

Framework for a process-based salinisation risk assessment methodology: solute recycling versus primary groundwater salinisation

E. MILNES, P. PERROCHET, P. RENARD, F. CORNATON

Centre d'hydrogéologie, Université de Neuchâtel, Rue Emile Argand 11, 2007-Neuchâtel, Switzerland

e-mail : ellen.milnes@unine.ch

Abstract A framework for a process-based salinisation risk assessment methodology is proposed that allows separation and mapping of areas prone to primary salinisation, such as seawater intrusion, agrochemical pollution or geogenic contamination and secondary salinisation derived from irrigation-induced solute recycling. By adaptation of the boundary conditions, the bulk salinity distribution is decomposed into components derived from the different salinisation processes. To obtain the respective risk index distributions, both the 'present state' and salinisation potentials (steady state salinity distributions) have to be simulated. The respective salinisation risk indices are defined as the potential of further salinisation induced by the respective salinisation process and are obtained by deducting the components of the 'present state' salinity distributions from the respective salinisation potentials. The risk index distribution maps are then overlaid with a defined threshold salinity, revealing areas requiring remediation or conservation measures. The risk index distributions are strictly related to a given exploitation scheme. Modification of an exploitation scheme leads therefore to modified risk index distributions which highlight areas that will suffer further salinisation from areas for which the modified exploitation scheme will have a remediating effect. The risk maps obtained for a real case site (Akrotiri aquifer, Southern Cyprus) are then presented, revealing the outcomes of the approach, as well as its limitations.

Key words risk assessment; coupled transport modelling; irrigation salinisation; seawater intrusion; Akrotiri aquifer (Southern Cyprus)

INTRODUCTION

Groundwater salinisation in irrigated areas can either be caused by primary salinisation processes, such as dissolution of geogenic salt deposits, agricultural inputs or seawater intrusion, or by solute recycling from irrigation and by evaporative processes. In contrast to primary salinisation processes, solute recycling from irrigation does not add any solutes to the system, but may lead to salinisation by redistribution of extracted solutes. Since the respective remedial or conservation measures may be very different for the different salinisation processes, it is crucial to correctly identify their spatial distribution.

A prominent example for the combined effects of solute recycling and primary salinisation is seawater intrusion in coastal irrigated areas. The primary salinisation, induced by seawater intrusion enhances the effect of solute recycling (secondary salinisation), which can lead to vast contaminated areas with intermediate salinities reaching much further inland than the actual seawater intrusion. The salinity observed in groundwater in coastal irrigated aquifers is usually attributed to seawater intrusion only, although, in many cases, solute recycling is superimposed and may in areas even be the dominant salinisation process.

Solute recycling can be described as the salinity observed in the groundwater caused by redistribution of the extracted salt load from the aquifer onto irrigated fields

and subsequent transfer to the groundwater by deep percolation. Depending on the fraction of applied water that leaves the system by evapotranspiration, the concentration of the irrigation return flow can be several times larger than that of the applied irrigation water (Aragüés *et al.*, 1985; Kelleners *et al.*, 2000; Sites & Kraft, 2000; Pearce & Schumann, 2001). Since solute recycling is a function of the solute mass flux extracted from irrigation wells, it is a coupled process, not included as a standard option in commercial software packages and therefore rarely quantified. Solute recycling might not always be of importance, but in areas where irrigation rates exceed infiltration rates (e.g. semi-arid and arid regions) it is fundamental to evaluate its impact. Neglecting solute recycling in areas where extracted groundwater is highly mineralised (e.g. in seawater intruded settings) may lead to significant errors in the solute mass balance (Milnes & Renard, 2004).

Groundwater protection and management issues are often addressed by either vulnerability or risk assessments. Vulnerability assessments identify sensitive zones of a system based on hydrogeological criteria, while groundwater risk assessments additionally consider the presence of potential contamination sources or polluting land-use activities (Gogu & Dassargues, 2000). The most commonly used vulnerability mapping procedures are based on empirical point rating systems that bring together key factors believed to influence the solute transport processes (e.g. Aller *et al.*, 1985). Since groundwater dynamics are rarely explicitly evaluated in such mapping approaches, Gogu and Dassargues (2000) emphasize the need for process-based risk and vulnerability assessments.

The main objective of this work is to elaborate a process-based framework for a risk assessment methodology that treats the superimposed effects of primary and solute-recycling-induced groundwater salinisation separately. It aims to map out zones in a system that are prone to further salinisation in response to different salinisation processes, making use of the proposed simulation procedures. Such salinisation risk maps can for instance be used within a decision-making context for the design of adequate remedial measures.

In the first section, we will present a simulation procedure that allows decomposition of the bulk salinity distribution into primary and solute recycling components. The risk assessment methodology is then presented step by step making use of a synthetic 2D homogenous horizontal aquifer system. The primary salinisation potential (PP) and solute recycling salinisation potential (RP), being the maximum salinity components at late times are compared to the respective 'present state' salinity components. This comparison yields the respective salinisation risk index distributions which highlight areas requiring remediation and conservations measures. The application to a real case site (Akrotiri aquifer, Southern Cyprus) reveals the outcomes and limitations of the proposed approach and the necessity for new monitoring strategies.

