

SOIL SALINISATION RISK ASSESSMENT USING SALINE IRRIGATION WATER IN THE LOWER NAMOI VALLEY

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Introduction

Dryland salinity is on the increase in the upper catchments of the central and northern river valleys of New South Wales (Murray Darling Basin Ministerial Council-MDBC, 1999). The consequence of this is increased salinity in river water. This could adversely affect irrigated schemes downstream; as irrigation with moderate to highly saline water can lead to increased salinity in the root-zone, if there is insufficient leaching. In order to determine the potential impact and long-term sustainability of irrigated production we need to know the spatial distribution of soil and effects of water quality changes. Important also is the soil-water balance, which needs to be modeled in order to provide estimates of potential salinity accumulation and deep drainage as affected by the current quality of irrigation water. Worst-case scenarios can be applicable in this case.

There are several models used for salinity prediction and estimation of leaching fraction and deep drainage. These include the steady-state leaching requirement model (United States Salinity Laboratory, 1954), SODICS-a transient mass balance model (Rose *et al.*, 1979) and the Salt and Leaching Fraction model SaLF (Shaw and Thorburn, 1985). The SaLF model is based on the assumption that soil leaching or deep drainage is related to the soil hydraulic conductivity, which in turn is influenced by the amount of clay (%), clay mineralogy (defined by Cation Exchange Capacity/Clay %) and exchangeable sodium percentage (ESP). Once these soil properties and water quality and quantity parameters have been determined the empirically-based model can be used to estimate the average root-zone EC_e at steady-state using progressively saline water.

Disjunctive Kriging (*DK*) can be used to estimate the conditional probability that an indicator variable (e.g. EC_e) exceeds a critical tolerance level (Yates *et al.*, 1986a; Wood *et al.*, 1990). The conditional probability can be targeted to the level at which some form of management action is needed. For example, Webster and Oliver (1989) applied the method to determine when and where remedial action would be necessary for soil pH. Finke and Stein (1994) used *DK* to estimate leaching fraction at field scale.

In this paper, we combine SaLF model predictions of EC_e with *DK* to assess the current status and potential threat of soil salinity using data from soil and water surveys in the lower Namoi valley of northern NSW, Australia. We tested different simulations based on the application of water of variable quality (i.e., EC_w 0.47, 1.5, 4 and 9 dS/m). We identified best management strategies to forestall the threat of soil salinisation to irrigation.

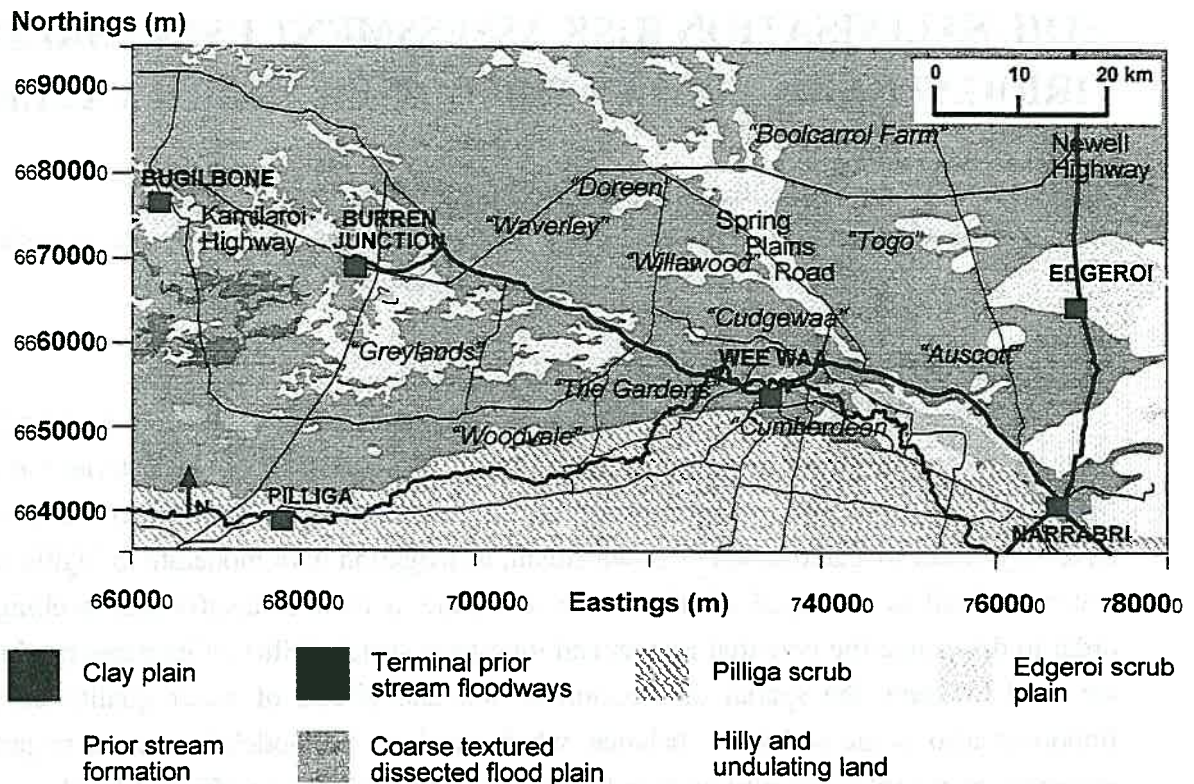


Figure 2. Physiographic units of the lower Namoi valley (after Stannard and Kelly, 1977).

