 1985, 1991; Hartung, 1987; Knauss, 1990; Glick, 1970; Schnitter, 1994; Petts et al., 1989). Similarly, navigation channels in Europe are being utilised since the medieval age, first for shipping purposes and now for recreation and tourism. On the other hand many examples are known where reservoir capacity has been quickly decreased due to sedimentation processes and large irrigation schemes are referenced which quickly lead to salinisation of soils to such an extent that the irrigated area had to be abandoned (Goldsmith and Hildyard, 1984).

These few examples clearly demonstrate the decision making process in water management has to consider beneficial and adverse impacts over long operation periods. In many examples an increase in economic benefits is accompanied with a loss in environmental quality or socio-economic inequity (Goldsmith and Hildyard, 1984). This was one of the reasons that an extended framework for water related decision making was already developed in the seventies including economic, social and environmental objectives (US-Water Resources Council, 1973, 79, 80). And about a decade later, the concept of sustainability entered the political and scientific discussion (WCED, 1987; Jordaan et al., 1993; IHP National Committee, 1994). This WCED-report, a political document, gained broad interest by the public and in the scientific community. The concept that sustainable development attempts to meet the needs and aspirations of the present without comprising the ability to meet future requirements is directly related to the statement that radical changes are called for in the way the world economy is run and that environmental constraints on growth have to be faced. Similar statements were already made in „The Limits to Growth" (Meadows et al., 1972) about ten years before. Although both address similar topics and reach somewhat similar conclusions (Common, 1995) the reactions were quite different. While Meadows et al. (1972) demand to keep the world total output at a certain level to be able to maintain it in the long-term, and which would also require an intensive redistribution of products among rich and poor nations, the Bruntlandt report (WCED-report) clearly states that the growth must be revived in developing countries and that there must be also a growth rate of about 3-4 percent in developed countries (WCED, p. 51). Such growth rates could be environmentally sustainable when more efficient technology is implemented to achieve less material and energy intensive consumption.

In both documents large periods have to be considered in evaluating the full range of impacts related to any decision. The longer the lifetime of a scheme the more it would require the analysis of the possible set of adverse outcomes. Simultaneously, it would lead to increasing uncertainty and imprecision. In some cases the uncertainty could be to large to allow any rational decision and therefore the degree of reversibility of an action would gain importance in decision making. in such cases the objective would be in the identification of alternatives with an acceptable level of reversibility, low risk and high social equity (Nachtnebel et al., 1994). This should express that if adverse impacts of an action are observed the system could be at least partially reversed to reduce disadvantageous outcomes. Complete reversibility is in most cases impossible but this criterion could be measured by the degree how an engineered natural resource system such as a contaminated groundwater can be remedied to its original, unengineered state. The time horizon and the required energy to achieve this state are seen as possible and stable indicators for reversibility while an economic indicator might dramatically change within such a long time period.

In this paper two examples are analysed where environmental impacts are evaluated by different indicators. The objective is to develop measures which evaluate the state of a system under consideration of several sources of uncertainties, like changing preference structures and the long-term performance of a system. Risk and reversibility related characteristics are addressed. The first example refers to fully irreversible actions such a utilising exhaustively a non renewable resource. To reduce the risk the long-term outcomes are evaluated in an extended framework considering various uncertainties in the decision making process. In the second example any preference structure or monetary loss function has been dropped. Rather the question is posed what could be done if disadvantages states of the system are observed in the future and which effort would be necessary to re-establish an acceptable state. The methodology tries to follow physical principles to assess the degree of reversibility.

2. Irreversibility Considerations in Economy

In economic sciences many decisions especially related to the utilisation of environmental resources, are analysed in the context of irreversibility. This means that a decision has to be taken to utilise completely a resource and to destroy it or to preserve it for further uses (Krutilla, 1967; Fisher et al., 1972; Arrow and Fisher, 1974; Conrad, 1980; Mitchell and Carson, 1989; Pindyck, 1991).This rigorously simplified decision making considering at each stage in time a yes/no decision has been modified by Reed, (1993), and Beltratti et al., (1994) by taking only partial destruction of the resource into account.

The non destructive decision to preserve the resource under consideration will result in a certain yield by utilising some part of the resource dependent on its growth rate and simultaneously, it keeps the option open for further utilisation if the preference structure of the decision maker would change. The possibility in keeping options open is credited with an option value due to not taking an irreversible action. The option value is defined here as the amount that people will pay for a contract which guarantees them the right to obtain a good for a specific price at a specific time on future (Mitchell and Carson, 1989). This problem is directly related to a stopping problem (Kim, 1992; Conrad, 1992; Wald, 1947), defining the time when an irreversible action becomes more favourable than to continue the preserving practice. Obviously, considering that future generations might have quite different preferences about environmental values the problem of irreversibility is directly linked to sustainability concepts.