DECOMPOSITION OF BULK SALINITY DISTRIBUTIONS INTO PRIMARY AND SOLUTE RECYCLING COMPONENTS

In a domain where the effects of different salinisation processes are superimposed, a major issue is to decompose the bulk salinity distribution into the components derived from the different processes. The concentration at any point and any time in a domain results from linear mixing of different fractions with different concentrations. The measurable entity is the bulk salinity and only few reliable methods exist to identify the different origins of solutes, i.e. geochemical techniques. Such techniques are crucial, but they are rarely appropriate to capture the dynamics of the involved

processes. Simulation procedures can therefore be a means to decompose the bulk salinity distribution into the respective components, allowing investigation of the dynamics and interplay of the superimposed processes.

The main difficulty in simulating solute recycling from irrigation is that the solute mass entering the system below the irrigated surfaces is a function of the solute mass flux extracted from the irrigation wells, and vice versa. Simulation of solute recycling can either be done numerically in a time stepping-procedure, by evaluating the extracted solute mass flux at the irrigation wells and subsequently reintroducing it below the irrigated surfaces as solute source (e.g. Milnes & Renard, 2004; Milnes, 2005). This procedure may be very labour-some if the solute recycling process is not directly implemented in the simulation code. Another, direct method to simulate transient or steady state solute recycling with any groundwater flow and transport code was proposed by Milnes & Perrochet (2006), valid only for steady state hydraulic conditions. Making use of the transfer function theory (Jury, 1982), a recycling source term RS in the advection dispersion equation (ADE) is defined that generates the equivalent amount of solute mass that is extracted by the irrigation wells. In its general form, the ADE accounting for solute recycling and any primary salinisation processes can be written as follows:

$$\frac{\partial(\phi C)}{\partial t} = -\nabla \cdot (\mathbf{q}C - \phi \mathbf{D} \nabla C) + \sum_{i=1}^n S_i + \sum_{j=1}^r RS_j \quad (1)$$

With the initial and boundary conditions:

$$\begin{aligned} C(0) &= C_{\text{ini}} && \text{on } \Omega \\ C(t) &= C_i && \text{on } \Gamma_i^- \end{aligned}$$

where ϕ is the effective porosity, C the concentration, \mathbf{q} the specific flux vector and \mathbf{D} the tensor of dispersion, Ω symbolises the domain and Γ_i^- the i inflowing boundaries with the respective Dirichlet type transport boundary condition. S_i denotes the solute sources of n primary salinisation sources, e.g. geogenic deposits or agricultural inputs. RS_j are the recycling source terms derived from the r possible primary salinisation mechanisms below the irrigated surfaces Δ and $RS = 0$ everywhere else. With Eq. (1) the bulk salinity distribution can be simulated, reflecting the combined effect of primary salinisation and solute recycling.

The distinction between the contributions to the bulk salinity distribution from the different salinisation processes can be made by adapting the boundary conditions in Eq. (1) to account for primary salinisation components or solute recycling only, while the sum of all components yields the bulk salinity at any point, at any time.

Primary salinisation components

The main characteristic of primary salinisation processes is that they add solutes to the system. Simulation of the effect of primary salinisation processes is either done by accounting for them in the transport boundary conditions or in the source term in the ADE. To simulate the effect of primary salinisation only, Eq. (1) is solved without the recycling source term RS as follows:

$$\frac{\partial(\phi C)}{\partial t} = -\nabla \cdot (\mathbf{q}C - \phi \mathbf{D} \nabla C) + \sum_{i=1}^n S_i \quad (2)$$

With the same initial and boundary conditions as Eq. (1):

$$\begin{aligned} C(0) &= C_{\text{ini}} && \text{on } \Omega \\ C(t) &= C_i && \text{on } \Gamma_i^- \end{aligned}$$

Simulation of the primary salinisation components can also be considered as the ‘classical’ simulation approach, where solute recycling is neglected. Most seawater intrusion models, as an example, do not consider the effects of solute recycling and therefore only simulate the effects of primary salinisation.

Solute recycling (secondary) salinisation components

The main characteristic of solute recycling salinisation is that it does not add solutes to the system, but leads to salinisation by redistribution of solutes. Therefore it can be considered a secondary salinisation process, since it depends on primary salinisation sources. To simulate the effect of solute recycling, the boundary conditions in Eq. (1) are adapted and the primary solute sources S_i are omitted, as follows:

$$\frac{\partial(\phi C)}{\partial t} = -\nabla \cdot (\mathbf{q}C - \phi \mathbf{D} \nabla C) + \sum_{j=1}^r RS_j \quad (3)$$

With the initial and boundary conditions:

$$\begin{aligned} C(0) &= 0 && \text{on } \Omega \\ C(t) &= 0 && \text{on } \Gamma_i^- \end{aligned}$$

However, the salinity distribution resulting from solute recycling can also be obtained by simple deduction of the primary salinity distribution (Eq. 2) from the bulk salinity distribution (Eq. 1). Although all solutes within the system are generated by primary salinisation processes in the first place, we assign a solute to the recycling component as soon as it has been recycled for the first time, i.e. as soon as a solute has been extracted from an irrigation well it ‘forgets’ its previous attribution.

SALINISATION POTENTIALS AND ‘PRESENT STATE’

To obtain the necessary elements required to define the risk indices, the above-described decomposition procedure has to be applied to the bulk ‘present state’ salinity distribution, corresponding to the measurable entity in a real case, as well as to the steady state bulk salinity distribution (bulk salinisation potential).