Soil and water data

The soil data used for this study were from two sources: 1) the Edgeroi data set (McGarry *et al.*, 1989), and 2) soil survey data for the area west of Edgeroi. The Edgeroi data consist of 210 sampling sites arranged in a systematic equilateral triangular grid with an approximate 2.8 km spacing. In this paper we did not use profiles east of the Newell Highway (Figure 3), which are associated with the hilly and undulating areas of the landscape close to the Nandewar Ranges. Additional sites were used from the Australian Cotton Research Institute and I.A. Watson Wheat Research Centre. Detailed transects were also taken at "Llano", "Noelurma", "Oakvale" and in the Wee Waa area. At each location a core was recovered and sampled for laboratory analysis at depths of 0.0-0.1, 0.1-0.2, 0.3-0.4, 0.7-0.8, 1.2-1.3, and 2.5-2.6 m. The samples were air-dried and ground to pass a 2-mm sieve. The soil was analysed for exchangeable cations (mmol(+)/kg) based on Tucker's (1974) method using a mechanical leaching device (Holmgren *et al.*, 1977); silt and clay (%) were determined using the pipette method (Coventry and Fett, 1979).

The soil survey data for the area west of the Edgeroi district consists of 125 sites, which were selected using a stratified simple random sampling design with site spacings ranging from 2 to 10 km (Figure 1). To be consistent with the Edgeroi data, soil samples were collected from the same depth ranges with particle size analysis and cation exchange capacity (ECEC) determined using the same methods.

Data on current water quality was obtained from two samples collected from along the Namoi River: one from Collins Bridge (near Wee Waa) and the other in the township of Narrabri. Another sample was taken from the Mooki River. At Collins Bridge and Narrabri water salinity (EC_w) was 0.569 dS/m and 0.366 dS/m, respectively. The EC_w sample from the Mooki River (tributary of the Namoi) was 0.759 dS/m. These values suggest that by the time the water reach Narrabri and Wee Waa (avg. 0.47 dS/m) the Namoi River water and other tributaries have diluted salts received from the Mooki River. As such, water available to irrigators is of good quality (avg. 0.47 dS/m).

SaLF Modeling

In order to determine the salinity risk associated with irrigated farming systems we chose three progressively saline water qualities for simulation using the SaLF model. These are: EC_w values of 1.5, 4.0 and 9.0 dS/m. The first value is predicted to be the salinity of water in the Namoi valley and available for irrigation in the year 2100 (MDBC, 1999). The other two values of salinity are used for irrigation in Colorado and Tunisia, respectively (Rhoades *et al.*, 1992). Each of the 329 sites were inputted to the SaLF program, including the attributes of clay content and CEC at four depths (i.e. 0-0.1, 0.3-0.4, 0.6-0.7 and 1.2-1.3m) and exchangeable sodium at a depth of 1.2m. An EC_w of 0.468 dS/m was used for estimating current salinity status of the study area. In the SaLF model, we assumed that average annual rainfall and irrigation water were 584 mm and 600 mm, respectively. Estimates of average root zone EC_e at steady-state were then calculated.

Geostatistical methods

Geostatistical methods of spatial interpolation are not new to the soil science community. Various methods – ranging from linear (ordinary-, simple-, co-kriging and kriging with an external drift) to non-linear methods (indicator-, multiple indicator- and disjunctive kriging) have been used. Ordinary kriging (*OK*) is one of the most basic geostatistical methods. However, when the distribution of the variable being interpolated is not normal (i.e. skewed) mean-type estimators such as *OK* rapidly lose their accuracy. As a result *OK* may be inappropriate when the distributional assumption is not met. Disjunctive Kriging (*DK*) can handle this type of data better and has the added advantage that estimates of the conditional probability that a measured variable (e.g. soil salinity: EC_e) exceeds a critical tolerance level (Yates and Yates, 1988) are also obtained. The conditional probability can be used in management decision-making to determine the level at which some form of management action needs to be implemented. Two types of information are required: the first is the critical level at which the variable becomes a threat (i.e. the cut-off); the second is the probability level that spurs management action (Yates and Yates, 1988). Many examples of its use exist in soil science (Yates *et al.*, 1986a and b: Yates, 1986; Yates and Yates, 1988; Webster and Oliver, 1989; and Finke and Stein, 1994). *DK* is presented in detail in Rivoirard (1994).

Prediction of conditional probability

Our primary aim was to conduct various water quality simulations in order to determine which soil types and what crops in the lower Namoi valley would be susceptible to salt build-up if water quality diminished. The cut-off values of EC_e at steady state considered in this study included 2, 4, 6 and 7.7 dS/m. Respectively, these values represent levels of salinity where some form of soil, water or crop management would be required to ensure continued use of legumes (e.g. *Dolichus Lab Lab*), most crops (Bowers and Wilcox, 1965), grains (e.g. wheat) and cotton.

Results

Estimates of soil salinity

Figure 5 shows the blob plots and frequency distribution of estimated soil EC_e using the current water quality (EC_w 0.47 dS m⁻¹). The average salinity value is 0.70 dS/m. This suggests EC_e in the root-zone would not accumulate to levels deleterious for crops predominantly used in the current irrigated farming system (i.e. *Dolichus lab lab*, wheat and cotton). This result is consistent with the prevailing soil salinity values in the lower Namoi valley around Wee Waa. With respect to the use of water of EC_w 1.5 dS/m in 2100 (MDBC, 1999), average EC_e will have been 1.79 dS/m. Figure 5b shows that sensitive crops such as *Dolichus Lab Lab* (i.e. $EC_e > 2$ dS/m) may require management to ensure continued use. This would be the case for almost half of the sites. Figure 5c shows frequency distribution of soil EC_e if water with quality of EC_w of 4.0 dS/m was applied. Potential average EC_e across the district would be 3.73 dS/m. Approximately 60 and 5 % of sites would require some form of management to enable inclusion of legumes and wheat production (i.e. $EC_e > 6$ dS/m) as part of the current irrigated cotton farming system. If water quality of EC_w 9.0 dS/m were applied, more than half the sites would require management to enable wheat cropping while all would require management for legumes and 30 % needing management to reduce salt build up for cotton production (i.e. $EC_e > 7.7$ dS/m).