Although water resources cannot be destroyed like a forest by clear cutting there are some examples which can be described within a similar framework based on irreversible decision making. Examples are in groundwater mining, in abstraction of water from its fluvial system for agricultural irrigation, and polluting a freshwater body by industrial wastes instead of preserving it for any other uses like water based recreation or for ecological needs.

Here, briefly the „optimal decision procedure“ will be analysed if and when such an irreversible action should be taken. The crude approach evaluating the expected present value of benefits and the expected present value of costs associated with any action and then identifying the point when the EV (benefits) exceed the EV (costs) will only be an appropriate tool if further development is completely known together with all value related changes. Therefore, an optimal decision should be based on all possible future monetarily expressed values and on future amenity services taking into account the associated probabilities.

Consider a resource R which if completely utilised and subsequently excluded from any other use at time t results in a net revenue $NR(t)$ which is subjected to a trend (drift), a random component (Reed ,1993; Nachtnebel et al., 1995) and another random component correlated to a non-monetary value function $A(t)$ which represents the amenities from the resource at time t.

$$\frac{d\,NR(t)}{NR(t)} = a\,dt + \alpha\,dw_1 + \rho\,dw_2 \tag{1}$$

$NR(t)$	net revenue
t	time
a	drift in net revenue
α	standard deviation of fluctuation
ρ	correlation coefficient
$w_1(t)$	Wiener process
$w_2(t)$	Wiener process

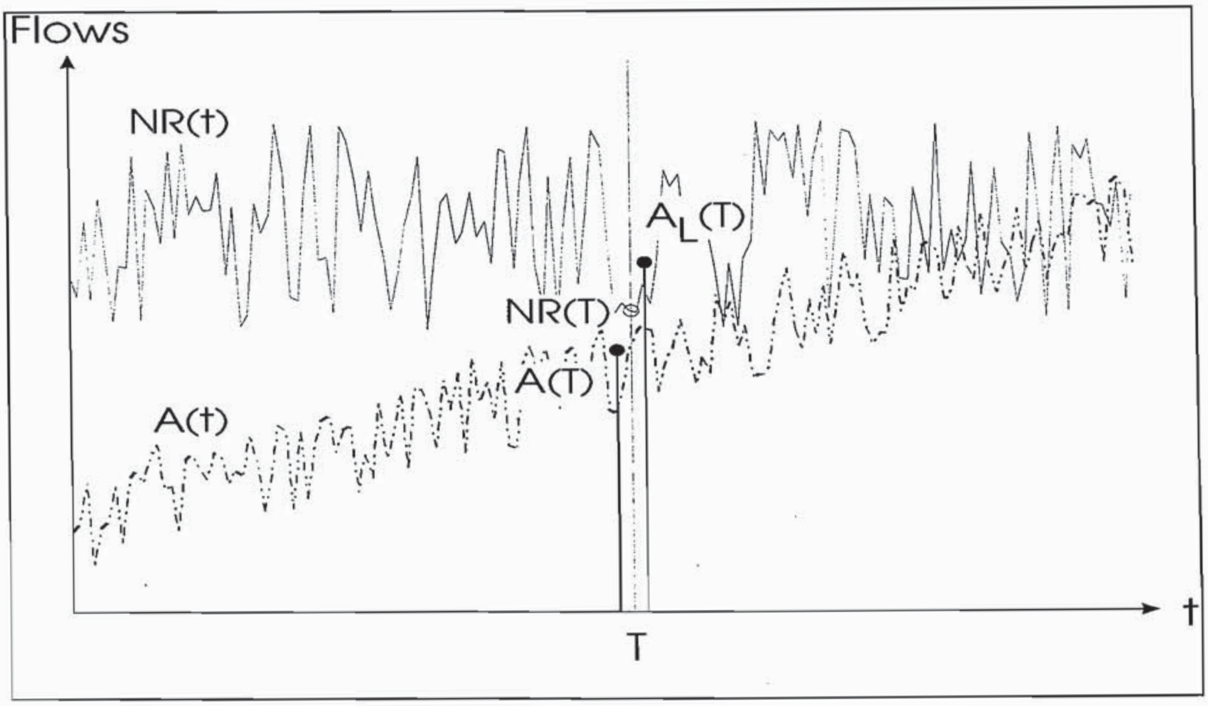

Fig. 1: Example for one set of development paths for $NR(t)$ and $A(t)$

$$\begin{aligned} A(T) &= \int_0^T c_t \cdot A(t)\,dt \\ A_L(T) &= \int_T^\infty c_t \cdot A(t)\,dt \end{aligned} \tag{2}$$