The steady state salinity distribution of either the bulk, the primary or solute recycling salinisation will be referred to as the respective salinisation potentials. The steady state bulk salinity distribution is denoted **BP** (Fig. 1a), the primary salinisation potential will be abbreviated **PP** (Fig. 1b), and the solute recycling salinisation potential **RP** (Fig. 1c). They are obtained from the decomposition procedure described above. The salinisation potentials reflect the maximum salinity distribution, or the worst-case, that may be reached in response to a given salinisation process for a given hydraulic setting, i.e. exploitation scheme and hydrological condition and has to be considered as a purely hypothetical future reality that reflects the state towards which a system is heading.

Fig. 1 shows a 2D homogeneous horizontal finite element model with hydraulic steady state conditions with two inflowing (Dirichlet type) boundaries with different concentrations and two extraction wells as well as a regional outlet in the southwest. Irrigation (i.e. infiltration) takes place homogeneously on the entire domain. Typically, this configuration could reflect a coastal setting, with a fresh groundwater boundary in the east and a seawater boundary in the north. In this case, the primary salinisation processes are the seawater boundary with a Dirichlet type transport boundary condition ($C = C_s$) as well as the freshwater boundary (with $C_f = 0.03C_s$).

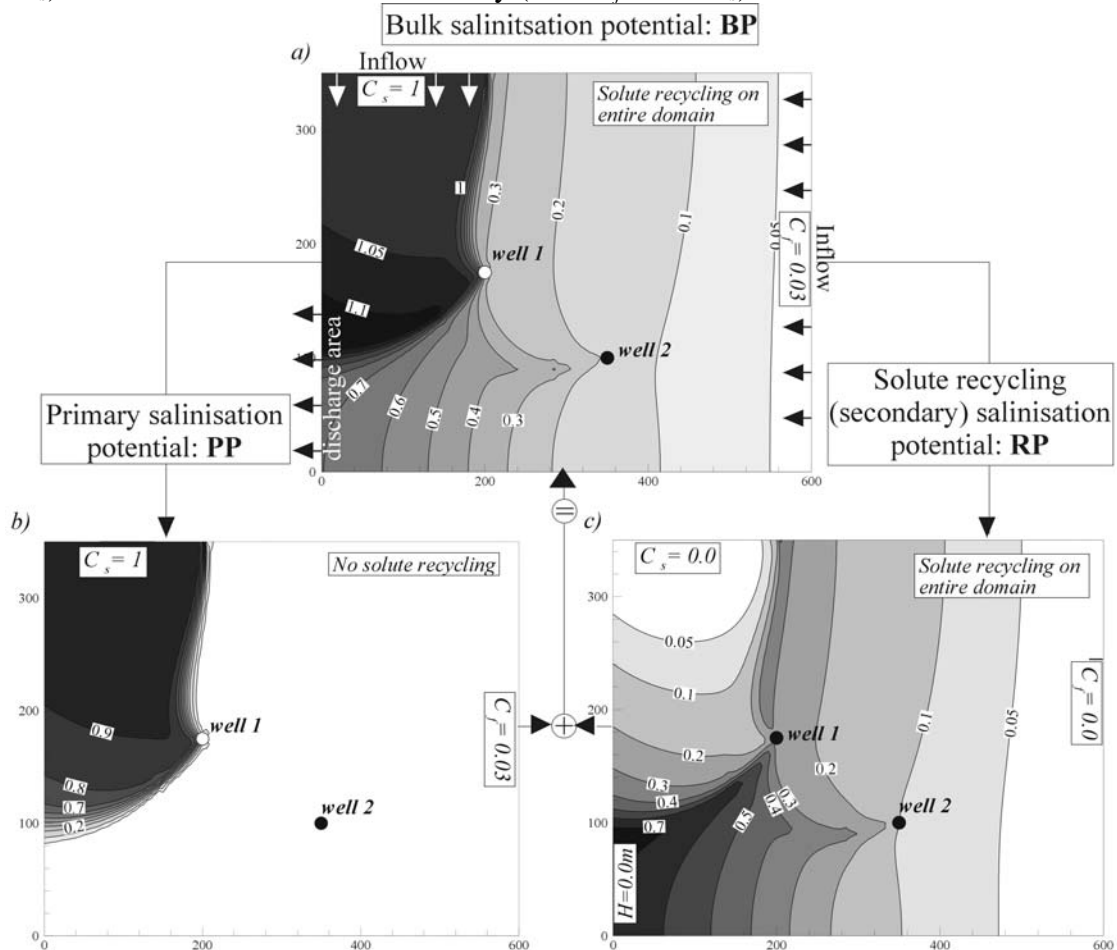


Fig.1 2D horizontal fully saturated finite element model with a seawater boundary in the north ($C_s=1$), a fresh groundwater boundary in the east ($C_f=0.03C_s$), two irrigation wells irrigating the entire surface of the domain and a regional outlet situated in the southwest; a) **BP**: bulk salinisation potential resulting from the steady state form of Eq. (1), showing the combined effect of primary and solute recycling salinisation, b) **PP**: primary salinisation potential resulting from the steady state form of Eq. (2) and c) **RP**: solute recycling salinisation potential obtained by deducting the PP (Fig.1b) from the BP (Fig. 1a).

Fig.1a shows the steady state bulk salinity distribution resulting from Eq. (1) of the combined effect of solute recycling and primary salinisation processes, corresponding to the bulk salinisation potential (BP).

