An investigation of solar evaporation pond leakage and possible remedial measures at Sua Pan, Botswana.

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Mechanisms responsible for subsurface leakage of soda ash solute from a solar evaporation pond complex have been identified. A two-dimensional (MODFLOW) groundwater flow model of the system has been constructed and successfully calibrated. This model, along with costing information, has been used to assess the cost effectiveness of various remedial options.

1. INTRODUCTION

Botswana Ash (Pty) Ltd. is a soda ash (Na_2CO_3) production operation located at Sua Pan in central eastern Botswana (Figure 1). Brine is extracted from the former lakebed sediments, concentrated in an extensive system of solar evaporation ponds where common salt (NaCl) precipitates, and pumped to on-site facilities for soda ash refinement. Analysis of operational data suggested that c.40% of soda ash solute was lost through subsurface leakage of brine during transit through the solar pond complex (1997-98). Reduction of solar pond leakage was viewed as an option for realising a planned increase in total soda ash production. Water Management Consultants Ltd. (WMCL) were commissioned to investigate and characterise subsurface leakage dynamics, and to define and assess the cost effectiveness of a range of remedial options.

Sua Pan forms the easternmost part of the Makgadikgadi area, a basin of internal drainage 200 km south east of the Okavango Delta. The pan is a large (3,000 km^2) very flat area with at least 60 m of fluviatile sediments (Kalahari Beds) underlain by the Ntane Sandstone. Subsurface brines are thought to have formed by simple evaporation of influent water over a long period (Houston, 1989).

Figure 2 shows the spatial arrangement and operation of the solar pond complex. Brine is pumped from the wellfield into the CS-pond where it is stored temporarily and used for plant cooling. From here it is directed around the outer E-pond circuit, where primary evaporation occurs, and into the X-ponds where precipitation and harvesting of common salt takes place. Soda ash-rich brine is stored in the ST-ponds before removal to the on-site refinement facility.

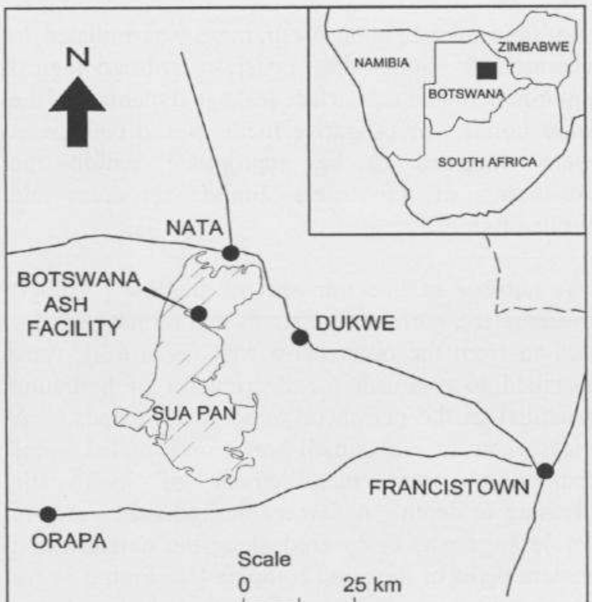

Figure 1 Location map

The berm walls which contain the solar ponds were constructed entirely with on-site materials. Figure 3a is a typical cross-section through one of these walls. It shows the large borrow trenches, excavated below the original ground surface, from which material was taken.