$c_t = e^{-\delta \cdot t}$	discounting factor
t	time
A(t)	amenity function
A(T)	benefits in amenities until T
$A_L(T)$	losses in amenities after time T
T	stopping time

As long as the decision is not made there is a revenue of external benefits $A(t)$ stemming from preserving the ecosystem or from public access for recreation. Obviously, this value however it is expressed is also subjected to trends and fluctuations. Similarly to (1) the amenity flows $A(t)$ are defined by

$$\frac{dA(t)}{A(t)} = b\,dt + \beta\,dw_2 + \rho\,dw_1 \tag{3}$$

$A(t)$	amenity value
t	time
b	drift in amenity value
β	standard deviation of fluctuation
ρ	correlation coefficient

This set of coupled stochastic differential equations yields solutions of the type

$$A(t) = A_o\, e^{b\,t + \beta\, w_2(t) + \rho\, w_1(t)} \tag{4}$$

The total return flow (monetary and amenity values) J(T) is expressed by the expectation values EV given by

$$\begin{gathered} J(T) = EV\left\{\int_0^T e^{-\delta t} A(t)dt + e^{-\delta T} \cdot EV\big(NR(T)\big) - \int_T^\infty e^{-\delta t}(t)dt\right\} \\ \text{with} \\ EV\big(NR(T)\big) = EV\left\{\int_0^\infty e^{-\delta t} \cdot NR(T+t)dt \middle| T\right\} \end{gathered} \tag{5}$$

and the optimal decision is obtained by maximising $J(T)$ which only depends on the time T when the irreversible decision is taken. Then the resource is completely utilised and no more accessible for any other use.

This approach considers an infinite number of development paths under different realisations of $NR(t)$ and $A(t)$ reflecting future appreciation of environmental utilisation by both monetary and non-monetary terms. The correlation introduced in equ. (1 and 3) assumes that the future realisations of these random terms are dependent on each other. Think about a surface water resource which supports basic functions of an ecosystem and is therefore gaining in its amenity value and subsequently the demand for water as a process material is increasing world-wide (World Watch Institute, 1996).

Reed (1993) has shown for a slightly modified model that the optimal stopping rule is satisfied if and only if:

$$NR(T) \geq \frac{(1+x)}{x} \cdot \frac{EV(A_L(T))}{e^{-\delta T}}$$

with (6)

$$\mathrm{EV}(\mathrm{A}_L(T)) = \int_T^{\infty} e^{-\delta t} A(t)\, dt$$

$$\frac{1}{2}\sigma^2 x^2 + \left(a - b + \frac{1}{2}\sigma^2\right)x + (a - \delta) = 0$$

σ^2 is the variance of the stochastic process $\left\{\ln\left(\frac{\mathrm{NR(t)}}{A(t)}\right)\right\}$ (7)

and is given by

$$\sigma^2 = \alpha^2 - 2\sigma\beta\rho + \beta^2 \tag{8}$$

Accordingly, the decision is optimal is obtained when the benefits $NR(T)$ from utilisation at time T exceed the discounted accumulated forgone amenities $EV(A_L(T))$. The coefficient $x \geq o$ is obtained from the solution of equ. (7) and (8).

This decision rule is still not satisfying because it is based on expectation values obtained by integrating over many (infinite) development paths and this implicitly assumes that many similar decision problems under the same degree of information and environmental settings have to be solved, which is rather unlikely. This approach is also based on the full information about the process neglecting uncertainty in model parameters and limited observation. Therefore, the obtained „optimal rule" should be replaced by a distribution function considering the parametric uncertainty in $a, b, \alpha, \beta, \delta, \rho$. Still using an expectation value as a stopping criterion would imply that about roughly 50 % of the decisions have been taken at the wrong time. To reduce risk it would be recommendable to estimate instead of the expectation value as given in equ. (5), the value J(x,T) where x refers to a given quantile (Nachtnebel et al., 1995) or to x in equ. (7). This coefficient $C = \frac{1+x}{x}$ has some useful characteristics (Reed, 1993). It is greater than one, it increases with a, α, β (drift in $NR(t)$, standard deviations in the random components), while it is inversely dependent on b, δ and ρ (drift in amenity, discount rate and correlation among random components).

Due to the fact that $C \geq 1$ is incorporated into equ. (6) a higher $EV(NR(T))$ is required than obtained from classical benefit-cost procedure and therefore the decision following the above procedure is more risk averse. This can be easily proved by trying different combination of $a, b, \alpha, \beta, \delta, \rho$ starting from zero.

