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Management of treated pulp and paper mill effluent to achieve zero discharge

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Abstract

Pulp and paper mills are one of the major effluent generating industries in the world. In most cases, mill effluent (treated or raw) is discharged back into a river, creek, stream or other water body; resulting in negative environmental impacts, as well as social concerns, among the downstream users. Pulp and paper mill effluent management, which could result in zero discharge into downstream water bodies, would present the best management option to address socio-environmental concerns. This paper presents such an effort aimed at closing the water cycle by using treated effluent from the mill to irrigate forage and fodder crops for producing animals feed. The treated effluent is delivered from the mill through gravity into a winter storage dam of 490 ML capacity. For irrigation applications on 110 ha of farmland, which is 42% of the total farmland, the water is pumped from the winter storage dam to five individual paddocks with Centre Pivot (CP) irrigators and one rectangular paddock with a Soft Hose Travelling (SHT) irrigator. From October 2001 to June 2006, a total of 2651 mm of wastewater was applied at the farm. The impact assessment results, obtained from field monitoring, investigations and analysis, indicated that the closed water cycle effluent management strategy described had resulted in a lessening of the impact on water resources usually associated with paper mills. However, social attitudes to the use of crops that have been irrigated with recycled waters and the resulting impact on market value of the produce may still be a major consideration.

Keywords: Paper mill; Effluent reuse; Zero discharge; Stream flows; Groundwater pollution; Closed water cycle; Soil contamination; Irrigation

1. Introduction

In terms of freshwater use, the pulp and paper making industry is a very water intensive industry; it is ranked third in the world after primary metals and chemical industries. The volume of effluent generated and its characteristics are normally governed by the technology adopted, the effectiveness of the treatment process and the amount of treated effluent recycled. Thus, a pulp and paper mill generates as low as 1.5 m^3 of effluent per tonne of paper produced (Szolosi, 2003) to as high as 60 m^3/tonne of paper produced (Thompson et al., 2001). In most cases, this effluent (treated or raw) is discharged back into a river, creek, stream or other water body; resulting in negative social and environmental impacts downstream. Urged by environmental and legislative pressure, together with improved techniques and commitment from industry leaders, the pulp and paper industry has reduced its environmental impacts to air, water and land by 80–90% over recent decades (Thompson et al., 2001); still this industry faces considerable challenges to reduce environmental pollution and human risks.

Within the pulp and paper mills, the practice of recycling a certain degree of water is commonplace. Recycling is achieved by closing up systems through the promotion of the process waters in the production cycle (Wiseman and Ogden, 1996). Thus, both the consumption of freshwater and the production of effluent are reduced. An alternative approach is to treat the effluent to such an extent that it can be reused within the mill (Norris, 1998). Both the recycling and reuse of water can increase the concentration of organic and inorganic pollutants, which in turns can affect paper formation, increase bacterial loading, or lead to corrosion and odours (Robertson and Schwingel, 1997). Therefore, a certain amount of effluent has to be managed or

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reused outside the pulp and paper mill; but if such practice is not properly monitored and managed, contamination of the produce, soil, groundwater and any other water body adjacent to the effluent reuse area could still be a concern (Fazeli et al., 1998; Dominguez-Mariani et al., 2003).

The effects of pulp and paper mill effluent on soils and crops has been documented, mostly dealing with agricultural soils irrigated with raw effluent in developing countries, like India (Juwarkar and Subrahmanyam, 1987; Fazeli et al., 1991, 1998; Kannan and Oblisami, 1990; Phukan and Bhattacharyya, 2003). The closed water cycle impact assessment of treated pulp and paper mill effluent has not been widely reported. This paper presents results of such an impact assessment on an agricultural farm that was located adjacent to a natural creek and was dependent on treated effluent from the mill to irrigate forage and fodder crops for animal feed. In the process of evaluating the irrigation system performance; particular emphasis was given to management issues concerning effluent reuse and its impact on the soil and groundwater under the effluent irrigated area and on the adjacent creek.