Spatial distribution of cut-off EC_e values for crop production

Figure 5 also shows patterns of spatial distribution of EC_e (SaLF estimates) using EC_w values = 0.47, 1.5, 4 and 9 dS/m. It is apparent that responses in the Edgeroi and the Wee Waa data sets are different. This is most obvious on either side of Spring Plains Road. To the northeast, soil EC_e is generally higher as compared with the area to the southwest and around the township of Wee Waa. The reason for this is attributable to the generally sandier and coarser textured sediments associated with the prior stream channel of the Namoi River, which flowed in a northwesterly direction, parallel with Spring Plains Road. As such fewer soluble salts (e.g. sodium) have accumulated and the soil is well drained compared to the clay plains to the northwest (Triantafilis *et al.*, 2000 and 2001a).

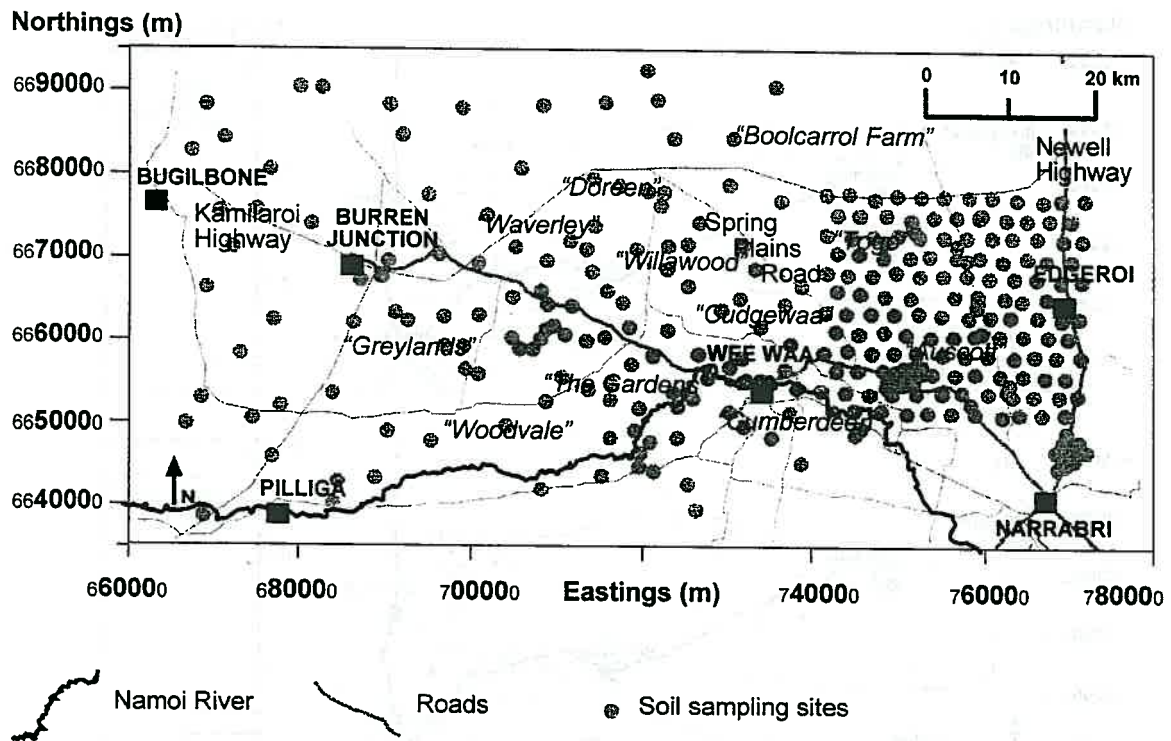


Figure 1. Location soil sampling locations in the lower Namoi valley study area.

Materials and methods

Study area

The study area is approximately centred on the small township of Wee Waa located in the lower Namoi valley in northern New South Wales, Australia (Figure 1). The area covers approximately 6,600 km² and includes one of the largest grazing properties in the district (i.e. "Boolcarrol Farm"). It also includes the large cotton growing farms of "Auscott" and "Togo" and the area known as "The Gardens" as well as several medium (e.g. "Waverley" and "Cudgewaa") and small sized operations (e.g. "Cumberdeen"). The area was selected for several reasons: 1) it is one of the oldest irrigated cotton-growing regions in Australia, 2) a large number of irrigated farms are concentrated in a relatively small area, and 3) dryland salinity is prevalent in the upper parts of the Namoi catchment.

Physiography

Stannard and Kelly (1977) carried out a reconnaissance soil survey of the lower Namoi valley and identified eight physiographic units: 1) the clay plains, 2) prior stream formations, and 3) the low dissected floodplains. These form the principal irrigation districts of the area, although some irrigation is practiced in and around the Pilliga Scrub complex (Figure 2). The dominant clay plains are generally uniform in topography except where dissected by current streams. The uppermost sediments are of a fine-textured nature, which are overlain by self-mulching clay soil.