In water management the question about when an action would be recommendable is mainly asked in relation to a sequenced expansion of water resources structures. Often, it is sufficient to know if an action should be taken now or later. Postponing an action is linked with collection of additional information resulting in improved estimation. This updating approach could be also included in the process, but it would only result in another x without changing the procedure substantially.

Summarising, the problem of decision making with irreversible consequences is treated in an extended stochastic framework considering monetary and non-monetary expressed outputs from a system. Both flows (revenues and amenities) are modelled by stochastic differential equations which describe potential future revenues and preferences. Because of the limited information, especially concerning amenity values of the next generation, this task is classified as extremely difficult or impossible for long periods such as the lifetime of water related structures and utilisation.

3. Reversibility Considerations in Physics

In the previous chapter already a rather complex model was obtained in considering several uncertainties in a socio-economic framework and still it is felt that the model is a crude abstraction of reality and the decision will be strongly dependent on future preferences which might be substantially different from ours. Now, these assumptions are being dropped and only physical principles which are independent from any economic level or preferences are applied to water management practices such as to evaluate the effort in cleaning a polluted ground water system. First, some principles of thermodynamics are briefly described and then some generalised applications are discussed.

Many physical laws like classical mechanics are independent from the time arrow. The movement of large bodies could be completely described under reversed trajectories in time and constitutes a perfect example of reversibility. With the formalisation of thermodynamics, entropy defined in the second law of thermodynamics was introduced and provided useful information about the direction of processes in time. Its formulation by Clausius in 1850 states that it is impossible to bring heat from a lower to a higher temperature without any changes in the environment. According to Thomson's definition in 1851 it is impossible to construct a periodically working machine by cooling only one reservoir (Becker, 1966; Landau and Lifschitz, 1970; Prigogine and DeFay, 1954). A summary, including an interesting account of the history of thermodynamic development has been given also by Partington (1949). Here, only a short selection of the basics of thermodynamics is given to provide the basis for applied case study. The entropy concept will be applied to estimate the minimum energy which is necessary to reverse a system to a certain degree. The required energy can be seen as a useful indicator for describing and quantifying reversibility.

The Gibbs formula relates any change in energy E of a system to a linear combination of all other energy changes which have to be from each other independent from each other

$$dU = \sum_{i=1}^{N} dE_i = \sum_{i=1}^{N} \xi_i dX_i \tag{9}$$

E_i	energy
ξ_i	intensive variables
X_i	extensive variables

An intensive variable will not change its numerical value when two subsystems with the same level in ξ_i are combined while the X_i is will add up. For example, someone can think of two boxes under the same pressure. When they are connected to each other the pressure remains constant while the volumes will add up. Dependent on the form of energy E_i there are different sets of intensive and extensive variables. In this context the first thermodynamics law states that energy can neither be generated nor annihilated corresponding to

$$dU = dQ + dA \tag{10}$$

Q	heat flow
A	mechanical energy

Applying this equation to the mixing of two gases which are initially separated into two boxes with volume V and which remains constant and utilising the universal gas law it follows:

$$dU = 0 = TdS - pdV = TdS - \frac{NRT}{V}dV$$

$$dS = \frac{NR}{V}dV$$

$$\begin{aligned}\Delta S = \; & \Delta S_1 + \Delta S_2 = \Delta\left(S_1\left(V_1 + V_2\right) - S_1\left(V_1\right)\right) \\ & + \Delta\left(S_2\left(V_1 + V_2\right) - S_2\left(V_2\right)\right) = 2N \cdot R \cdot \ln 2\end{aligned} \tag{11}$$