2. The study area

The studied pulp and paper mill currently produces 240,000 tonnes of paper per annum consuming over 800,000 tonnes of local pine plantation pulp wood and sawmill residues per annum. The raw materials are further supplemented with up to 60,000 tonnes per annum of domestic and commercial wastepaper, to produce high-quality 'kraft' linerboard paper. The freshwater consumption of this mill is 5.5 m^3/tonne of paper produced, while its effluent discharge is only 1.5 m^3/tonne of paper produced. Before diverting this wastewater for effluent irrigation at the farm, this effluent is treated in the Waste Water Treatment Plant (WWTP). This WWTP is a sequencing batch reactor with a biological nutrient removal activated sludge process. The sludge from the WWTP, the lime mud from the lime kiln, and the ash from the boiler is used as a combined fertiliser for the soil.

The treated effluent is then delivered from the mill through a 250 mm diameter pipeline, under gravity into a Winter Storage Dam (WSD). Current capacity of the winter storage dam is 490 ML, which was sized based on the annual effluent generation from the mill and a 90 percentile wet year design inflow. The treated effluent in the WSD is then used for irrigating pasture (forage and fodder) crops for silage and hay production. The farm also incorporates around 2000 head of cattle. For irrigation applications on 110 ha of farmland, which is 42% of the total farmland, the water is pumped from the WSD to five individual paddocks with Centre Pivot (CP) irrigators and one rectangular paddock with Soft Hose Travelling (SHT) irrigator. Table 1 describes the main features of effluent reuse paddocks.

Historic climatic records for the study area show a potential evaporation deficit exists from October till April (Fig. 1). For the months of September and May, rainfall equals potential evaporation; allowing very little scope for

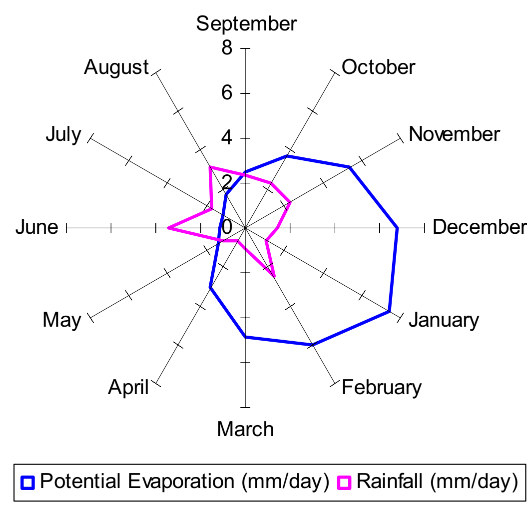

Fig. 1. Average daily rainfall and potential evaporation in the study area.

Table 1
Salient features of the wastewater reuse paddocks

Paddocks	Per single rotation					
	Area (ha)	Radius (m)	Flow rate (L/s)	Time (h)	Application quantity	
					(mm)	(ML)
Central Pivot (CP) paddocks						
CP 1	28.27	300	39.40	5.60	2.81	0.79
CP 2	12.06	196	16.80	3.50	1.73	0.21
CP 3 (high flow)	25.70	286	35.80	5.60	2.81	0.72
CP 3 (low flow)	25.70	286	17.30	5.60	1.36	0.35
CP 4 (high flow)	16.60	230	23.24	4.48	2.21	0.37
CP 4 (low flow)	16.60	230	17.30	4.48	1.65	0.27
CP 5	10.18	180	16.90	3.36	1.92	0.20
Rectangular paddock for Soft Hose Travelling (SHT) irrigator						
SHT single setting	3.24		15.50	12.00	20.67	0.67
SHT all area	17.50		15.50	64.81	20.67	3.62

irrigating crops. In winter (June–August) rainfall exceeds potential evaporation and hence there was no scope for irrigation and runoff was collected in the winter storage dam. The period starting from May till September provides a natural opportunity for leaching salts away from the root zone, since rainfall exceeds potential evaporation.

