4. Soil salinisation

E. Bloem, S.E.A.T.M. van der Zee, T. Tóth and A. Hagyó

4.1 Notion of threat, definitions and terminology

Soil (and groundwater) salinity is often used as a comprehensive term to refer to several different salinity forms. These forms are known under the names of, respectively, (1) saline soil, that have elevated salt concentrations, (2) sodic (or alkali) soil, with a disturbed monovalent/divalent cation ratio in favour of the monovalent alkali cations (Na, K), and (3) alkaline soil, for which the chemical composition is disturbed towards alkaline (high pH) compositions and often due to a dominance of (bi)carbonate anions in solution. These three salinity issues may be related, but this needs not be the case (Bolt and Bruggenwert, 1976).

The adverse consequences of salinity generally vary, depending on which form of salinity occurs. For saline soil, the impeded plant transpiration due to large osmotic values of soil water (Koorevaar et al., 1983) that render soil water poorly available for plants often dominates, whereas for sodic soil, the structural degradation caused by too large concentrations of sodium (Na) is generally most important. For alkaline soil, toxicity and deficiency effects due to altered plant availability of elements is the main problem, although such effects have also been observed for saline and sodic soils.

Of the three salinity forms, saline soils can be regarded as rapidly developing and easily cured whereas sodic soils develop slowly but may be very difficult to remediate. Alkaline soils are left out of consideration in this chapter as a sort of soil pollution case. For brevity, we do not discuss in detail the various involved processes of formation and remediation, but refer to handbooks (Bolt, 1982, Bresler et al., 1982).

Soil salinity, in its various manifestations, is an old problem in (semi)arid regions and has therefore become the focus of attention much earlier than (other) soil pollution problems. A major milestone towards managing salinity is the famous Handbook 60 (Richards et al., 1954), that compiled the hazards, measurable soil characteristics, and approaches for sustainable management of salinity. This handbook was both timely and appropriate for conditions where good laboratory facilities were limited or scarce, and has in this way become the reference worldwide.

Soil salinity is a widespread problem worldwide. Besides many semi-arid countries in irrigated regions, regions with shallow groundwater, and low-lying coastal areas and deltas (Salama et al., 1999) are confronted with it. An impression for Europe is given in Figure 4.1. It is only an impression as e.g. coastal area of The Netherlands that are troubled by salinity do not appear so on the map. Older maps such as provided by Szabolcs (1981) may over-estimate the problem. Within the EU, the major areas with SAS are found in various regions of the Iberic Peninsula, Italy and Greece, and Hungary and Romania.