Fig.1b shows the primary salinisation potential (PP) resulting from the steady state form of Eq. (2) in which the effect of solute recycling is neglected, i.e. the solute source RS is omitted ($RS = 0$ everywhere in the domain). In this example, the effects of the two primary salinisation processes (fresh and seawater boundaries) were considered together, since the main aim is to show the separation between primary and

solute recycling salinisation. However, the simulation can be run for each primary salinisation process separately which will then lead to several primary salinisation components.

Fig. 1c shows the solute recycling potential RP, which was obtained by deducting the PP (Fig. 1b) from the BP (Fig. 1a). The RP reveals the salinity increase towards the downstream areas, which is a typical characteristic observed in irrigated areas (i.e. Konikow & Person, 1985). Hence, it is fundamental to state that if the solute recycling process had been neglected in the simulation approach (primary salinisation only, Fig. 1b) the salinity distribution would, in places where solute recycling is dominant, be the exact opposite, i.e. dilution towards the downstream areas (Milnes and Perrochet 2006).

In addition to the decomposed bulk salinisation potential BP, the proposed risk assessment methodology requires decomposition of the 'present state' bulk salinity distribution, which is situated on the time-axis somewhere within the transient evolution. To obtain the 'present state' primary and solute recycling components, the transient bulk salinity evolution has to be simulated in a first step. This will then allow to place the 'present state' bulk salinity distribution on the time-axis and to decompose it accordingly into a 'present state' solute recycling and primary salinity component. This is done by running the same transient simulation again, but neglecting the solute recycling process, yielding the transient primary salinity evolution and thus the 'present state' primary salinisation component. Deducting the primary salinity evolution from the bulk salinity evolution leads to the transient solute recycling evolution and yields the solute recycling 'present state' distribution.

Fig. 2 shows the same 2D horizontal model as in Fig. 1 with the same boundary conditions. The transient salinity evolution is shown in the graphs for the two wells for the bulk salinity evolution (lines with symbols), for the primary salinisation component (thin lines) and for the solute recycling component (thick lines). The 'present state' bulk salinity distribution is shown in Fig. 2a, revealing the salinity distribution at the time that was chosen as 'present state' for this synthetic example (indicated on the time axis in the graphs). Fig. 2b shows the 'present state' primary salinisation component and Fig. 2c the 'present state' solute recycling component. Comparing the primary and the solute recycling components reveals that either process is dominant in different areas, although the absolute impact of the seawater boundary at this stage is far more prominent. However, in the areas that are unaffected by the seawater boundary, solute recycling increases the groundwater salinity up to twice the concentration of the fresh groundwater boundary concentration.