3. Materials and methods

The whole wastewater reuse operation is strictly monitored: (i) wastewater irrigation monitoring, (ii) soil monitoring, (iii) groundwater monitoring, and (iv) plant tissue monitoring. Fig. 2 shows the study area, and presents an overview of the monitoring network installed at this farm to monitor the surface and groundwater flows and salt status.

Information regarding the quality and quantity of effluent discharged from the WWTP to the WSD was recorded. The inclusion of WSD in the adopted effluent management strategy is an excellent provision to improve the quality of effluent. If effluent is diluted before irrigation applications with a 3:1 ratio of freshwater to effluent, the resulting mix

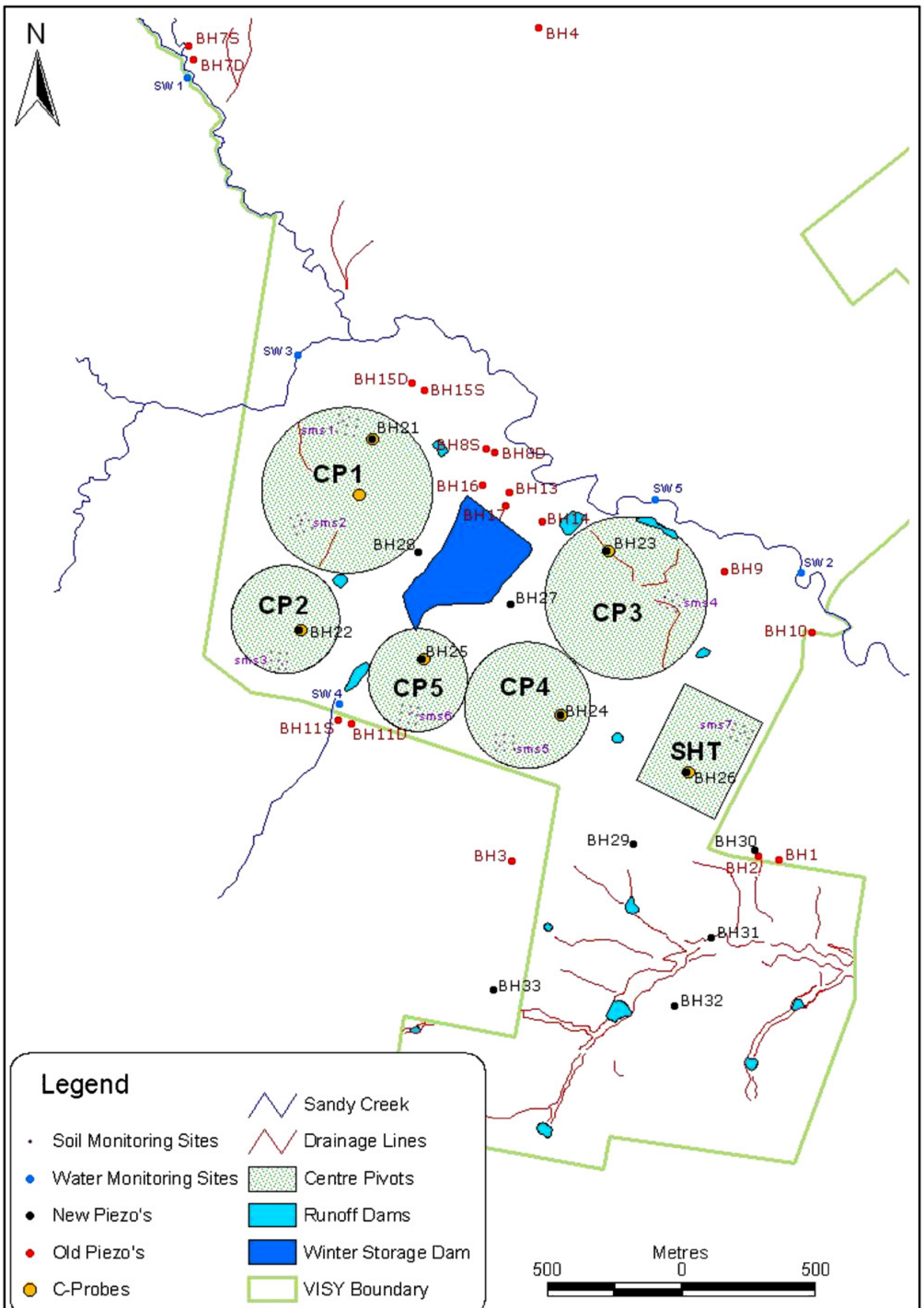

Fig. 2. Map of the study area.

could be successfully used for irrigating crops without increasing the soil exchangeable sodium percentage (Juwarkar and Subrahmanyam, 1987). To release the groundwater pressure under the WSD, a series of subsurface drains were constructed beneath the clay liner. This will help avoiding the entry of groundwater inflows into the WSD.

To monitor the quantity of effluent used for irrigation applications, a logged flow metre is installed on each centre pivot. Every paddock has one C-probe installed, except for CP 1 where there are two C-probes. These probes monitor volumetric moisture contents at 10, 30, 50 and 100 cm depths in the soil profile. A 30×30 grid was used to collect a composite soil sample at each soil monitoring location in every paddock. In accordance with the EPA licence conditions, topsoils (0–10 cm) were monitored on an annual basis, and subsoil (30–100 cm) on a 3 yearly basis. To keep consistency in the temporal monitoring results, the same area was used, within each paddock, at each soil sampling. Once collected, these soil samples were analysed for electrical conductivity (EC), exchangeable sodium percentage (ESP), pH, cation exchange capacity (CEC), Emerson Aggregate Test (EAT) and organic matter.

To observe the groundwater dynamics resulting from irrigation applications and rainfall at each paddock, a number of shallow and deep piezometers had already been installed at the farm. In this study, creek flows were also observed at five different locations: (i) upstream at SW 1 and SW 3 before entering the farm, (ii) upstream of the winter storage dam at SW 4 for observing flows coming from the neighbouring farm, (iii) downstream of the winter storage dam at SW 5, and (iv) downstream of the creek at SW 2 after leaving the farm.