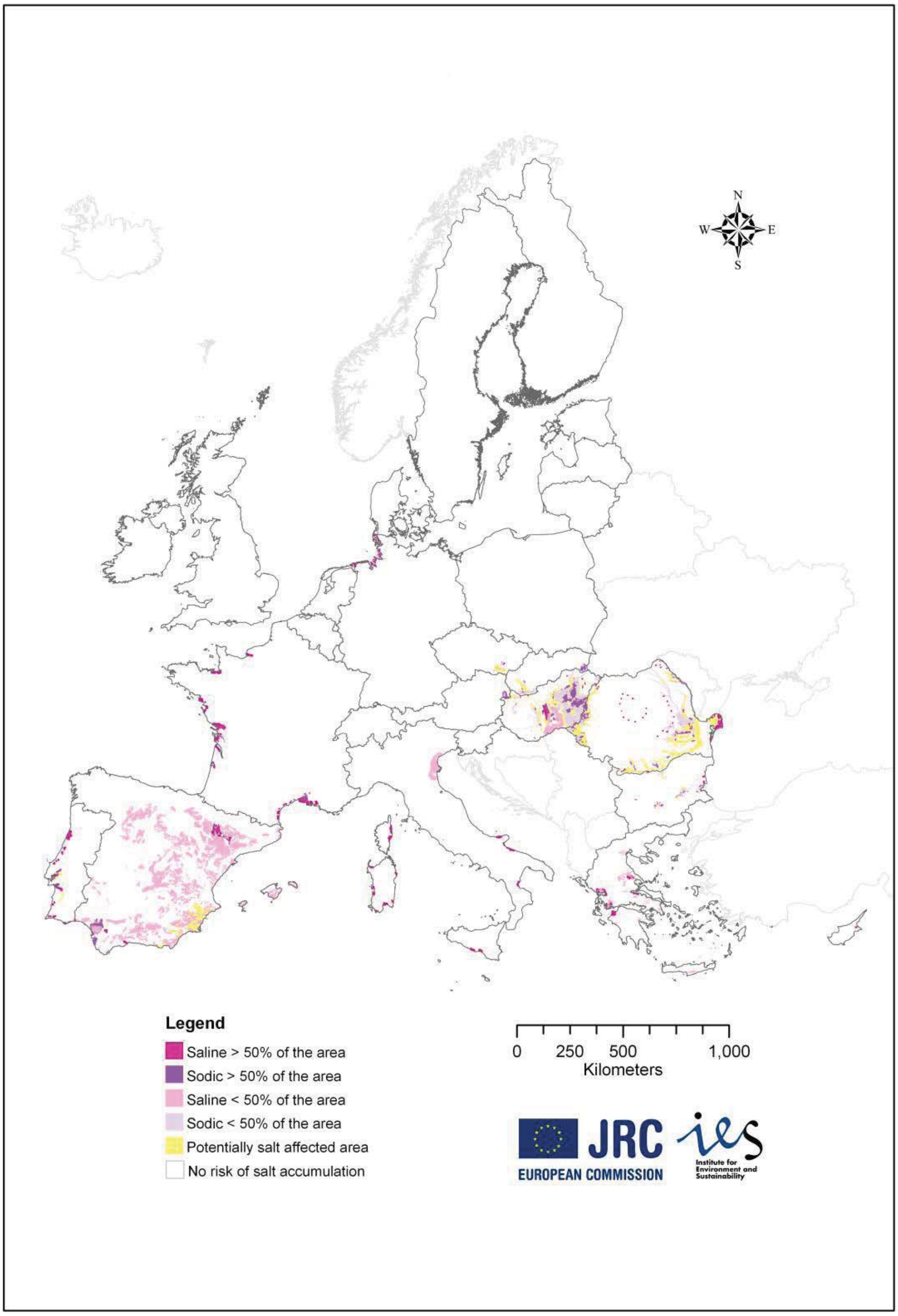

Figure 4.1. Map of saline and sodic soils in Europe according to Tóth et al., 2008.

The distribution of saline and sodic soils is shown by a recently compiled map of Tóth et al., 2008. Fig 1 shows that this maps is based largely on the 35 years old map of "Salt-affected soils in Europe" developed in the collaboration of FAO and the Subcommisson A of the International Union of Soil Science under the leadership of I Szabolcs, and on current databases.

4.2 Data collection

Salinity is quantified by a number of variables, that to some degree may be related. For instance, the concentration of ions in the soil or groundwater solution has been quantified by the molar (total) concentration (mol/L) which represents all cations and anions in solution, the electrical conductivity of solution (dS/m), and TDS or Total Dissolved Solids (mg/L). Such variables are related (Richards et al., 1954) and hence, we assume they are different operational quantities of the same property and in fact an early form of salinity-related harmonization. They differ usually for practical reasons (ease of measurement in field conditions). Total concentration, as we refer to it, represents the osmotic aspects of water availability for the biosphere, as ion-specific aspects are left out of consideration.

Besides non-specific aspects, also ion-specific parameters are of importance. Related to sodicity, the ratio of monovalent (Na, K) over divalent (Ca, Mg) cations is of importance. The underlying reason is that monovalent cations are less able to counter the negative electric field of clay colloids in soil and if dominant, make soils more susceptible for unrestricted swelling and shrinking. This behavior is causing soil structure deterioration, which is often poorly reversible. The major data pertaining to sodicity are, respectively, the Sodium Adsorption Ratio, SAR, and the Exchangeable Sodium Percentage, ESP, defined as:

$$SAR=[Cat+]/\sqrt{[Cat2+]}; \quad ESP=100\% \text{ x } \gamma(Cat+)/CEC$$

Where [Cat+] refers to monovalent cation concentration in solution (usually in $mmol_c/m^3$), γ refers to the adsorbed species in brackets (here monovalent cations), and CEC to the cation exchange complex.

Besides monovalent and divalent cations, also the composition of the anionic part is of importance, as the tendency of various cations to form insoluble salts differs for each cation. The chemical interactions between cations and anions determines which of the cations dominate (divalent cations are more susceptible to form insoluble salts) and the resulting pH-values that develop (alkalinity). Chemical analyses to determine with more detail the composition of the soil solution and the soil exchange complex are quite standard in soil chemistry (Bolt 1976).