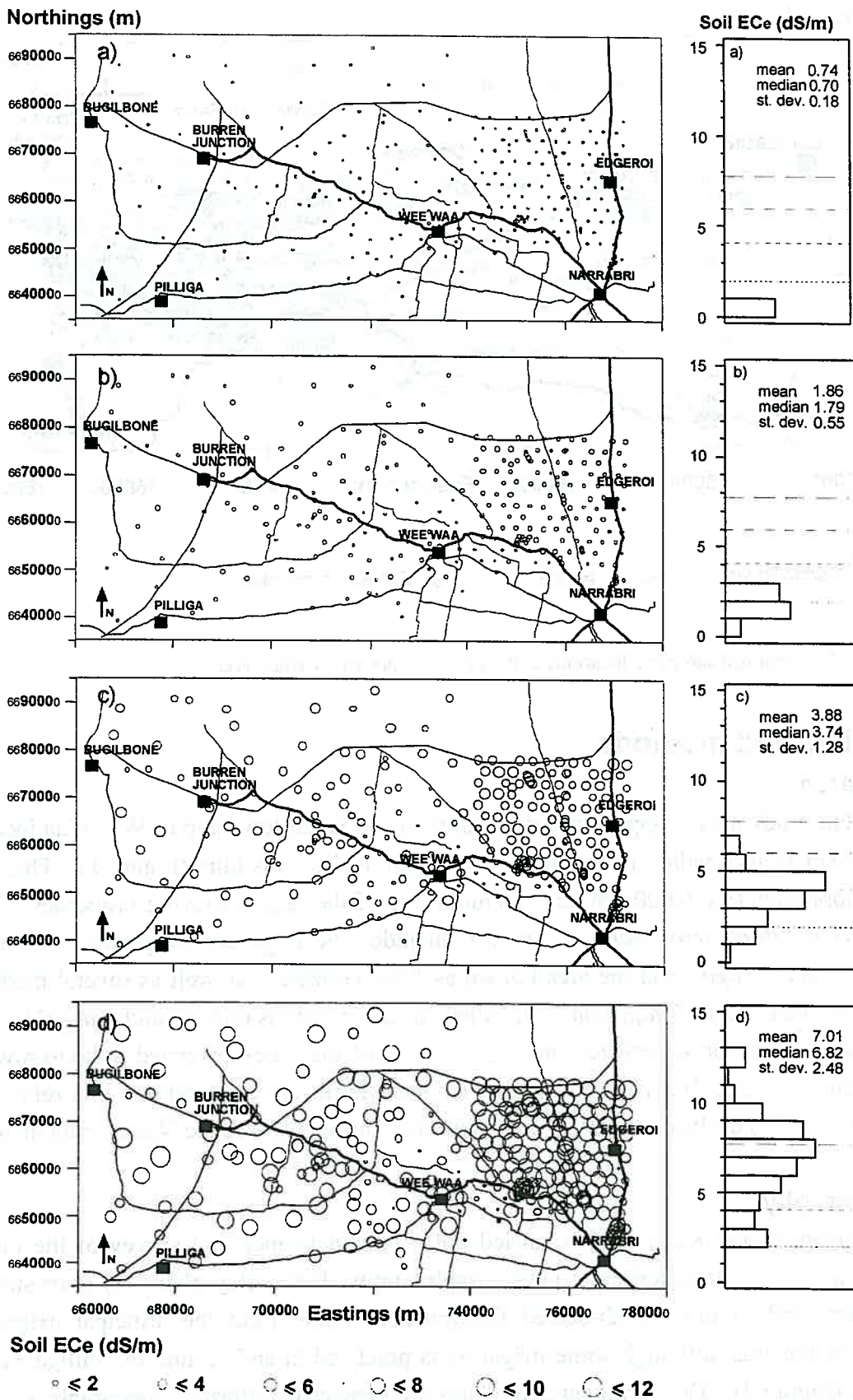


Figure 3. Blob plots and frequency distribution showing concentration of EC_e (dS/m) as predicted using SaLF when EC_w of a) 0.47, b) 1.5, c) 4, and d) 9 dS/m was simulated. NOTE: EC_e cut-off values for legumes (2 dS/m), most crops (4 dS/m), wheat (6 dS/m) and cotton (7.7 dS/m).

Spatial estimates of conditional probability

In order to better understand the results described above, the conditional probability (i.e. risk) produced by each of the simulations were mapped. The results are shown in Figures 4-7. Figure 4 shows the spatial distribution of conditional probability (CP) where soil EC_e exceeded 2 dS/m if water with quality of EC_w 1.5 dS/m was simulated. The white areas indicate lowest risk (i.e. $CP < 0.2$) whilst the progressively darker gray scale areas indicate higher probabilities (darkest shade: $CP \geq 0.8$). It is evident that much of the area surrounding the township of Wee Waa exhibits a low risk that the critical value for legume crops (i.e. $EC_e \geq 2$ dS/m) would be exceeded. The areas of highest risk are associated with the clay alluvial plains; north of the Kamilaroi Highway and Spring Plains Road and north and south of Burren Junction and Bugilbone. In these areas, the continued use of sensitive crops such as legumes would require some form of soil, crop or irrigation management if this water quality was used. This is particularly the case on the heavy clay plains soil types evident at "Togo" and "Auscott" (Triantafilis *et al.*, 2001b and c). The risk map when EC_e exceeds 4 dS/m if water of 4 dS/m was simulated was similar to that shown in Figure 4. As such, it indicates that most crops would require management in the high-risk areas ($CP \geq 0.6$) in order to be included in an irrigated farming system using moderately saline water. With respect to wheat and cotton production, (i.e. $EC_e \geq 6$ and 7.7 dS/m, respectively) the risk (i.e. CP) was less than 0.2 across the entire area and therefore irrigating for production of these crops could conceivably be sustainable with minimal soil, water and crop management.