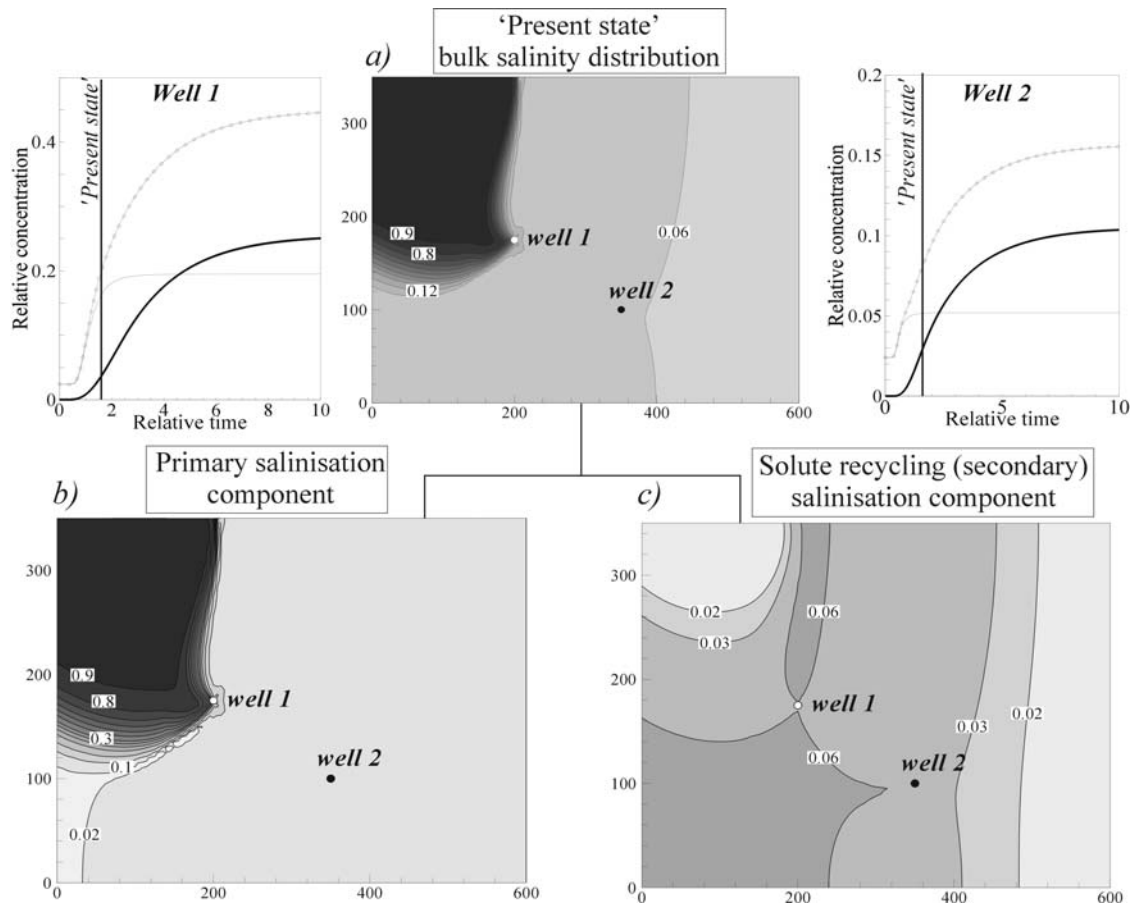


Fig.2 'Present state' salinity distributions for the same 2D horizontal finite element model as in Fig. 1. The graphs show the transient evolution for the two wells of the bulk salinisation (lines with circles), the primary salinisation component (thin lines) and the solute recycling component (thick lines). The time chosen as 'present state' is indicated on the graphs at $t = 1.7$ system turnover times. a) 'Present state' bulk salinity distribution, b) 'Present state' primary salinisation component and c) 'Present state' solute recycling component.

SALINISATION RISK INDEX MAPPING PROCEDURE

Risk assessment is based on comparison of a present state of the environment with a possible future adverse state of the environment, having negative impacts on human interests. Risk can be defined as the probability of the adverse state actually occurring, multiplied by the severity of the impact (Helm 1996). Relating this general definition to the salinisation processes we are focussing on, requires definition of an adverse state. Although we are dealing with primary and secondary salinisation processes, we will define an adverse state in both cases on the same basis: an adverse state is defined as any further salinity increase induced by the respective salinisation process in response to a given hydraulic condition. Since all evaluations are based on deterministic model simulations, we will not define a 'probability' of the adverse state to actually occur, but will define a risk index, being a measure of the future potential magnitude of salinity increase.

The above-described decomposition procedure of the bulk salinity potential (Fig. 1) and 'present state' salinity distribution (Fig. 2) yields the necessary elements that are required to obtain the spatial risk index distributions of the different salinisation processes. These are obtained by deducting the 'present state' salinisation components from the respective salinisation potential and subsequent normalisation by the overall

salinisation potential (BP). Denoting the salinisation processes with i , the respective salinisation risk index $R_i(x)$ at any point x in the domain can be written as follows:

$$R_i(x) = \frac{S_{\text{Pot}}(i, x) - S_{\text{Pres}}(i, x)}{BP(x)} \quad (4)$$

$S_{\text{Pot}}(i, x)$: salinisation potential of the i^{th} salinisation process at a point x , i.e. with i = solute recycling, $S_{\text{Pot}}(i, x) = \text{RP}(x)$ and for i = primary salinisation, $S_{\text{Pot}}(i, x) = \text{PP}(x)$

$S_{\text{Pres}}(i, x)$ = ‘present state’ salinisation of the i^{th} salinisation process, analogue to $S_{\text{Pot}}(i, x)$.

Eq. (4) shows that ‘present state’ salinities which are close to the respective salinisation potential ($S_{\text{Pot}}(i, x)$) will yield a small risk index $R_i(x)$, whereas small ‘present state’ salinities relative to the respective salinisation potential will yield large risk indices. The bulk salinisation potential is used to normalise the risk indices, thereby scaling the risk indices of the different processes. The risk index is a measure for the stability of the system, and does not yield an absolute measure for the risk of groundwater salinisation. As an example, an area that is already entirely intruded by seawater and has already reached the steady state salinisation will suffer no further salinisation by seawater intrusion. Hence, the primary risk index may be zero, although the groundwater quality is far beyond the limit of exploitability.

Therefore, to identify areas that require remediation and conservation with respect to the different salinisation processes, the risk index distributions have to be confronted with a threshold salinity C_{thersh} which has to be defined based on criteria related to numerous fields (e.g. agronomy, irrigation science and economy). Since definition of such a threshold concentration is beyond the scope of this work, we will just illustrate the mapping procedure for the case that a threshold concentration has been defined (e.g. limit of exploitability). Overlaying the threshold concentration C_{thersh} with the ‘present state’ respective salinity components leads to a subdivision of the domain into areas that exceed this limit ($C_i(x) < C_{\text{thersh}}$) and areas where the salinity is below the threshold concentration ($C_i(x) > C_{\text{thersh}}$). Then, by intersecting these areas with the risk index distributions and defining a critical risk index value R_{lim} not to be exceeded (to be defined similarly to C_{thersh}), sub-areas can be mapped that represent different risk levels requiring different management actions, as shown in Table 1.

Salinisation risk areas	‘Present state’ salinity $C_i(x)$ vs. threshold concentration C_{thersh}	Risk index $R_i(x)$ vs. critical risk index R_{lim}	Action
Low risk	$C_i(x) < C_{\text{thersh}}$	$R_i(x) < R_{\text{lim}}$	(Conservation)
Intermediate-high risk	$C_i(x) < C_{\text{thersh}}$	$R_i(x) > R_{\text{lim}}$	Conservation
High risk	$C_i(x) > C_{\text{thersh}}$	$R_i(x) > R_{\text{lim}}$	Conservation, Remediation
High risk	$C_i(x) > C_{\text{thersh}}$	$R_i(x) < R_{\text{lim}}$	Remediation

Table 1 Subdivision of the domain into areas above and below a defined threshold salinity C_{thersh} and overlaying it with areas above and below a critical risk index R_{lim} yields the respective salinisation risk areas requiring different management actions, such as conservation or remediation measures.