Other data that need to be collected differ, depending on the complexity of the RAM. For sodicity, the mineralogy is of importance, whereas for salinity that is much less the case. The underlying reason for the various data are the factors that affect salt hazards:

- Sources and quality of rainfall and irrigation water
- The evaportranspiration demand of crops and vegetation
- The quality and proximity to the soil surface of ground water
- Soil textural and mineral composition
- Temporal and seasonal variations in soil dessication
- Managed or natural leaching of salts towards drainage infrastructure or groundwater.

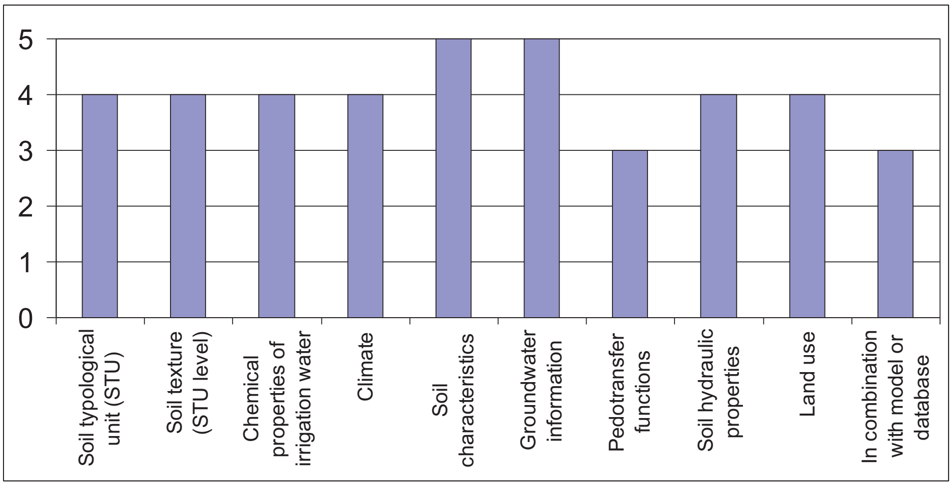

Figure 4.2. Common data used by risk assessments for salinity problems in 5 EU countries.

The return rate of the questionnaires was 21% for salinization. This relatively low response may reflect the fact that salinization is a regional and local phenomenon in Europe, related to poor drainage and seasonally dry weather conditions. Salinization is most severe in Hungary and only Hungary and the Czech Republic have an official assessment methodology. RAMs for salinization mainly differed in the indicators used to evaluate the risk, which is in part related to the specific objective of the RAM.

All RAMs (of 5 questionnaires returned in this project) use soil characteristics and groundwater information in their assessment (Figure 4.2). Soil typological, soil texture, chemical properties of irrigation water, climate, soil hydraulic properties, and land use are used in 80 % of the RAMs and pedotransfer function and combinations with models are used in 60 % of the RAMs. Case studies prevail although Hungary and Slovakia have RAMs which are used at the national or regional scales. Four of the five countries use field observations in combination with laboratory analysis. Two of them use also GIS and Slovakia is the only country with a different approach, they use remote sensing.

4.3 Data processing

The information provided reveal that all RAMs are based on quantitative based methods (measurement of water and soil properties) except for Slovakia. Usually, a combination of methodologies (Figure 4.3) is applied that is partly quantitative and partly qualitative, e.g. quantitative expert analysis or process based modelling.

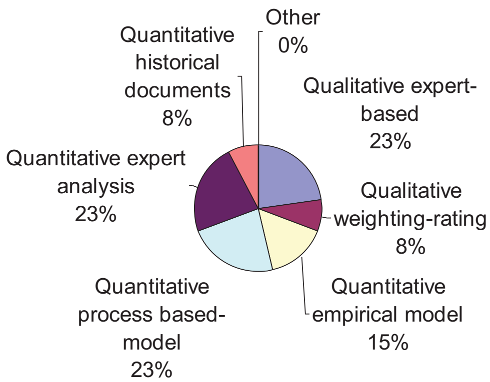

Figure 4.3. Type of methodology

The most common way to present results is by producing maps. Three countries have only one output document. Greece has a vulnerability map, Spain a risk map and Slovakia elements at risk map. Cyprus has an output of risk and vulnerability mapping, and Hungary has an output of risk, vulnerability, and hazard mapping. Risk and vulnerability zone mapping are both used for 30 %; other output maps are less used.