$$\begin{aligned} with \quad & V_1 = V_2 = V \\ & N_1 = N_2 = N \end{aligned}$$

p	pressure
V_i	volume
T	temperature
S	entropy
R	gas constant

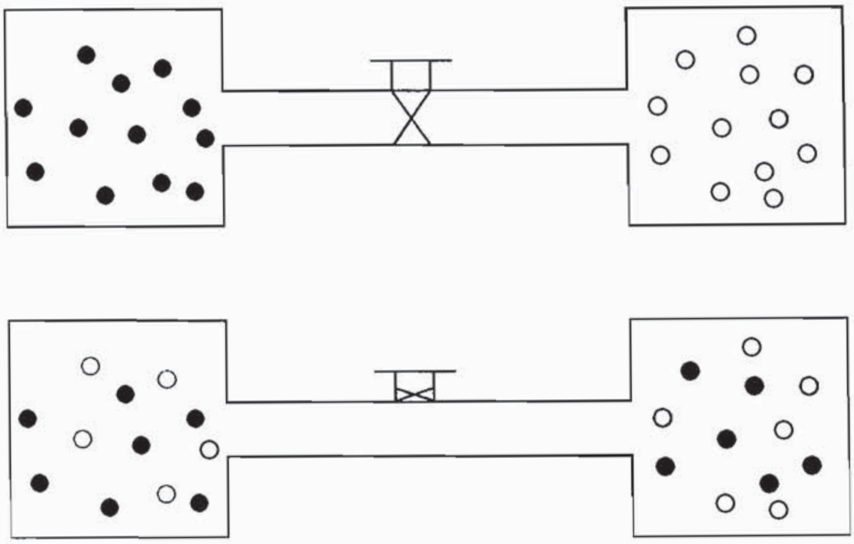

Figure 2: Complete Mixing of Two Gases (Initial State, Final State)

A similar approach will hold for the mixing of two fluids and will be applied in the subsequent chapter for a groundwater remediation problem.

The second law, in a simplified form, is given by

$$dU = T \cdot dS \tag{12}$$

T	temperature
S	entropy

and due to $dU \geq 0$ and $T \geq 0$ dS is also always ≥ 0. Entropy can only be generated but not annihilated but considering more than one system entropy can be exchanged among them. In the whole system entropy can be only increased but the entropy exchange can be utilised to decrease the entropy in a subsystem (equ. 13).

$$dS_1 = dS_{EX} + dS_{GEN} \tag{13}$$

S_{EX}	amount of exchange entropy between 1 and 2
S_{GEN}	generated entropy in the whole system ≥ 0

The entropy of system 1 might be decreased by transferring dS_{EX} to system 2 but the transferred amount must exceed the generated entropy associated with the exchange process. A simple example will demonstrate the exchange of entropy, assuming two reservoirs with T_1, S_1, and T_2, S_2 and exchanging energy only by heat flow.

$$\begin{aligned} &T_1 dS_1 + T_2 dS_2 = 0 \\ &dS_2 = -\frac{T_1}{T_2} dS_1 \\ &dS = dS_1 + dS_2 = \left(1 - \frac{T_2}{T_1}\right) \cdot dS_2 \end{aligned} \tag{14}$$

Assuming $T_1 \rangle T_2$ the following conclusions can be drawn:

- if $dS_1 \rangle 0$, $dS_2 \langle 0$, then $dS \langle 0$
- if $dS_2 \rangle 0$, $dS_1 \langle 0$, then $dS \rangle 0$.

The second conclusion describes the well known fact that the heat flow is in direction to the lower temperature. The first conclusion refers to the opposite case which requires an additional system to be involved compensating the decrease in S_2. Independently from any technical realisation the energy $T_1 dS_1$ has to be removed requiring at least the same amount of energy from outside to achieve this. This characteristics is of fundamental importance for any biological system interacting by flows of energy and matter with the environment which provides the flow of entropy to the environment enabling the biological system to maintain is structure (DeFay, 1929; Bertalanffy, 1932; Schrödinger, 1945; Prigogine, 1947; Nicolis and Prigogine, 1977).

For abiotic systems at least two aspects are interesting referring to the spatial and temporal scales. The spatial scale is important because decrease in entropy requires an external system which will absorb the entropy flow while the temporal scale is important for non-equilibrium states.

4. Reversibility in Environmental Management

4.1 Complete Cleaning of a Polluted Groundwater System

Assuming a homogeneously polluted groundwater system which should be cleaned up. This means that the opposite procedure described in the previous chapter has to be applied. It is assumed that a substance m is available in dispersed form and the question is what would be the effort to enrich and extract the material from the environment. To extract a certain raw material at least two steps are necessary. First, an amount V of material containing the pollutant with a certain concentration c_m^o has to be extracted from the environment. Second, assisted by technological processes such as purification, filtering etc. the separation of pollutant has to be achieved (Faber et al., 1983).