The concentration levels of arsenic, cadmium, chromium, copper, lead, mercury, nickel, manganese and zinc were periodically monitored. Particular emphasis was given to concentration levels of these heavy metals and trace elements in irrigation effluent, surface runoff dams, winter storage dam, top soil surface (0–15 cm) of the different paddocks, underlying groundwater, and at different locations on the adjacent creek. In the case of groundwater, concentrations of these heavy metal and trace elements were monitored for areas: (i) outside the effluent reuse paddocks, (ii) around the winter storage dam, and (iii) under the effluent reuse paddocks.

4. Impact assessment

4.1. Wastewater applications

The study area has been under wastewater reuse since October 2001. Mainly irrigated pasture (forage and fodder) crops were grown. The summer crops include maize and forage sorghum; and clover, forage wheat, triticale, oats and ryegrass were grown in winter season. Initially, oats has been the main crop, but now, as part of new cropping rotation, ryegrass and forage wheat are being grown in winter, whereas lucerne would predominantly be the summer crop. A summary of the wastewater application data starting from October 2001 to June 2006 is given in Table 2. During this period, a total of 2651 mm of wastewater was applied on different wastewater reuse paddocks at the farm.

4.1.1. Comparing wastewater application, rainfall and evapotranspiration

Fig. 3 presents the monitored daily wastewater applications against the observed rainfall and the estimated evapotranspiration for all the paddocks during July 2002–June 2006. In case of CP 1 and CP 2, wastewater applications do coincide with the temporal crop water requirements but trends are also observed where wastewater applications were more than the crop water requirements. Where as for CP 3 and CP 4, the wastewater applications occasionally follow the temporal crop water requirements; however generally wastewater applications were more than crop water requirements. On the other hand, for CP 5 and SHT, the temporal wastewater applications do not generally follow the crop water requirements.