Fig. 3 illustrates the risk index mapping procedure on the synthetic 2D horizontal example, shown in Fig. 1 and Fig. 2. To obtain the salinisation risk index distributions,

shown in Fig. 3a and Fig. 3b the ‘present state’ salinisation components (Fig. 2b and Fig. 2c) at each point x in the domain were deduced from the respective salinisation potentials (Fig. 1b and Fig. 1c) and normalised by the bulk salinisation potential (Fig. 1a), according to Eq. (4). To obtain the subdivision into risk areas requiring different management actions, the risk index distributions were overlain with a defined threshold concentration C_{thresh} (defined in this example as $C_{\text{thresh}} = 0.06$: twice the salinity of the eastern boundary) and evaluated for a critical risk index value of R_{lim} (defined for this example as $R_{\text{lim}} = 0.05$).

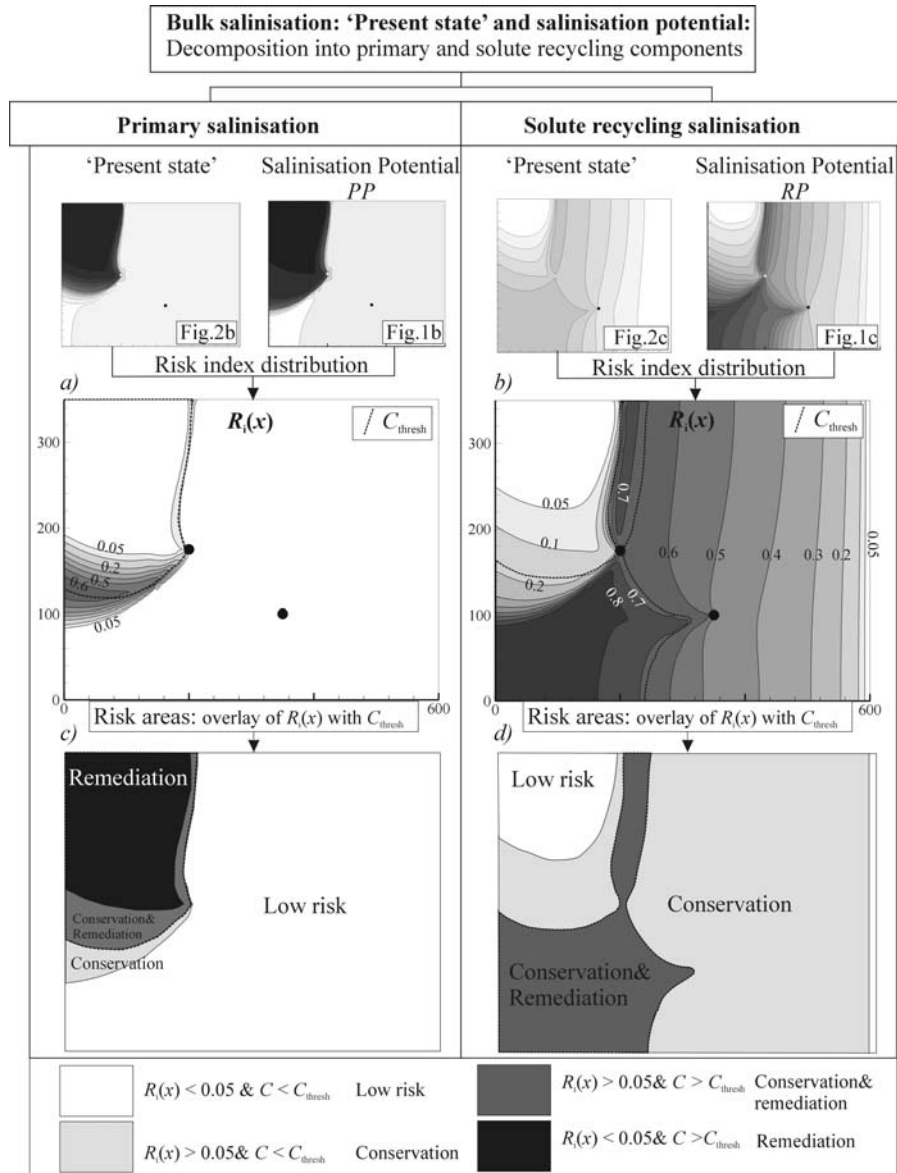


Fig. 3 Salinisation risk mapping procedure schematising the various steps, from the decomposition of the bulk salinity distributions into the respective components, yielding the risk index distributions, Eq. (4). a) Primary salinisation risk index distribution; b) Solute recycling risk index distribution with threshold concentration indicated as dashed line. Delimitation of the domain into areas of low risk, conservation and remediation areas: c) Primary salinisation risk area distribution; d) Solute recycling salinisation risk area distribution.

The proposed mapping procedure provides a tool with which the impact of exploitation and irrigation schemes can be evaluated by reducing the effects of

dynamic processes to static images. Overlaying the spatial salinisation risk index distributions with a threshold concentration or salinity allows thus to identify low and intermediate risk areas that require conservation measures, e.g. enhanced monitoring, from areas that require both conservation and remediation or remediation measures only, e.g. modification of exploitation and irrigation schemes.