4.4 Data interpretation

Commonly, a first step in risk assessment involves a general identification of the threat and areas at risk, derived from existing data. The used data are mainly the factors given in part 4.2, in particular the determined soil and groundwater salinity, irrigation water quality and quantity, and the ionic composition of the different water sources. In the terminology of Eckelmann et al, (2006) this is the second stage of a tiered approach. The first approach identified by Eckelmann et al., (2006), i.e., expert knowledge, is generally an integral part of the interpretation of the mentioned data, except for sodicity which is a more complicated feature that is understood less broadly in a geographic sense (awareness is more restricted to countries where sodicity is a recognized problem). To some degree, also the third, model approach is used but as a national risk assessment tool, models are usually still unproven technology.

Because of their relevance for the first approaches of risk assessment, we can identify the following simple, experimental RAMs: salt concentration, making use of the 1:1 relationship between salinity concentration and electrical conductivity EC (in mS/cm) often quantified as the latter. To this purpose, the EC is classified in different classes with regard to salinity hazard. An important classification is that of USDA Salinity Laboratory (Richards, 1954; Table 4.1), that is still commonly used.

Table 4.1. Classification of the electrical conductivity or irrigation water (EC_{iw}) with regard to the hazard of adverse salinity effects

EC_{iw} (mS/cm)	**SALINITY HAZARD**
0-0.25	Low; water use is safe
0.25-0.75	Medium; water quality is marginal
0.75-2.25	High; water unsuitable for use
>2.25	Very high

An experimental RAM that directly refers to whether a soil must be considered to be saline or not, is based on the electrical conductivity of the saturated soil paste. The procedure is comparable to the RAM 1 approach, but involves a soil paste at water-lubrication level and intrinsically involves an expert judgement regarding crop vulnerability.

Table 4.2. Classification of electrical conductivity of soil saturation extract (EC_e) with regard to salinity effects on crops (Richards, 1954)

EC_e (mS/cm)	Class	Effect
0-2	Non saline	Negligible
2-4	Mildly saline	Yield reduction of sensitive crops
4-8	Medium saline	Yield reduction for many crops
8-12	Very saline	Normal yields for salt tolerant crops only
>16	Extremely saline	Reasonable crop yield for very tolerant crops only

It has been recognized early that crops have a different vulnerability for soil salinity. For this purpose, the RAM 2 has been related to a classification for different crops.

Table 4.3. Vulnerability of different crops for salt damage.

ECe (mS/cm)	CROP
2-4	Clover
3-4	Bean, sellery, radish
4-10	Flax, maize/corn, oats, wheat, rye, cucumber, peas, onions, carrots, potato, lettuce, cauliflower, cabbage, tomato
10-12	Spinach, asparagus, cabbage flower, red beet
10-16	Rape, sugar beet, barley

Whereas the above refers to elevated salt concentrations, the basis for risk assessment (experimentally) of sodicity is ESP, $ESP = \frac{\gamma_{Na}}{\gamma_T}.100\%$, where γ refers to the exchangeable quantity of cations (subscripts are *Na* for sodium, and *T* for the total cation exchange capacity). If ESP exceeds 15%, a soil is called sodic (in Australia, this is already the case if ESP exceeds 6%).

The USDA Soil Salinity Laboratory (Richards, 1954) has developed a widely adopted salinity classification system that considers the total salt level estimated from the electrical conductivity of the saturation extract (ECe), expressed in dS/cm at 25 degrees C temperature, and the exchangeable sodium present (ESP) or sodium adsorption ratio (SAR) to classify among saline, saline-alkaline and alkaline soils, and different degrees of them.

Table 4.4 Salinity/alkalinity/sodicity classification schemes (Richards, 1954)

Soil type	Soil property			
	SAR	ESP	pH	ECe (mS/cm)
Non saline, non alkaline	< 13	< 15	< 8.5	< 4
Saline	< 13	< 15	< 8.5	> 4
Alkaline	> 13	> 15	> 8.5	< 4
Saline - alkaline	> 13	> 15	> 8.5	> 4