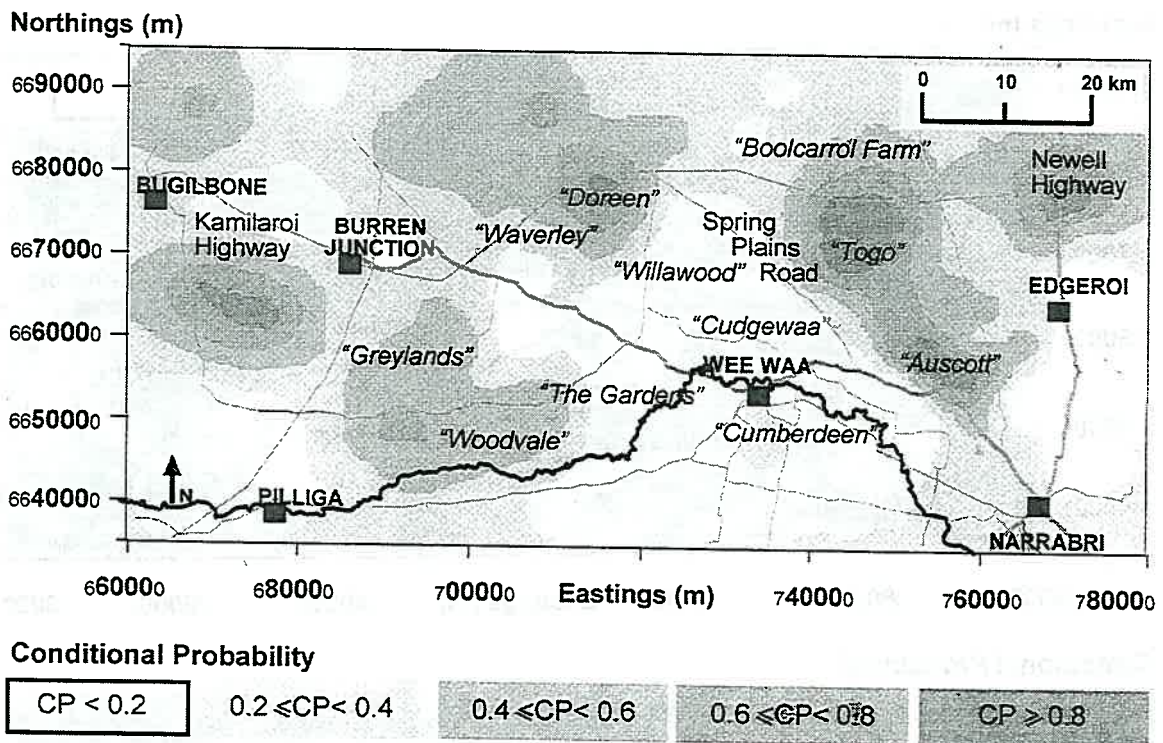
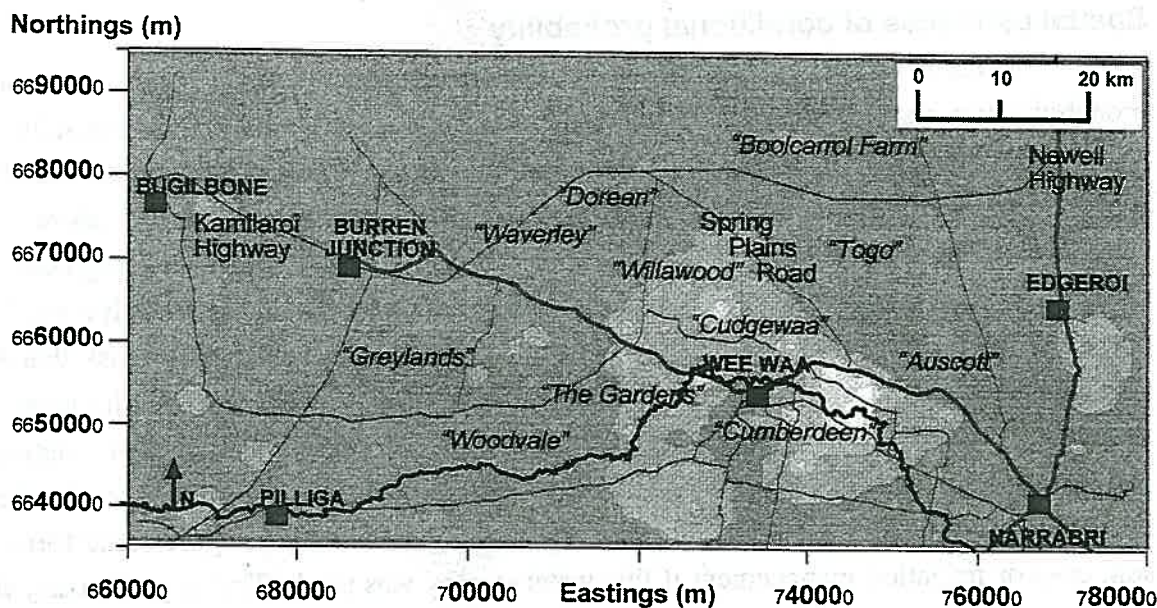


Figure 4. Spatial distribution of conditional probability (CP) that soil EC_e at steady state exceeds 2 dS/m if $EC_w = 1.5$ dS/m was simulated using disjunctive kriging (DK).

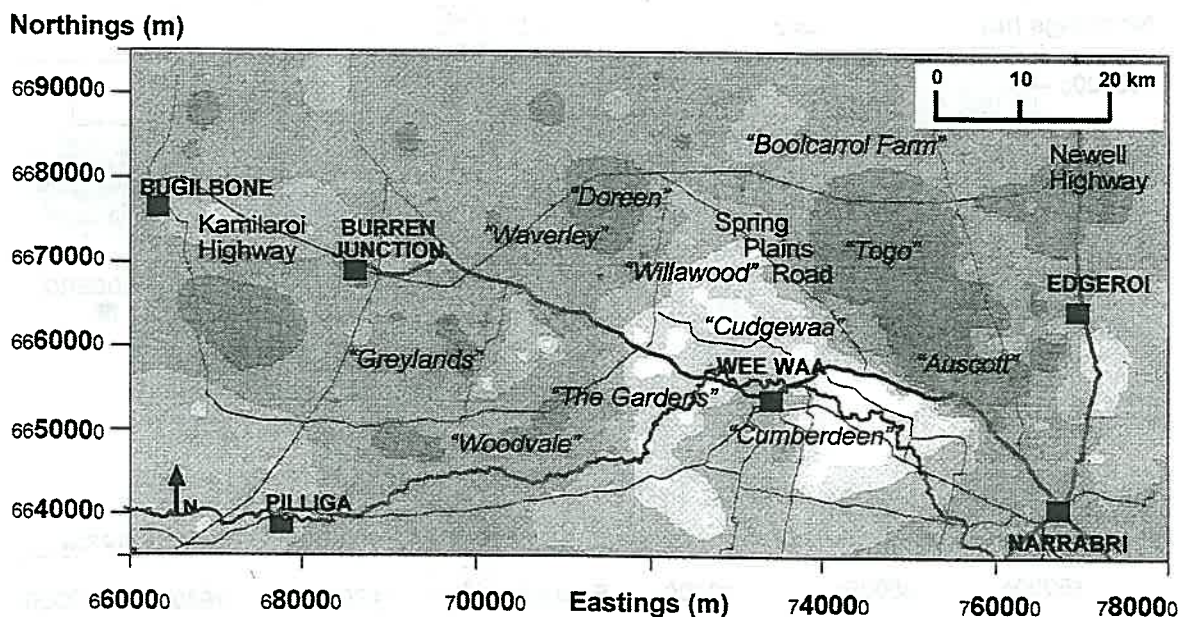


Conditional Probability



Figure 5. Spatial distribution of conditional probability (CP) that soil EC_e at steady state exceeds 4 dS/m if $EC_w = 9.0$ dS/m was simulated using disjunctive kriging (DK).