During July 2002–June 2006, rainfall was around 2427 mm in the study area, which corresponds to around 40% of the total crop water requirements on all the paddocks (Table 3). Including rainfall into the irrigation schedule would have an additional advantage of increasing efficiency for leaching of salts below the root zone. Salts require time to get dissolved, depending upon their chemical properties, before leaching below the root zone. If irrigation is scheduled after rainfall, which will help in

Table 2
Summary of wastewater applications to different irrigation paddocks during October 2001–June 2006

Irrigation season	Volume irrigated per Centre Pivots (CP) /Soft Hose Traveller (SHT) (in ML)					
	CP 1	CP 2	CP 3	CP 4	CP 5	SHT
Oct 2001–Jun 2002	135.00	56.51	135.27	111.68	60.70	0.00
Jul 2002–Jun 2003	99.25	80.42	102.94	129.17	47.01	0.26
Jul 2003–Jun 2004	157.40	43.61	171.45	42.60	43.36	109.15
Jul 2004–Jun 2005	200.33	85.10	111.86	67.00	79.37	71.45
Jul 2005–Jun 2006	180.48	81.11	55.38	103.56	64.08	25.76
Total	772.46	346.75	576.90	454.01	294.52	206.62

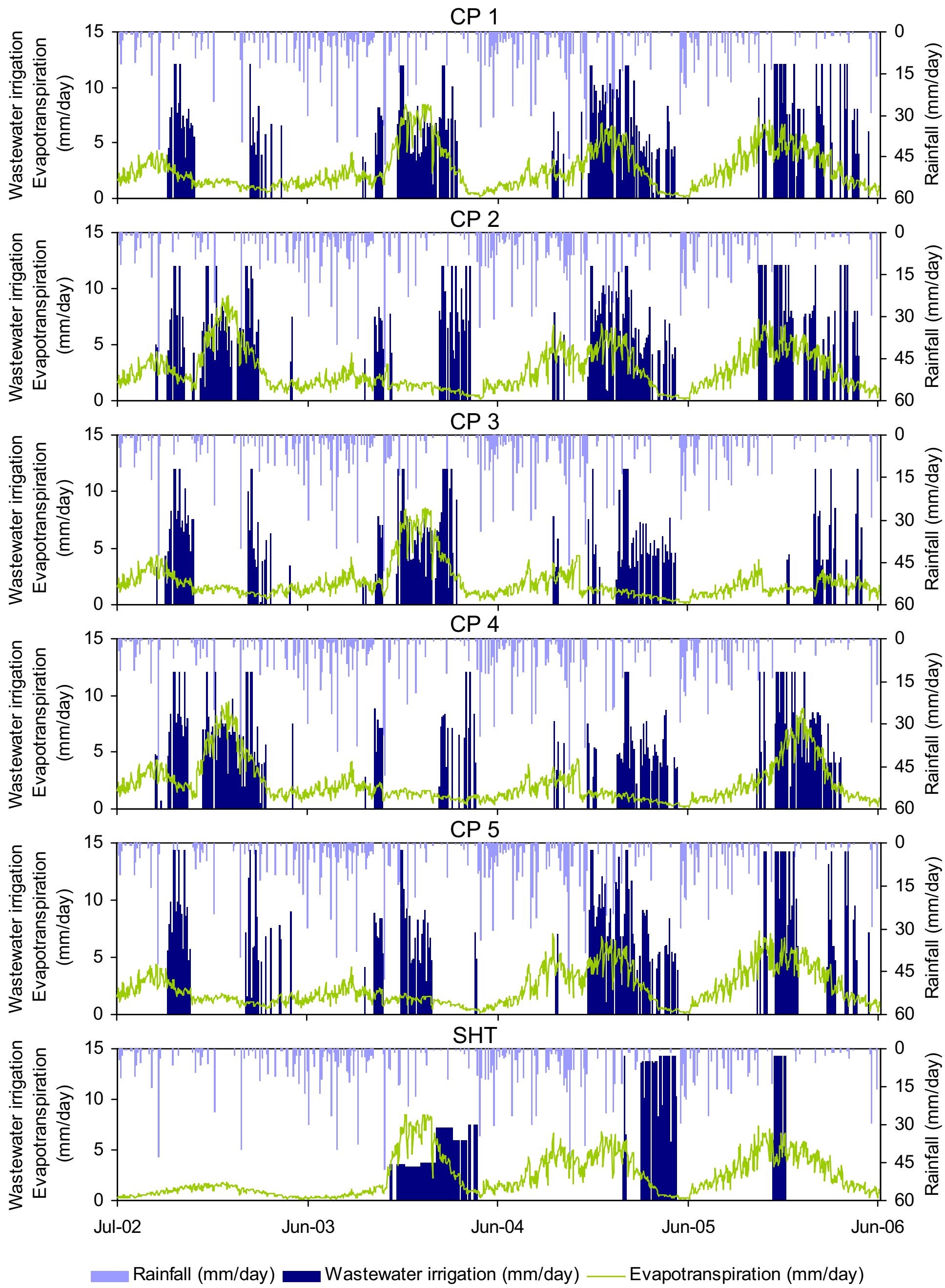

Fig. 3. Daily wastewater irrigation, rainfall and evapotranspiration for all the paddocks during July 2002–June 2006.

dissolving the salts in the root zone, then leaching efficiency of the applied irrigation will be increased.

4.1.2. Deep percolation incidences