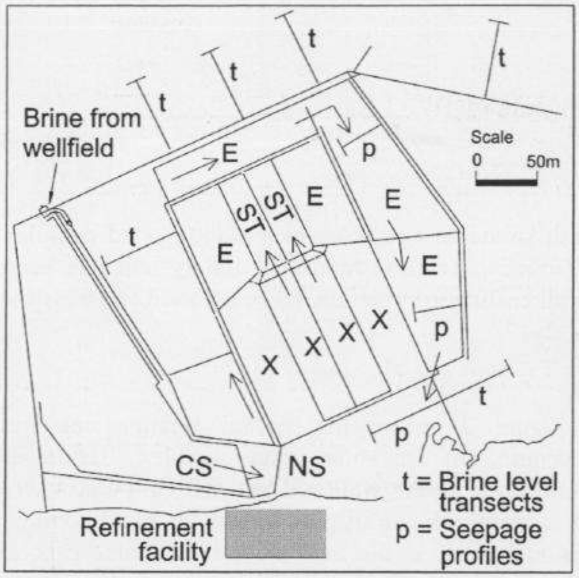

Figure 2 Solar pond complex

2 FIELD INVESTIGATIONS

A field investigation programme was initiated to characterise both the general hydrogeological environment and subsurface leakage dynamics of the solar ponds. Investigative methods and equipment were designed to be appropriate within the constraints of remoteness, limited resources and limited time.

A number of line transects of shallow (2 mbgl) piezometers, radial to the ponds and running out for 700 m from the outer berm wall (Figure 2), were installed to establish the distribution of hydraulic potential in the peripheral zone to the ponds. A piezometer is a small-bore open-ended pipe facilitating point measurement of hydrostatic pressure at depth. A favourable hydraulic gradient for leakage was discovered along the northern and eastern walls of the pond complex (see Figure 3e for typical examples), suggesting that leakage was concentrated under this 7.5 km length of outer berm wall. Combined with the results of the analysis of operational data, this suggested that brine was leaking from the ponds at a rate of 137 m^3/100 m (outer berm wall)/day. This figure was sensitive both to the percentage of soda ash co-crystallising with common salt in the X-ponds and to the brine concentration at which leakage takes place. Re-measurement of brine levels on a bi-monthly basis has proved that subsurface brine levels fall significantly during the dry season (March to September).

Seepage meters were constructed on-site from available materials (Figure 4). The principal of these meters is that a small area (0.25 m^2) of pond bed is physically, but not hydraulically, isolated from the larger pond. Displacement of fluid through pond bed seepage causes an equivalent change in the volume of an attached flexible bladder. Using initial and final bladder volumes, the pond bed seepage rate can be calculated (Lee & Cherry, 1978). Seepage meters were placed in lines running from the outer berm wall into the E-ponds, in order to develop longitudinal seepage profiles. Downward seepage was high (2 mm/d) close to the outer berm wall, reducing to less than 0.1 mm/d in the centre of the ponds (see Figure 3e for a typical example).

In-situ hydraulic conductivity was measured by hydraulic testing in shallow hand-augered holes close to the pond complex.

3 NUMERICAL MODELLING

3.1 Conceptual model

A conceptual model was developed using available information, including previous reports on the geology and hydrogeology of the area. It was established that the local shallow geology was a complex system of layered sands, silts and clays, with ancient desiccation cracking in near-surface (<2 mbgl) layers. Figure 3b shows the two-dimensional conceptual model of subsurface leakage dynamics at the solar ponds. A hydraulic gradient across the outer berm wall was recognised to exist. Brine levels within the ponds are maintained at 0.4 m above the original pan surface. Brine levels immediately outside the ponds are typically 0.5 m below the original surface of the pan, maintained at this level, or below, by evaporation.