The above scheme makes no distinction between ion types that enable to differentiate harmful from harmless salts, unlike the classification system based on anion types developed by Russian soil scientists (Plyusnin, 1964) (Table 4.5). In this approach, salt-affected soils are classified on the basis of salt types, in terms of chloride, sulphate and carbonate anion ratios present in the soil saturation extract. As not all salts are equally harmful, and so require different reclamation and management measures, it is of value to know the spatial distribution of salt-affected soils and their composition. The World Reference Base for Soil Resources also follows an approach based upon anion assemblages, distinguishing in Table 4.6 six facies of salt affected soils (Spaargaren, 1994). (Source: Metternicht, 2003)

Table 4.5. Harmful (above the line) and harmless (below the line) salts (Plyusnin, 1964)

$NaCl$	Na_2SO_4	Na_2CO_3	$NaHCO_3$
$MgCl_2$	$MgSO_4$	$MgCO_3$	$Mg(HCO_3)_2$
$CaCl_2$	$CaSO_4$	$CaCO_3$	$Ca(HCO3)_2$

Table 4.6. The World Reference Base for Soil Resources salinity approach upon anion assemblages (Spaargaren, 1994)

Soil type	Facie	Characteristics
Chloride soils	Acid chloride soils	$Cl >> SO_4 > HCO_3$, and $Na >> Ca$
	Neutral chloride-sulphate soils	Nearly neutral pH
Sulphate soils	Neutral sulphate soils	Nearly neutral pH, $Na >> Ca$, and $SO_4 >> HCO_3 > Cl$
	Acid sulphate soils	Very low pH (< 3.5)
Carbonate soils	Alkaline bicarbonate-sulphate soils	pH > 8.5, $HCO_3 > SO_4 >> Cl$, and $Na > Ca$
	Strongly alkaline soils	pH > 10, $HCO_3 >> SO_4 >> Cl$, and $Na >> Ca$

4.5 Risk perception

Whereas the quality of natural resources is important for a first assessment, modeling is usually required for the analysis of risks that are also dependent of management. In principle, it is quite easy to develop an equation that relate the RAMs called water resource salinity (EC) and soil salinity (ECe), and this relationship is commonly known as the Leaching Requirement (LR). Leaching requirement can be defined as the fraction of infiltrated water that must pass through the root zone to keep soil salinity from exceeding levels that would significantly reduce crop yield under steady-state conditions with associated good management and uniformity of leaching.

This concept can be formulated in terms of easily measurable properties (Richards, 1954, Rhoades, 1974), such as the water content of soil at field capacity and in the saturated paste, which are quite robust measures. Hence, also LR is quite a robust RAM for soil salinization:

$$LR = \frac{D_{DW}}{D_{IW}} \approx \frac{w_{FC}}{w_{SP}} . \frac{EC_{IW}}{EC_e^*}$$

Where *D* denotes an amount of water (mm/year), *w* stands for water content by weight, and *EC* is the electrical conductivity. Subscript *DW*, *IW*, *FC*, and *SP* denote drainage water, irrigation water, field capacity of soil, and saturation extract, respectively. Finally, the asterisk denotes that the electrical conductivity of the saturated paste may not exceed this particular value. This LR concept has been fine-tuned to account for nonideal flow of water through soil and other causes for deviation from the relatively simple LR-approach (Corwin et al., 2007, Letey et al., 1985)

Despite its simplicity, the LR concept is a robust way to convince stakeholders of the need for drainage and has motivated research on drainage improvements (Bos, Ritzema, 2009). In some cases, for instance if more factors of interest need to be taken into account, the complexity of required modeling is higher and for that purpose, various models have been developed, though scarcely used in national/regional RAM. Strongly focussed towards salinity/sodicity type of problems is UNSATCHEM (Simunek et al., 1996). This advanced code has been used succesfully to understand both salinity and sodicity process dynamics at a very local scale (Kaledhonkar et al., 2001, Jalali et al, 2007). Advantage of this code is that boundary conditions can be variant in time, whereas flow and transport are both transient. As was mentioned, Corwin et al. (2007) considered the leaching requirement as defined above, with more complicated models such as WATSUIT, TETrans, and UNSATCHEM. They found that transient modeling with the mentioned three models may lead to leaching requirements that are smaller than the steady state LR concept given above. Obviously, the demands regarding computation, model parameterization, and expertise of the modelers are much larger than for applying the LR concept. However, to save water in semi-arid regions, such an effort may appear to be economically sound.