Risk index distributions for modified exploitation schemes

If a change in hydraulic setting is eminent for instance due to well concentrations exceeding the exploitation limit, the impact of a change in the exploitation scheme on the salinisation risk index distribution can be evaluated by making use of the same salinisation risk index definition (Eq. 4). The 'present state' salinisation components are in this case compared to the salinisation potential resulting from the modified hydraulic conditions (PP_{modif} and RP_{modif}), reflecting the new directing towards which the system is heading. This allows identification of zones that will either tend towards improved water quality, characterised by negative risk indices, or suffer further deterioration in response to the modification of the hydraulic setting (positive risk indices).

To illustrate the effect of a modified exploitation scheme, the same 2D horizontal model was used as in the previous sections. The risk index distributions were elaborated for a modified hydraulic setting resulting from the deactivation of *well 1*, increasing the extraction rate of *well 2* by the previous amount of *well 1*. The irrigation plot location remained unchanged, covering the entire domain.

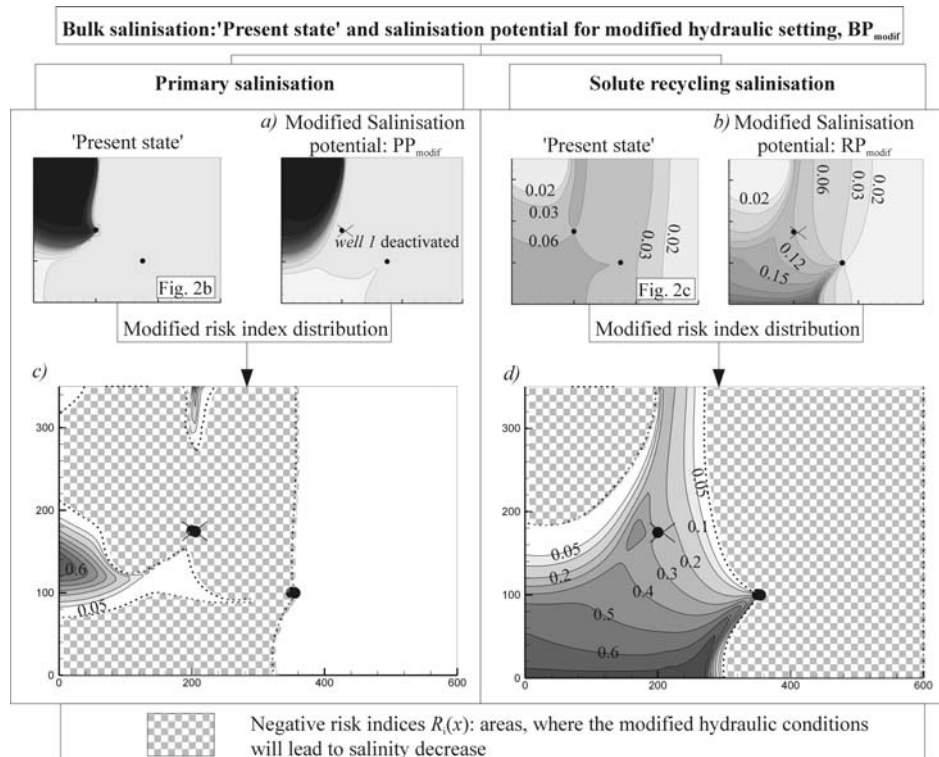


Fig. 4 Risk index mapping procedure for a modified exploitation scheme. a) Modified primary salinisation potential PP_{modif} , b) Modified solute recycling salinisation potential RP_{modif} , c) Primary salinisation risk index distribution, d) Solute recycling salinisation risk index distribution. Chequered pattern indicates the areas with negative risk indices: improvement of groundwater quality in response to the modified exploitation scheme.

Fig. 4a shows the modified primary salinisation potential PP_{modif} and Fig. 4b the modified solute recycling salinisation potential RP_{modif} , resulting from the decomposition of the bulk salinisation potential BP_{modif} reflecting the steady state salinity distribution in response to the modified exploitation scheme. The respective modified risk index distributions are shown in Fig. 4c for the primary component and in Fig. 4d for the solute recycling component. The chequered areas show the zones where the resulting risk indices are negative, thus indicating where the groundwater quality will improve in response to the modified hydraulic conditions. This procedure could for instance be used for optimisation purposes, i.e. to maximise the areas where groundwater quality will improve (minimising the risk indices).

APPLICATION TO A REAL CASE SITE (AKROTIRI AQUIFER)

Although the proposed salinisation risk assessment is process-based, in contrast to risk and vulnerability approaches based on the empirical evaluation of key-factors (e.g. Aller et al. 1985), the results will entirely depend on the model used for the purpose. To carry out the proposed risk assessment methodology for a real case study, the different salinisation processes and their spatial distribution have to be identified and monitored in the field. Returning to the example of coastal aquifers, a large number of monitoring strategies have been developed to follow the evolution of seawater intrusion (e.g. Custodio 1997), whereas monitoring networks focussing on solute recycling or other salinisation processes in coastal settings are rarely reported in literature. This fact leads to a considerable discrepancy in the availability of data sets necessary during the calibration process of a model when several salinisation processes are superimposed.