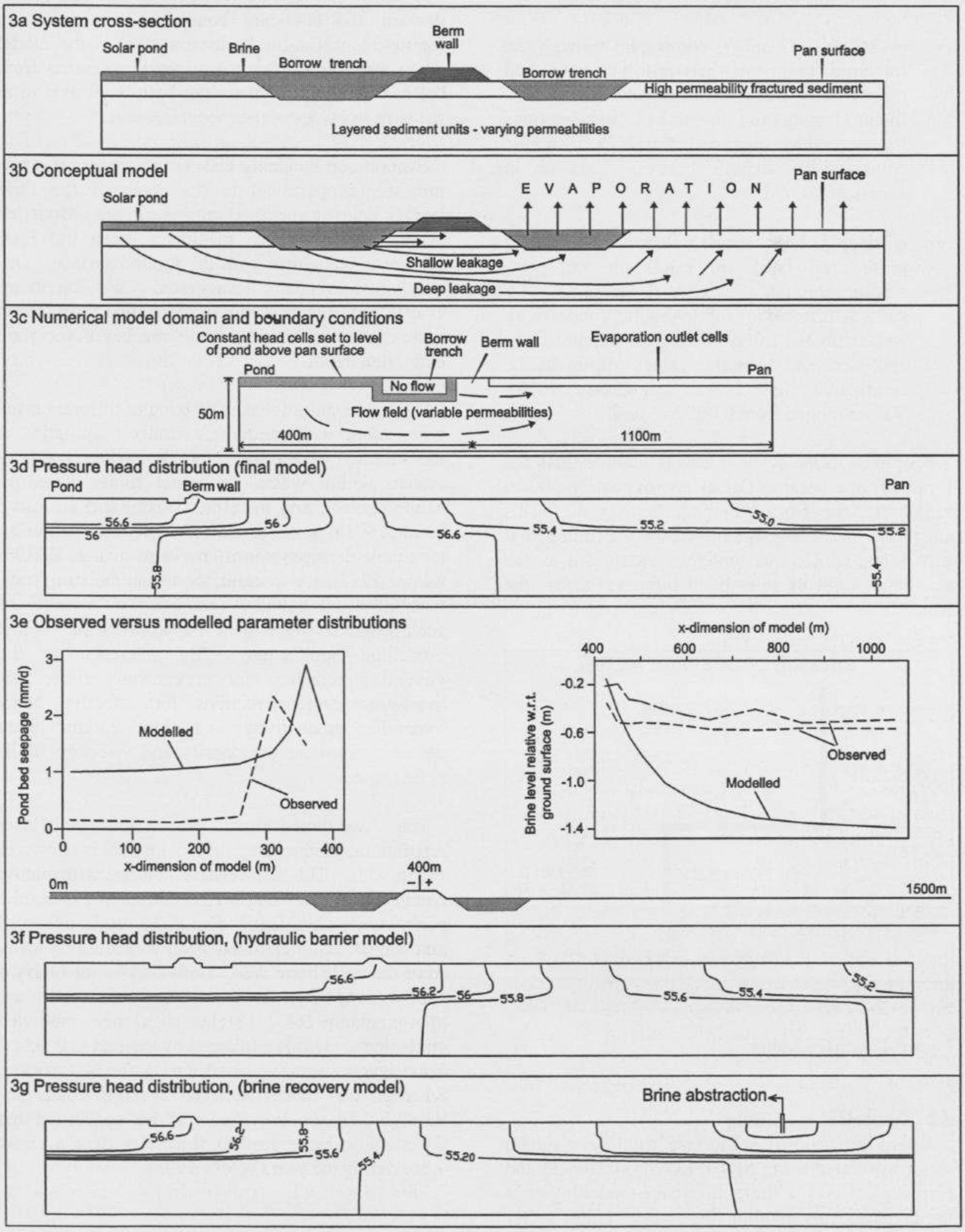

Figure 3 Two dimensional system representations

Two components of leakage were postulated;

- a shallow (0-2 mbgl) component through the fractured sediments between the inner and outer borrow trenches of the outer berm walls. In-situ testing and theoretical considerations (Snow, 1968) suggested that bulk hydraulic conductivities in this horizon could be in excess of 50 m/d.

- a deep (2-50 mbgl) component through unfractured layers of sand, silt and clay, seeping through the base of the ponds. A vertical distribution of hydraulic conductivity was estimated using lithological borehole logs and accepted generic values of hydraulic conductivity (e.g. Freeze and Cherry, 1979). Values ranged from 0.005 to 5 m/d.

Peripheral brine level transects showed that the brine surface became flat at approximately 600 m radial distance from the outer berm wall. This suggested that subsurface brine flow was minimal at this point, which was therefore interpreted as the maximum limit of solar pond influence across the pan.