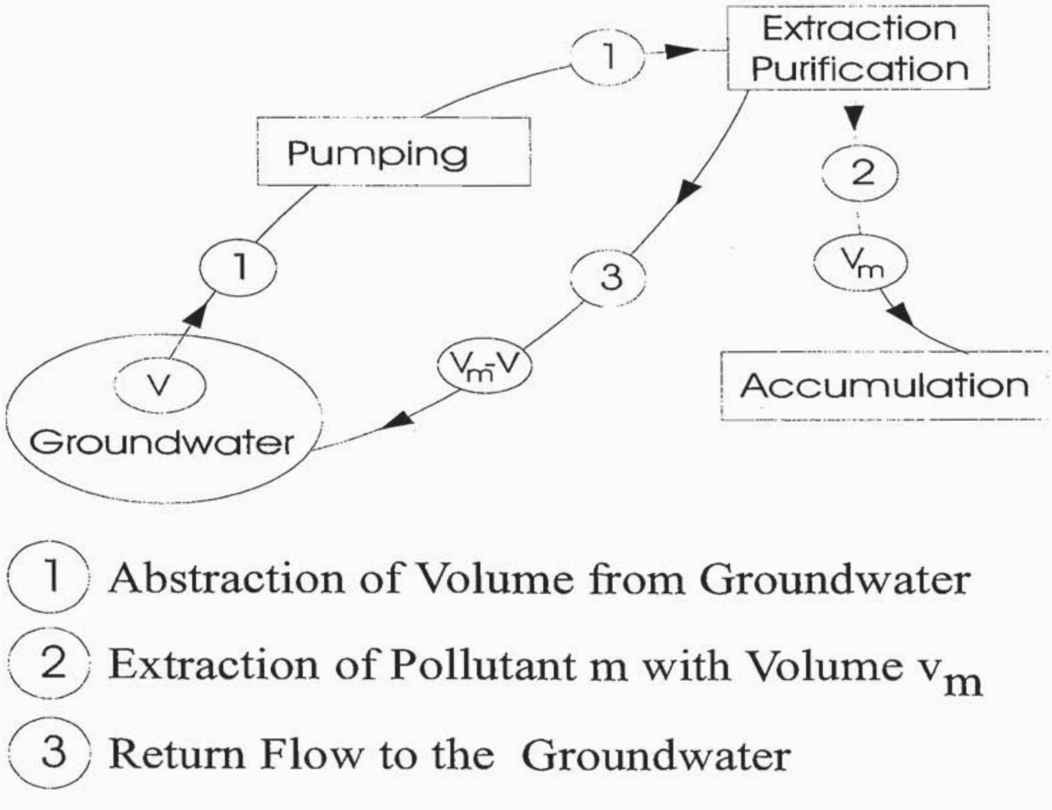

Figure 3: Extraction of Material m from Groundwater

$$c_m^o = \frac{N_m}{\sum_{i=1}^{I} N_j} = \frac{N_m}{N} \tag{15}$$

i	substance indicator $\{i = 1, I\}$
m	polluting material
N_j	number of moles of substance j in Volume V
c_m^o	initial concentration of substance m in volume V
N	total number of moles in Volume V

Assuming for the sake of simplicity that the various substances do not interact and that the chemical energy is sufficiently described by the number of particles the necessary energy amount for the enrichment process can be estimated in a similar way as described in the previous chapter by using Gibbs potential (Falk and Ruppel, 1976). The volumina V_i associated to the moles N_i remain thus unchanged during purification. This process is associated with increased ordering of the location of the particles and this results in a decrease of entropy. Considering the theoretical case of full extraction of material m is possible then the material m which was contained in V is reduced in its pure state to V_m and according to equ. (11) this is related to a change in entropy ΔS_1

$$\Delta S_1 = -N_m \cdot R \cdot \ln \frac{V}{V_m} \tag{16}$$

Also, the polluted groundwater has undergone a change of its volume from V to $(V - V_m)$ corresponding to a change in entropy of

$$\Delta S_2 = \sum_{E_i \neq m}^{I} \Delta S_{2i} = -\sum_{E_i \neq m}^{I} N_i R \ \ln \frac{V}{V - V_m} \tag{17}$$

The total change (reduction) in the entropy of the system is

$$\Delta S = \Delta S_1 + \Delta S_2 = -\left\{ N_m R \ln \frac{V}{V_m} + \sum_{E_i \neq m}^{I} N_i \ R \ln \frac{V}{V - V_m} \right\} \tag{18}$$

which can be transformed into a functional expression dependent on the initial concentration c_m.

$$\Delta S = N_m \ R \left\{ \ln c_m + \frac{1 - c_m}{c_m} \cdot \ln\left(1 - c_m\right) \right\} \tag{19}$$

The specific reduction in entropy, defined per mole of substance m, is

$$\Delta S = R\left\{\ln c_m + \frac{1-c_m}{c_m}\ln\left(1-c_m\right)\right\} \tag{20}$$

The results for different initial concentrations are given in figure 4 together with its first derivative (Faber et al., 1983).