Figure 5 shows the result when EC_e exceeds 4 dS/m if $EC_w = 9$ dS/m was simulated. It is evident that most crops would require some form of management to enable production, except in the area southeast of Wee Waa (i.e. Pilliga Scrub Complex soil).



Conditional Probability



Figure 6. Spatial distribution of conditional probability (CP) that soil EC_e at steady state exceeds 6 dS/m if $EC_w = 9.0$ dS/m was simulated using disjunctive kriging (DK).

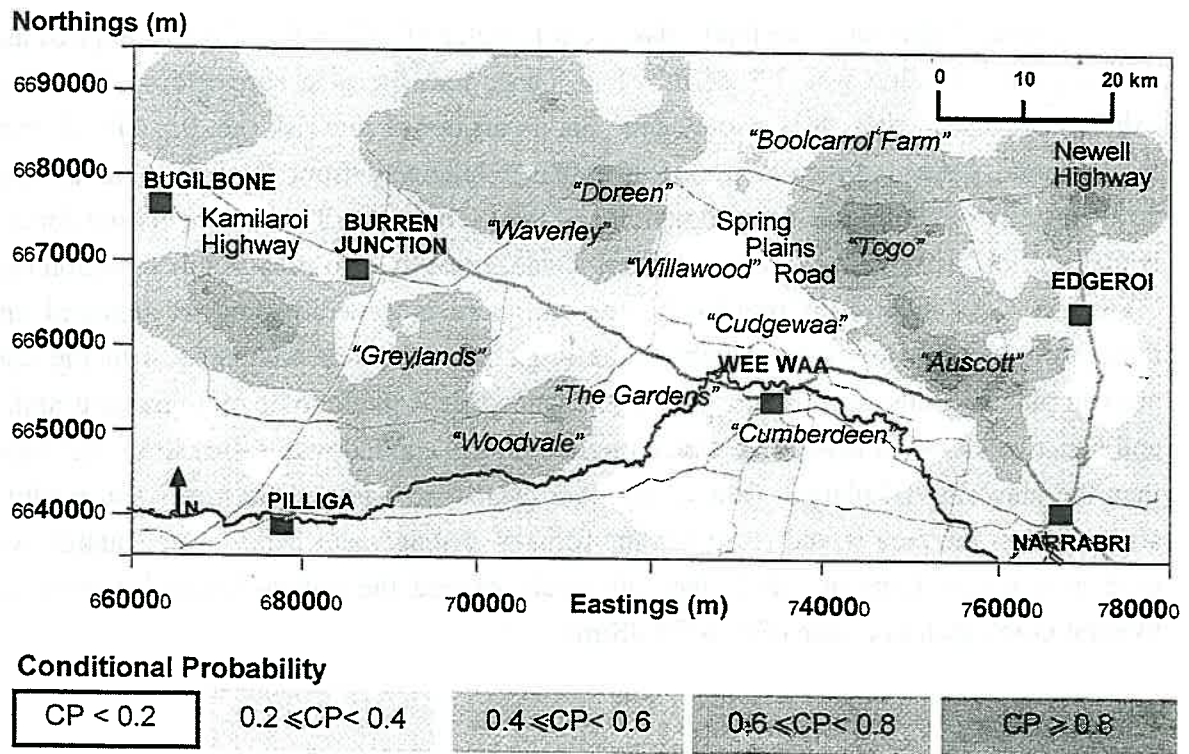


Figure 7. Spatial distribution of conditional probability (CP) that soil EC_e at steady state exceeds 7.7 dS/m if $EC_w = 9.0$ dS/m was simulated using disjunctive kriging (DK).

The risk map shown in Figure 5 was similar to where EC_e exceeds 2 dS/m and if EC_w of 4 dS/m was applied. In this case leguminous crops would not be able to included in an irrigated farming system if the moderately saline water quality of $EC_w = 4$ dS/m was applied without some for of soil, water or crop management.

The results achieved if EC_e cut-off value of 6 dS/m was considered along with the application of 9 dS/m of water is shown in Figure 6. It is clear from this figure that the soil salinisation risk, with respect to continued wheat cultivation, is highest ($CP \geq 0.80$) in the areas associated with the clay alluvial plains northeast of Spring Plains Road. This is particularly evident on "Auscott" and "Togo," as well as to the north of the township of Edgeroi. This is similarly the case in smaller areas adjacent to "The Gardens," "Woodvale," "Greylands" and "Doreen" and the area south of the Kamillaroi Highway between Burren Junction and Bugilbone. Apart from the area north of Edgeroi the other areas have been extensively developed for irrigated cotton production and would therefore require a combination of soil, water and crop management to remain viable with respect to including wheat as part of an irrigated farming system with this water quality.

Conversely, the areas of lowest risk ($CP < 0.4$) are mostly associated with the area southwest of Spring Plains Road and associated with the sandier soil types associated with the prior stream channels, which runs in this general direction and past "Cudgewaa" and "Willawood." This is similarly the case southeast of Wee Waa at landholdings such as "Cumberdeen," and around the township of Pilliga, except at these locals the lower risk is due to the coarser sediments of the Pilliga Scrub Complex.