Alternative software, such as LEACHM, (Wagenet, and Hutson, 1989) PHREEQC (Parkhurst and Appelo, 1999) and HYDRUS (Simunek et al., 1998, in Bastinaanssen), are less focussed to soil salinity issues . A relatively new code, ORCHESTRA, is object oriented and has recently been extended to incorporate transient flow and transport (Meeussen et al., 2005, Van der Broek et al., 2008). However, it has not yet been applied to salinity or sodicity issues.

The limitations of above software are commonly the same: they are complex, much a priori knowledge is required from the modeler, and important feed backs have been ignored. Possibly for these reasons, a less formal but potentially more focussed and appropriate involvement of expert knowledge is favoured and sufficient. In a recent overview of the state-of-the-art of modeling (Bastiaanssen et al., 2007), a selection of deterministic models was described, categorized as Bucket, Richards equation, SVAT, multi-D, and crop production models. They also observe the high qualifications needed of the modelers, which may impede the use of such models for routine risk assessments. A serious gap is identified between model complexity and the demands for application by the irrigation and drainage community.

In practice, despite the availability of complex models, the limitation of RAM for sodicity seems to be the gradual, stealthy way of development of sodicity, which makes the problem owners (often farmers and local authorities with limited academic education) unaware and and not easily convincible for its hazards.

4.6 Options for harmonization

Different for other soil quality threats, salinity has been recognized and partly undergone harmonization as early as 1954. The basic properties to consider and even the way of measurement in the field or the laboratory and classification schemes have been developed and become accepted. Despite that the framework of Richards (1954) has been challenged in about every aspect, and improvements for the first tiers of Eckelmann et al.'s (2006) scheme are feasible, it can be debated whether further harmonization or perhaps even standardization is necessary and urgent. For instance, considering the way of measuring the ESP of soil, it can be shown that the involved errors of e.g. different measurement protocols leads to negligible errors.

Figure 4 shows that if the ESP is measured by extracting a certain mass of soil with a designated volume of extractant solution (as all measurements are based on exchange between a solid and a liquid phase) the measured ESP* after adding the extracting water differs from the ESP that corresponds to the initial soil sample, that is usually air dry.

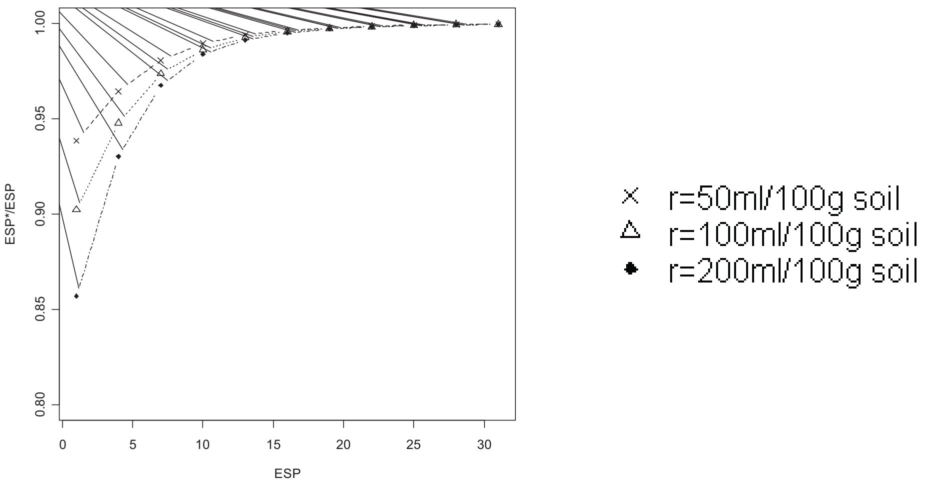

Figure 4.4. Relationship between the ESP/ESP where ESP* is the value after suspending soil in water and ESP is the value of the solid phase before suspension. Results for constant* C_{tot}*=0.01mmol*$_c$*/ml, CEC=30mmol*$_c$*/100g*$_{soil}$ *and w=25 ml/100g*$_{soil}$

It appears that the assessment of ESP for solution:solid ratios ranging from r=0.5-2, a systematic error may occur that ranges from neglible to 15% due to the shift in the solid/liquid equilibrium. This error is largest for relatively small ESP-values, where a correct assessment is the most important for a good anticipation of changes.

Obviously, the systematic bias, that can not be prevented completely if soil samples are stored under room-dry conditions, increase if the volume of water used for suspending the soil increases. For two relevant cases regarding initial ESP (before adding water), the bias is shown in Figure 4.2 to be limited to within 5-10%. Such a limited bias seems acceptable, as it will not affect the anticipation of the situation concerned and therefore we conclude that the liquid:solid ratio does not much affect our risk assessment.