Deep percolation is estimated while considering the soil capacity to hold water. The soil moisture above field capacity (FC) is estimated as deep percolation; negative values of deep percolation mean that there is still a capacity in the root zone to hold more water. The volumetric moisture content represents the depth soil moisture per depth of soil profile; therefore, for 1 m depth of root zone, the soil moisture and water holding capacity at any given time were estimated using volumetric soil moisture data observed from 10, 30, 50 and 100 cm soil profile depths:

$$\text{Root zone soil moisture (mm)} = \{(\text{C-Probe } 10\,\text{cm} \times 10) + (\text{C-Probe } 30\,\text{cm} \times 20) + (\text{C-Probe } 50\,\text{cm} \times 20) + (\text{C-Probe } 100\,\text{cm} \times 50)\} \times 10$$

$$\text{Soil water holding capacity (mm)} = \{(\text{FC } 10\,\text{cm} \times 10) + (\text{FC } 30\,\text{cm} \times 20) + (\text{FC } 50\,\text{cm} \times 20) + (\text{FC } 100\,\text{cm} \times 50)\} \times 10$$

where C-Probe 10 cm, C-Probe 30 cm, C-Probe 50 cm and C-Probe 100 cm are the observed volumetric moisture

Table 3
Monitored wastewater applications and observed rainfall against the estimated evapotranspiration under different paddocks during July 2002–June 2006

Irrigation paddocks	Hours of operation	Effluent applications (ML)	Rainfall (ML)	Evapotranspiration (ML)
		A	B	C
CP 1	4502	639	652	1067
CP 2	4775	289	278	474
CP 3	3412	436	593	733
CP 4	4082	340	383	539
CP 5	3850	234	235	337
SHT	3616	202	286	428

content at 10, 30, 50 and 100 cm depths of the soil profile. Similarly, FC 10 cm, FC 30 cm, FC 50 cm and FC 100 cm are the estimated FC for the soil profiles at 0–10, 10–30, 30–50, and 50–100 cm depths.