Figure 7 illustrates the likely risk areas if water of $EC_w = 9$ dS/m was applied and the EC_e cut-off value was 7.7 dS/m. It is clear, that the area surrounding Wee Waa exhibits the lowest risk. It is also evident that a corridor of low risk (i.e. 0.2 CP 0.4) runs in the same general direction as the Kamillaroi Highway from Wee Waa in a west-northwesterly direction to Burren Junction and thence onto Bugilbone. The reason for this is that a prior stream channel of the Namoi River generally also runs in this direction (see Figure 2). As mentioned previously, the soil here is generally coarser textured and therefore generally lower in soluble salts (e.g., Na, etc.,) as compared with the clay alluvial plains. Consequently, this part of the landscape is likely to be more freely draining and hence possesses a lower risk of accumulating salts applied with saline irrigation water than the clay alluvial plains. Conversely, it is clear that many of the larger and medium size farms in the area would require some form of management if this water quality was used as concentrations of salt in the soil would exceed the critical levels for even salt tolerant crops such as cotton ($EC_e > 7.7$ dS/m).

Discussion

Soil, water and crop management strategies

There are several strategies that can be employed if the water quality diminishes to moderately saline levels (i.e. $EC_w = 4-9$ dS/m) or soil salinity becomes a problem in an irrigated area. These can be broken down into three main management strategies, namely soil, water and crop (Rhoades *et al.*, 1992). In terms of soil management the suitability of soil for cropping depends principally on its ability to conduct water and air and on aggregate properties that control friability of the seedbed. As such the preparation of the soil and its condition prior to germination is of critical importance to crop germination and productivity. In order to ensure optimal conditions a number of soil management considerations are of importance particularly in an irrigated system. Some of these include land preparation, the use of ameliorants, mulch and seedbed orientation.

Land Management: Land preparation is critical in preparing soil that is to be flood irrigated. Care should be taken at the land planning stage of development to ensure that a uniform grade is achieved across the field. This will produce an area of land that will have a more uniform water application and as a result better salinity control

Seed bed design: Despite the preparation of a uniform grade, problems may arise in the seedbed due to the movement of salts during wetting of the soil by furrow irrigation. Salts in low concentrations within the irrigation water and the soil will be mobilised and concentrated in particular areas of the seedbed. Therefore, it is critical to ensure that the design of the seedbed and the subsequent placement of the seed is not where salts will concentrate after water application

Ameliorants: When considering sodic soil profiles particularly those affected at the soil surface, crusting and consolidation of the soil will occur and may prevent seed

emergence. The most commonly used ameliorant is gypsum, particularly for sodic soil reclamation and when using saline water with a high SAR value for irrigation. Calcium chloride, a highly soluble molecule, would also be a satisfactory ameliorant especially when added to irrigation water. The ameliorants are usually applied to either neutralise soil reaction (decrease pH of an alkaline soil), or exchange sodium and with calcium. As a result of these ameliorants improve the water entry and storage of the soil with the removal of salts, a desirable effect in the long term. The maintenance of large amounts of organic material at the surface will also maintain good soil tilth.

In terms of water management, the most important considerations for salinity control in irrigated schemes are frequent irrigations, adequate leaching, drainage and water table depth control. In any irrigation scheme the efficient transport, application and reuse of water is also of paramount importance, since it is these processes, which can seriously impact the long-term sustainability of the system.

On farm irrigation: General improvements in salinity control can be made from maximizing on-farm irrigation efficiency. This is achieved by supplying the necessary amount of water at the appropriate time with high uniformity. The ideal irrigation scheme should provide water more or less continuously to the growing crop to match evapotranspiration losses and to keep water content in the root zone within narrow limits. Continual irrigation will reduce salt buildup around the growing roots ensuring a low osmotic potential in this volume of soil and optimal conditions for water and nutrient uptake.

Leaching: The earliest remediation of saline soil involved leaching by ponding water on the soil surface. To prevent the accumulation of salts in the root zone, irrigation must be sufficient to leach out harmful salts. At the same time accumulations of salt near the soil surface as a consequence of excessive irrigation, must be minimized. Salt will accumulate in the root zone as the plant extracts water necessary for growth. The removal of the water due to transpiration and evaporation creates the potential for water to flow upwards. This may lead to the steady accumulation of salts if a shallow saline water table begins to rise.

Irrigation Timing: The success of irrigation on a saline soil is heavily reliant on a sufficient irrigation strategy. The more frequent the irrigations the lower the osmotic stress the plant will encounter and the less chance there will be of salts accumulating near the developing root mass. Scheduling in this way will enable the depth of leaching water to be accurately determined and will prevent excessive deep percolation. More frequent irrigation will also tend to soften surface crusts on sodic soil and will encourage better stands.

Conjunctive water use: Often irrigators have access to two or more sources of water. The primary source may be river water, water from aquifers or water tables or even tail or drainage waters. Each will vary in levels of soluble salt. Therefore, each can be

utilised at different times with respect to the irrigation management of a particular crop. When the crop is most susceptible to salinity stress, at germination, good quality water can be used to ensure establishment. Subsequent irrigations may be facilitated with water of poorer quality where the plant is not nearly so sensitive to saline conditions. At crop maturation a return to the use of good quality water is used to leach out any undesirable or excess salts that may have accumulated and ensure that the crop is able to set satisfactorily.

Finally, there are various crop management options also available. The most important stage in crop growth is germination. In most cases it is the most sensitive growth stage and is crucial in terms of maximizing economic return. That is, optimal productivity is not possible without satisfactory establishment. The choice of crop as well as planting strategies can be used to great effect where the presence of excessive amounts of salts have the potential to reduce productivity.

Choice of Crop: The tolerance of plants to salinity varies between species and cultivars. Where salinity cannot be contained within suitable limits by leaching, selection of a particular crop of greater tolerance is suggested. Many sensitive crops can still be grown in soils of high salinity. This is achieved by nursing them through critical stages of growth, particularly at germination when plants are most vulnerable. Often as part of the management strategy temporary sprinklers are installed that enable the surface soil to remain constantly moist and free of the harmful effects of salt. Pre-irrigation to remove these salts can also be used to great effect. Surface irrigation is then applied to grow the established crop.

Planting techniques: In a furrow or seedbed that contains excessive amounts of soluble salts, concentrating these salts in parts of the seedbed away from the germinating crop is sufficient to enable establishment. Designing a seedbed or furrow may be accomplished by a simple alteration to existing tillage implements. The seeds are then planted on the sides of these furrow ridges away from the saline areas. Further, on replanting of an annual crop an effort should be made to place the seeds in that part of the seedbed where the previous years crop was grown. To ensure a good stand, plant density can also be increased to compensate for smaller plant sizes that occur under saline conditions.