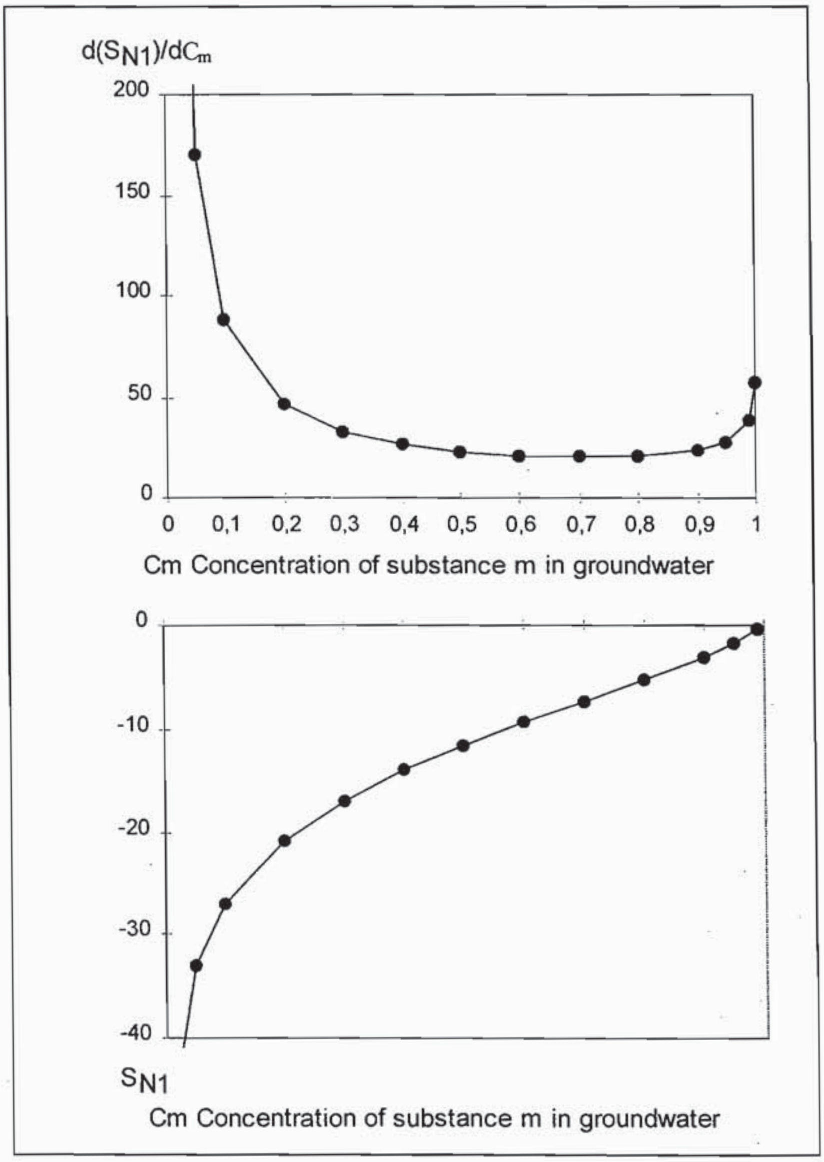

Figure 4: Specific Change in Entropy Versus Initial Concentration and First Derivative

According to equ. (9) the minimum required energy to change entropy is $dU = TdS$ assuming that there is no inefficiency in the energy utilisation to run the purification process. Thus, following (18-20) the energy for purification is given by

$$U = \int dU = \int T \cdot dS = RT\left\{\ln c_m + \frac{1-c_m}{c_m}\cdot \ln\left(1-c_m\right)\right\} \qquad (21)$$

where T refers to the temperature of the groundwater system. It can be seen from Fig. 4 that at a low grade of the pollutant a high amount of energy is required to extract it. This also implies that a nondegradeable substance (conservative tracer) in a groundwater system being dispersed during its transport will pollute an increasing volume with a smaller concentration and will require therefore an energy for removal which increases in time.

Considering, both the abstraction of the material and its enrichment and considering in good approximation only the first term of equ. (21), which constitutes a lower bound for the energy, the total amount of energy necessary to obtain finally a unit (mole) of pollutant m is

$$E(c_m) = l_A(c_m) + l_E(c_m) = \frac{\alpha}{c_m} + \left[-RT \ln c_m\right] \qquad (22)$$

α	energy (pumping work per mole of groundwater)
l_A	pumping work
l_E	extraction work
c_m	initial concentration of pollutant
T	temperature

This approach implicitly assumes that the concentration is constant in time and space which is only possible if there is no groundwater recharge, neither from outside nor from the waste water from the purification process.

4.2 Partial Cleaning of a Polluted Groundwater System

Next, a polluted zone with recharge Q of the process water containing a certain concentration c_{MIN} which defines the efficiency of the purification system is considered. It is also assumed that only the pollutant will be extracted.