The elaborated risk assessment methodology was applied to a coastal aquifer in Southern Cyprus (Akrotiri aquifer). Groundwater salinisation has been observed over the past two decades leading to implementation of a strict management plan imposed by the authorities. The entire aquifer is managed in the belief that seawater intrusion is the only salinisation process, which is the case for many coastal irrigated areas. To carry out the proposed risk assessment methodology, simulations were run with a 3D finite element code developed at CHYN (Cornaton 2004), which was extended to allow solute recycling in a time stepping procedure. The details of the 3D finite element model description are given in Milnes (2005). Field investigations confirmed the existence of solute recycling salinisation and allowed identification of the spatial distribution of different dominant salinisation processes, shown in Fig. 5a (Meilhac, 2003). The resulting seawater intrusion (primary salinisation) and solute recycling risk areas are shown in Fig. 5b and Fig. 5c, indicating that the central area of the aquifer is a zone endangered with respect to salinisation from solute recycling, whereas the western area is endangered with respect to seawater intrusion, requiring remediation measures. This correlates well with the spatial distribution of the dominant salinity sources as derived from the field investigations (Fig. 5a) and indicates that the central area of the aquifer requires a management scheme adapted to the process of solute recycling.

Essential data for the model simulations, i.e. the distribution pattern of the extracted groundwater from the irrigation wells onto the irrigated surfaces, was not available, rendering the results of the simulations 'hypothetical'. Solute recycling is rarely monitored, but data is essential for the calibration and cross-validation of the proposed salinisation risk assessment procedure.

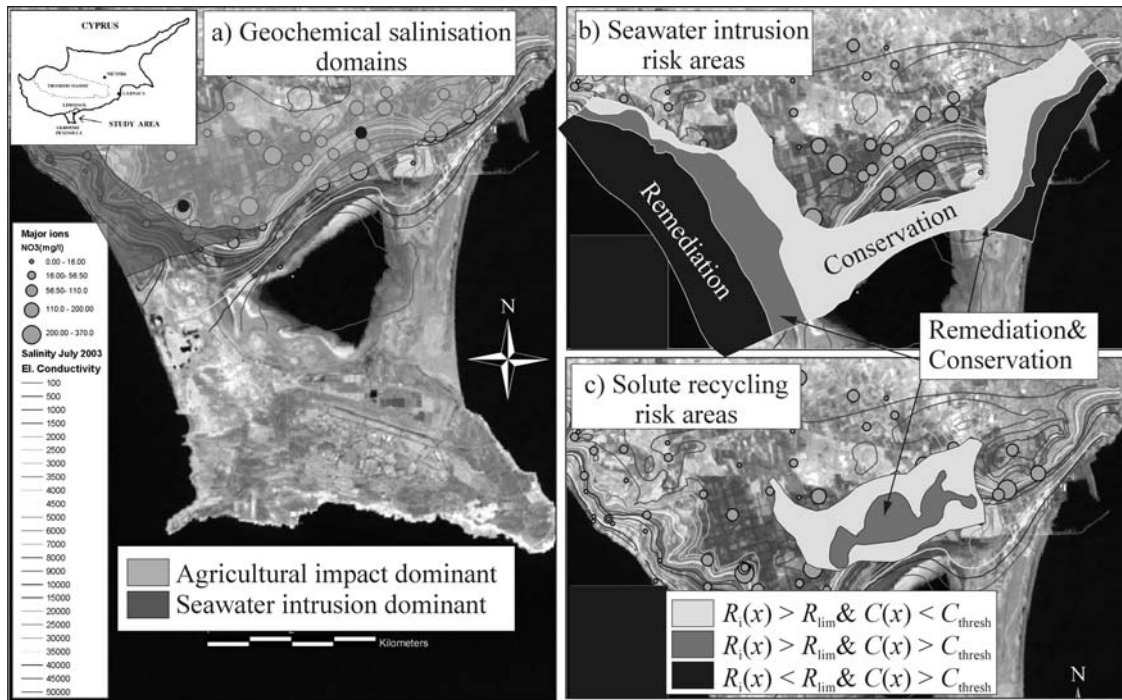


Fig. 5 Showing results from the risk assessment applied to a real case site in Southern Cyprus (Akrotiri aquifer). a) Geochemical salinisation domains (modified after Meilhac, 2003). b) Seawater intrusion risk areas, c) Solute recycling risk areas based on $R_{lim}: 0.5$, $C_{thresh}: 0.06$.

DISCUSSION AND CONCLUSIONS

A framework for a risk assessment methodology for systems with superimposed salinisation processes has been presented that is based on the decomposition of bulk salinity distributions into different salinisation components. The impact of the different salinisation components are then evaluated separately by means of defined salinisation risk indices, allowing to map the spatial distribution of the potential future primary or solute recycling salinisation and to highlight areas requiring remediation and conservation, respectively.

The most delicate aspect in the proposed risk assessment methodology is that the 'present state' salinisation has to be obtained by simulation, which may be extremely difficult in real case studies due to lack of adequate calibration data, as was encountered in the case of the Akrotiri aquifer.

An inherent problem with the proposed approach is that the dependency between the primary salinisation process and solute recycling is not accounted for, i.e. both salinisation processes are treated in the same way, although solute recycling entirely depends on primary salinisation. Also, primary salinity increase is not constant over time and the potential of attaining the steady state salinity is heterogeneous in time and may therefore in places be an inappropriate measure. However, the approach can also be applied when only primary salinisation processes exist.

In the proposed salinisation risk assessment methodology, time has not been included, e.g. the time to reach certain salinity. However, this aspect could possibly be added, by, for instance, evaluating the time-span for a given salinity increase

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