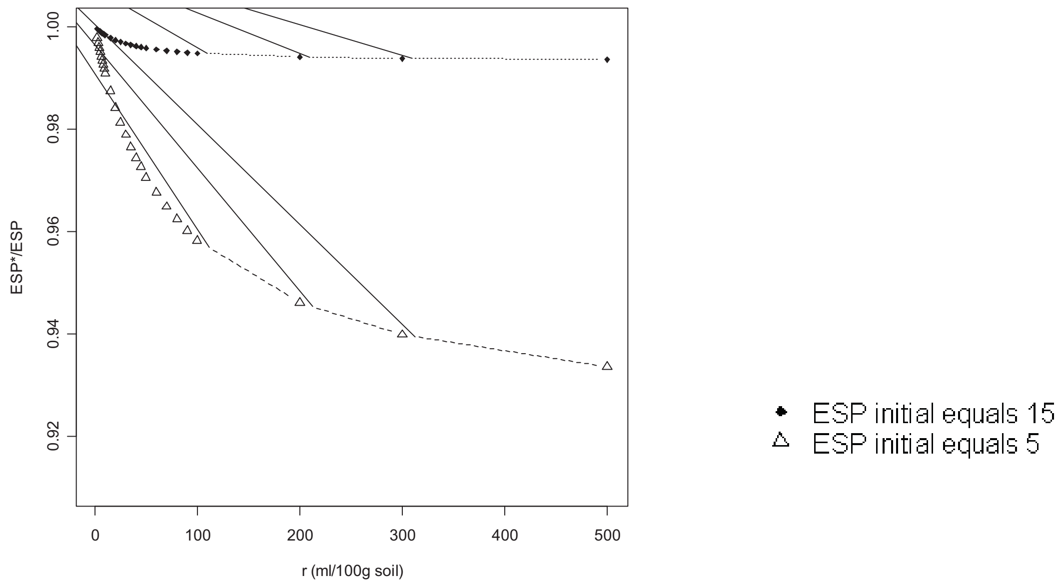

Figure 4.5. Relationship between ESP/ESP and r for different initial ESP keeping constant constant the amount of water w=20ml/100g$_{soil}$,and CEC=30mmol$_c$/100g$_{soil}$ and C$_{tot}$=0.01 mmol$_c$/ml*

In this research, we have varied several other parameters besides the solid: solution ratio, and found that systematic errors are limited to tens of %. Although clearly scientifically considered to be significant, it is unlikely that such biass would lead to a different anticipation of the situation (regarding hazards of sodicity). Hence, these results are not presented here, as for the present purpose of policy support they are not important enough.

For reasons given above, it can be concluded that *further* harmonization/standardization of present, predominantly experimental RAMs is not urgent. Whereas this may be the conclusion for the current, strongly experimentally inclined RAM of soil salinity, it is debatable whether it holds for further developments. Risk assessment in the GIS context, with more advanced numerical or analytical modeling is likely to be an unstoppable trend. Since this strongly model based larger-scale approach has received limited attention in the soil salinity context, is seems to have an excellent potential for harmonization before different authorities and scientific institutes have made their choices and have become less flexible.

So, logically, a further harmonization involves RAMs that use modeling as a dominant tool. The harmonization may involve different aspects, such as (i) the used model concepts, or even (ii) the used numerical software, (iii) the extent of data of diverse types to be integrated in modeling, (iv) the proper calibration and validation approaches, (v) scenario development, and (vi) more technological methods of 'good modeling practise' such as keeping a blog. Such aspects always have to be considered in a common sense context of gains and costs, which may affect the level of detail of model concepts to be considered, the available data, etcetera (Shah et al., 2009, Van der Zee et al., in pres). As is the case with other fields of decision making, we deal with growing knowledge and awareness, and for this reason, strong top-down forcing is less attractive than iterative learning processes by all stakeholders. Such a learning and development experience may significantly benefit from advances made in the dialogue regarding e.g. pesticide admission and evaluation policies, which dialogue is quite prominent in the EU. A similar dialogue between stakeholders (e.g. EU, different land use sectors, science, etcetera) with clear and increasingly focused Terms of References to avoid adverse effects of salinity, might be the best way of harmonization.