Conclusions

This paper provides a step-by-step account on how the Salt and Leaching Fraction (SaLF) model in conjunction with non-linear methods of kriging was implemented to identify salinity risk for various worst-case scenarios in the lower Namoi valley. The results suggest the use of water of good quality ($EC_w = 0.4$ dS/m) drawn from the Namoi River does not pose as a threat to the irrigated-cotton farming systems as it may not result in potential increase in soil salinisation. If water of slightly lower quality ($EC_w = 1.5$ dS/m) is used there may be some cause for concern about the viability of growing *Dolichus*

Lab Lab and other sensitive leguminous crops in the area studied. This is particularly the case for the irrigation farms located in the clay alluvial plains, where large amounts of sodium are stored. As a consequence this is likely to impede deep drainage and hence cause salts to accumulate in the root zone.

Further, if water of even lower quality is used ($EC_w = 4$ or 9 dS/m), the worst-case scenarios eventuate. Potential threat of soil salinisation increases dramatically to levels where some management would be necessary in order to continue with the inclusion of wheat in the irrigated cotton farming system. The area to the northeast of Spring Plains Road is particularly vulnerable. Conversely, the areas associated with the prior-stream channels and the Pilliga Scrub (which runs along the southern border of the study area), potentially have a lower risk of accumulation of salts. However, the expected that deep drainage is higher and the saline water may contaminate the groundwater reserves. This would reduce management options to farmers who could use the good quality groundwater as currently exists in the valley.

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References

- Bowers, C.A. & Wilcox. L.V. 1965. Soluble Salts, Methods of Soil Analysis, Monograph 9:933-951. American Society of Agronomy, Madison Wisconsin.
- Coventry, R.J. & Fett. D.E.R. 1979. A pipette and sieve method of particle size analysis and some observations on its efficacy. CSIRO Australia Div. of Soils, Div. Rep., No. 38. CSIRO, Australia.
- Finke, P.A. & A. Stein. 1994. Application of disjunctive co-kriging to compare fertiliser scenarios on a field scale. *Geoderma*, 62, 247-263.
- Holmgren, G.G.S., Juve, R.L. & Geschwender. R.C. 1977. A mechanically controlled variable rate leaching device. *Soil Science Society of America Journal* 41, 1207-1208.
- McGarry, D., Ward, W.T. & McBratney, A.B. 1989. Soil studies in the Lower Namoi Valley - methods and data 1: The Edgeroi Data Set. CSIRO, Australia, Division of Soils.

- Murray-Darling Basin Ministerial Council. 1999. The Salinity Audit of the Murray-Darling Basin. Murray-Darling Basin Commission. Canberra.
- Rivoirard, J. 1994. Introduction to Disjunctive Kriging and Non-Linear Geostatistics, Clarendon Press Oxford.
- Rhoades, J.D., Kandiah, A. & Mashali, A.M. 1992. The use of saline waters for crop production. FAO irrigation and Drainage Paper 48, pp 133.
- Rose, C.W., Dayanada, P.W.A., Nielson, D.R. & Biggar, J.W. 1979. Long term solute dynamics and hydrology in irrigated slowly permeable soils. *Irrig. Sci.* 1, 77-87.
- Shaw, R.J. & Thorburn, P.J. 1985. Prediction of leaching fraction from soil properties, irrigation water and rainfall. *Irrigation Science*, 6, 73-83.
- Stannard M.E. & I.D. Kelly. 1977. The irrigation potential of the lower Namoi valley. Water Resources Commission, New South Wales, Australia.
- Triantafyllis, J., Laslett, G.M. & McBratney, A.B. 2000. Calibrating an electromagnetic induction instrument to measure salinity in soil under irrigated cotton. *Soil Science Society of America Journal*, 64, 1009-1017.
- Triantafyllis, J., Ward, W.T., Odeh, I.O.A. & McBratney A.B. 2001a. Creation and interpolation of continuous soil layer classes in the lower Namoi valley. *Soil Science Society of America Journal*, 65, 403-413.
- Triantafyllis, J., Odeh, I.O.A. and McBratney. A.B. 2001b. Five geostatistical models to predict soil salinity from electromagnetic induction data across irrigated cotton fields. *Soil Science Society of America Journal*, 65, 869-878.
- Triantafyllis J Ward WT Odeh IOA & McBratney AB 2001c. Land suitability assessment in the lower Namoi valley of Australia, using a continuous model. *Australian Journal of Soil Research* 39, 273-290.
- Tucker, B.M. (1974). Laboratory procedure for cation exchange measurements in soils. CSIRO Division of Soils, Technical Paper No 23. (CSIRO, Australia).
- United States Salinity Laboratory Staff (1954). 'Diagnosis and improvement of saline and alkali soils.' US Department of Agriculture handbook No. 60, (US Government Printer: Washington).
- Wood, G., Oliver, M.A. & Webster, R. 1990. Estimating soil salinity by disjunctive kriging. *Soil Use and Management*, 6, 97-104.
- Webster, R. & Oliver, M.A. 1989. Optimal interpolation and isarithmic mapping of properties. VI. Disjunctive kriging and mapping the conditional probability. *Journal of Soil Science*, 40, 497-512.
- Yates, S.R. & Yates, M.V. 1988. Disjunctive kriging as an approach to management decision making. *Soil Science Society of America Journal*, 52, 1554-1558.
- Yates, S.R., Warwick, A.W. & Myers, D.E. 1986a. Disjunctive kriging 1, Overview of estimation and conditional probability. *Water Resources*, 22, 615-622.
- Yates, S.R., Warwick, A.W. & Myers, D.E. 1986b. Disjunctive kriging 2, Examples. *Water Resources*, 22, 623-630.
- Yates, S.R. 1986. Disjunctive kriging 3, Co-kriging. *Water Resources*, 22, 1371-1376.