The initial conditions for the system are

$$N_m(t=o) = N_m^o \qquad \text{(moles of pollutant)}$$
$$\mathrm{N}(\mathrm{t}=\mathrm{o}) = N \qquad \text{(moles of water)}$$

$$c_m^o = \frac{N_m V_o}{N \cdot V_o} = \frac{V_m}{V}$$

with the mole volume V_o, the total volume of the polluted groundwater V and the volume V_m of the pollutant.

It is assumed that the volume Q containing $N_m(t) \cdot \frac{Q}{V}$ moles is pumped and that the same amount of water is recharged containing $N_{m,MIN}$ moles per unit volume V(1). The difference is extracted and stored separately. The assumption that the same volume is pumped and recharged is a simplification which holds in any practical case. Within each cycle full mixing of the recharged water is assumed and thus the concentration of the pollutant is continuously decreasing to the level $N_{m,MIN}/N$.

The change in the concentration of pollution is derived from the mass balance and is given by the number of moles of pollutant N_m (t) in the groundwater system

$$N_m(t) = (N_m(t=0) - \frac{N_{m,MIN} \cdot Q}{V(1)}) \cdot e^{-\frac{Q \cdot t}{V}} + \frac{N_{m,MIN} \cdot Q}{V(1)} \tag{23}$$

The related change in entropy follows equ. (16-18) and is mainly dependent on the different volumes in which the pollutant was found at the beginning and at the end. Obviously, the state of $N_{m,MIN}$ in groundwater will be only asymptotically reached. Although this has no major consequences for the entropy it has severe impacts on the pumping energy term in equ. (22). The change in entropy and subsequently the required energy are given in equ. (24) and (25).

$$\Delta S_m = -R \cdot (N_m^0 - N_{m,MIN}) \cdot \ln \frac{V}{V'}$$

$$\Delta S_{GW} = -R \cdot (N \;\; - N_m^0 + N_{m,MIN}) \cdot \ln \frac{V}{V - V'}$$

$$\text{with V'} \;\; = (N_m^0 - N_{m,MIN}) \cdot V_0 \tag{24}$$

$$dU = R \cdot T \cdot (1 - c_m^0 \cdot c_{m,MIN}) \cdot \ln(c_m^0 - c_{m,MIN}) +$$
$$R \cdot T \cdot (\frac{1}{c_m^0} + c_m^0 \cdot c_{m,MIN} - 1.) \cdot \ln(1 - c_m^0 + c_{m,MIN})$$

The required energy $l_E\left(c_m^o\right)$ to clean up a polluted groundwater system considering recharge of partially purified water is finite. This implies that the state is reversible to its unengineered state. Although the change in entropy is finite and therefore the amount of energy to achieve the change in entropy is limited, one has to consider that the abstraction energy will be constant in time and is therefore linearly increasing with the length of pumping period. Therefore, it is impossible to reach the level $c_{m,MIN}$, corresponding here to the 'unpolluted state', if recharge is considered.

From this simple example several conclusions can be drawn:

- entropy is a measure to describe reversibility also for water related problems
- instead of preference structure and loss functions a simple methodology based on physical principles is proposed
- several water related problems can be described in a thermodynamic framework
- energy requirements can be estimated to reverse a system close to its initial state
- further, phase transitions could be also considered in the methodology. These process could result in large increase of energy to remove such a pollutant.

5. Summary and Conclusions

Sustainability concepts are based on longterm aspects of decision making. Water related decisions have often long repercussions which are difficult to assess. One way to cope with adverse consequences would be in trying to reverse the system under concern in its previous state. In this paper two examples were investigated which addressed the degree of reversibility of a system. The first example, refers to an irreversible decision resulting in the complete consumption of a resource excluding it from any other future use. Some aspects of uncertainty describing net revenue and amenity values are analysed. These explicitly formulated uncertainties lead to a more risk averse decision making. Still many other sources of uncertainties should be additionally considered.

To overcome the time dependence in preference functions which are extremely difficult to estimate an physically based approach is proposed to assess the reversibility of a system. Instead of societal values the thermodynamic laws are used to estimate the required amount of energy to reverse a system. This approach was demonstrated by the remediation of a polluted groundwater system. The energy input is seen as a useful indicator to describe some aspects of sustainable development. It was also shown that the improved state could only be achieved by the help of an external system. Thus, the adequate definition of boundaries attracts attention.

Any action in nature is related to a modification of flows of energy, water and entropy. Therefore, the thermodynamic laws and their extension to non-equilibria and interconnected systems provide a useful tool for rational decision making. This framework could provide information about the possibility and about the minimum required energy to reach a certain state. No information about the technology is necessary because the estimated energy amount constitutes a lower bound and any improvement in technology will only smoothly reduce the additional energy losses.

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