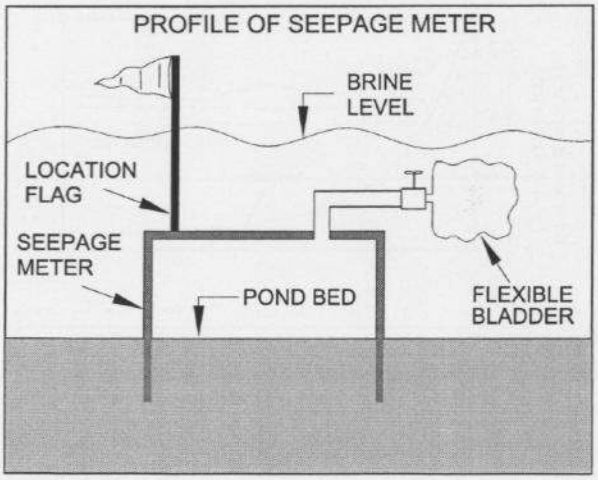

Figure 4 Seepage Meter

3.2 Numerical modelling

A two-dimensional subsurface fluid flow model was constructed using MODFLOW (McDonald and Harbaugh, 1988), a finite-difference modelling code used extensively within the water industry for groundwater flow modelling.

A steady-state model was developed. The model domain and boundary conditions are shown in Figure 3c. Non-linear discretisation of the model space was employed with cell sizes increasing from 0.1 m directly under the outer berm wall to 5 m at the base and sides of the model.

Evaporation boundary cells remove water at a rate inversely proportional to the depth of the fluid surface below a specified ground surface. Modelled evaporation reaches a maximum when the fluid surface is coincident with the ground surface. On-site measurements suggested a maximum evaporation rate of 8 mm/d. Modelled evaporation ceases when the fluid surface reaches a specified extinction depth.

It was recognised that the mixing of different brine types, along with continuous surface evaporation in the vicinity of the solar ponds, would create a system within which interstitial fluids varied in solute content, and therefore density and viscosity. Ideally, this type of system would be modelled using a variable density/viscosity package such as HST3D (Kipp, 1987). At present, however, the run times, instability and boundary condition inflexibility of such programs make them inappropriate for routine modelling application. By reference to the governing equations for groundwater flow, pre-/post-processing corrections for effective head, hydraulic conductivity and flow volume were defined, based on the density and viscosity of E-pond brine.

The two-dimensional brine pressure head distribution produced by the final model is shown in Figure 3d. The non-regular contour distribution results from the marked variation in hydraulic conductivity with depth. Figure 3e shows observed and modelled longitudinal head distributions away from the outer berm wall. Both distributions have a similar shape but brine levels in the field are approximately 0.4 m higher than their modelled equivalents. This is explained by the fact that actual brine levels were measured during the wet season, whereas the model reflects average conditions through the year. Previous work has confirmed that the shallow brine surface fluctuates over at least 1.5m during the year (WMC, 1998).

Figure 3e also shows observed and modelled pond bed seepage profiles across the E-ponds. The profiles have similar shapes and maximum seepage values. However, the model slightly over-estimates seepage towards the middle of the ponds.

The model predicted a brine seepage rate ($122\ m^3/100$ m/day) within 11% of the calculated actual value. The remaining unaccounted leakage amounts to a brine seepage rate of 0.2 mm/d over the non-modelled central area of the pond complex. Leakage dynamics as interpreted from the model showed that 42% of leakage was occurring through shallow (0-1.6 mbgl) layers between the inner and outer borrow trenches, with the remaining 58% through deeper layers. Pond leakage was concentrated close to the outer berm wall within the ponds, and evaporative losses were highest close to the berm wall outside the ponds. Sensitivity analysis showed that model dynamics were most influenced by changes in the ratio adopted for horizontal:vertical hydraulic conductivity (K_h:K_v).

4 REMEDIAL OPTION ASSESSMENT

4.1 Remedial options

Four generic strategies for remediation were proposed;

- Vertical barrier: construction of a vertical low- or zero-permeability curtain in line with and beneath the outer berm wall. Barrier types included clay-filled trench, sheet piling and grout curtain, installed to various depths.
- Pond lining: impermeabilisation of various critical areas of solar pond bed using synthetic membranes or puddled clay.
- Hydraulic barrier: establishment of a balancing hydraulic head adjacent to the outer berm wall using the fluid waste stream from the refinement facility.
- Recovery: installation of boreholes and pumps outside the solar ponds to recover lost brine.

The option of realising the required increase in soda ash production by augmentation of primary brine extraction was also considered.

4.2 Cost-benefit analysis

Preliminary cost-benefit analysis was performed on each of the remedial options within the four generic strategies. Physical effectiveness (leakage prevented) was predicted using the numerical model. For none of the options were disproportionate operating costs anticipated, so construction costs only were assessed in order to establish a relative cost-benefit ranking.

Table 1 presents the results of the cost-benefit analysis, ranked by cost-effectiveness (benefit/cost). For realisation of the required increase in soda ash production, approximately 45% leakage prevention was required.

Table 1
Results of the cost-benefit analysis

Remedial option	Leakage prevented (%)	Benefit/ cost
Hydraulic barrier	53	23.0
Recovery at 4 mbgl*	64	5.8
Recovery at 8 mbgl*	63	4.8
Recovery at 15 mbgl*	51	3.4
Line borrow trench	10	1.5
Membrane to 100 m$^{\Delta}$	35	1.1
Slurry trench to 10 mbgl*	26	0.9
Slurry trench to 5 mbgl*	22	0.8
Membrane to 200 m$^{\Delta}$	50	0.6
Slurry trench to 20 mbgl*	61	0.6
Slurry trench to 2 mbgl*	4	0.5
Augment brine extraction	(45)	0.4
Membrane to 50 m$^{\Delta}$	24	0.3

* vertical depth
$^{\Delta}$ distance into E-pond from outer berm wall

The preliminary cost-benefit analysis revealed that the hydraulic barrier and brine recovery options were the most cost-effective. Except for these, only the installation of a slurry trench to 20 mbgl, a very expensive operation, produced the required leakage prevention effectiveness. Augmentation of primary brine extraction sufficient to meet the planned increase in production is the most expensive option by some margin.

Figures 3f and 3g show the model-predicted brine pressure head distribution for the hydraulic barrier and brine recovery (at 4 mbgl) remediation options. Sensitivity analysis of these models showed that in both cases the remedial effectiveness varied directly with the value adopted for K_h:K_v. A conservative approach of adopting the lowest likely value for K_h:K_v will be adopted in future modelling.

5 CONCLUSIONS

- 40% of soda ash solute is lost through subsurface leakage during transit through the solar pond complex.
- The planned increase in soda ash production could be realised by a 45% reduction in solar pond brine leakage.
- The most cost-effective options which result in sufficient saving of brine to realise the planned increase in production are a hydraulic barrier and brine recovery.
- MODFLOW has been successfully utilised to model a complex, small-scale system in two-dimensions.

6 FUTURE WORK

The preliminary cost-benefit assessment has narrowed the range of viable remediation options significantly. Future work is expected to include most or all of the following;

- Optimisation of remedial option designs using the numerical model. For example, the effectiveness of the hydraulic barrier option varies with the width of the peripheral balancing pond. Three-dimensional optimisation of the recovery option for borehole position and pumping rate will be required.
- Refine costings and include ongoing operational costs.
- Investigate the practicality and sustainability of the favoured options. The hydraulic barrier option places waste stream fluids in close proximity to uncontaminated brines. Both the significance and likelihood of contamination must be assessed. The recovery option promotes more gross leakage of brine from the E-ponds whilst producing a net reduction in leakage. The possibility of inducing an increase in the bulk hydraulic conductivity of subsurface materials, thus reducing the net effectiveness of the technique over time, must be investigated.
- Establish field-scale pilot remediation trials.

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