For soil moisture monitoring, a series of soil moisture probes were installed in 2001, however due to operational issues encountered with these probes, these probes were replaced with C-probes in June 2004. Every paddock has one C-probe installed, except for CP 1 where there are two C-probes. The calculated FC, permanent wilting point (PWP) and bulk density for different paddocks are presented in Table 4.

Fig. 4 presents daily changes in soil moisture at different depths in the root zone observed as compared to the soil capacity to hold water under different paddocks during November 2004–June 2006. This figure identifies incidences when deep percolation occurred (i.e., when soil moisture becomes greater than the soil moisture holding capacity in the root zone). Under every paddock, there are periods when the soil moisture status in the root zone is greater than the soil capacity, which may be due to the combined effects of rainfall and wastewater applications.

4.1.3. Water balance estimations

In this study, the guidelines of Allen et al. (1998) were used to compute the water balance for the root zone; however, capillary rise was considered negligible. Thus, the water balance for the root zone under different paddocks can be estimated as: $I+R=\mathrm{ET_c}+D+S\pm\Delta\theta$, where, I represents wastewater applications (ML), R is rainfall (ML), $\mathrm{ET_c}$ is crop evapotranspiration (ML), D is deep percolation (ML), S is surface runoff (ML), and $\Delta\theta$ is change in soil moisture storage in the root zone. Table 5 presents the summary of the different components of the water balance at different paddocks during November 2004–June 2006. In these water balance results, surface runoff was calculated as a balance parameter in the water balance equation.

During November 2004–June 2005, CP 2 and SHT were having 7% and 26%, respectively, less wastewater applications to meet the evapotranspiration from these paddocks.

Table 4
Soil physical properties under all the wastewater reuse paddocks

Soil profile	FC (cm/cm)	PWP (cm/cm)	Bulk density (mg/m^3)
CP 1			
0–10 cm	0.33	0.14	1.51
10–30 cm	0.35	0.23	1.44
30–50 cm	0.35	0.23	1.44
50–100 cm	0.38	0.26	1.42
CP 2			
0–10 cm	0.27	0.12	1.49
10–30 cm	0.27	0.12	1.49
30–50 cm	0.39	0.29	1.39
50–100 cm	0.39	0.29	1.39
CP 3			
0–10 cm	0.24	0.07	1.51
10–30 cm	0.29	0.17	1.53
30–50 cm	0.29	0.17	1.53
50–100 cm	0.36	0.19	1.42
CP 5			
0–10 cm	0.21	0.07	1.51
10–30 cm	0.24	0.07	1.53
30–50 cm	0.24	0.07	1.53
50–100 cm	0.35	0.23	1.44
SHT			
0–10 cm	0.24	0.07	1.51
10–30 cm	0.24	0.07	1.51
30–50 cm	0.26	0.10	1.50
50–100 cm	0.29	0.12	1.46

However, in case of CP 3, there was 47% more wastewater applied than the evapotranspiration requirements. Similar findings were found for CP 4 and CP 5, where there were 34% and 11%, respectively, more wastewater was applied than the requirements.

Such wastewater application practices would result in either deep percolation or surface runoff, which would endanger the environmental sustainability of effluent reuse for irrigation applications at the farm. Deep percolation was maximum under CP 3 (around 150 ML), followed by CP 1 (around 120 ML). The CP 2 and CP 5 have around 50 ML of deep percolation. The minimum deep percolation occurred under SHT (around 25 ML), which attributes to fact that minimum wastewater applications were made on this paddock.

Although, surface runoff occurred under all irrigation paddocks; it was minimal (i.e., 16 ML on an average from every paddock). When surface runoff occurs, contour banks in every paddock direct this water to runoff dams from where it is pumped back into the winter storage dam for reuse.

During July 2005–June 2006, less irrigation was applied compared to the evapotranspiration for all paddocks. Such wastewater application practices will obviously have minimum adverse environmental impacts at the farm, but if water applied does not meet the crop water requirements, crop yield would be affected.

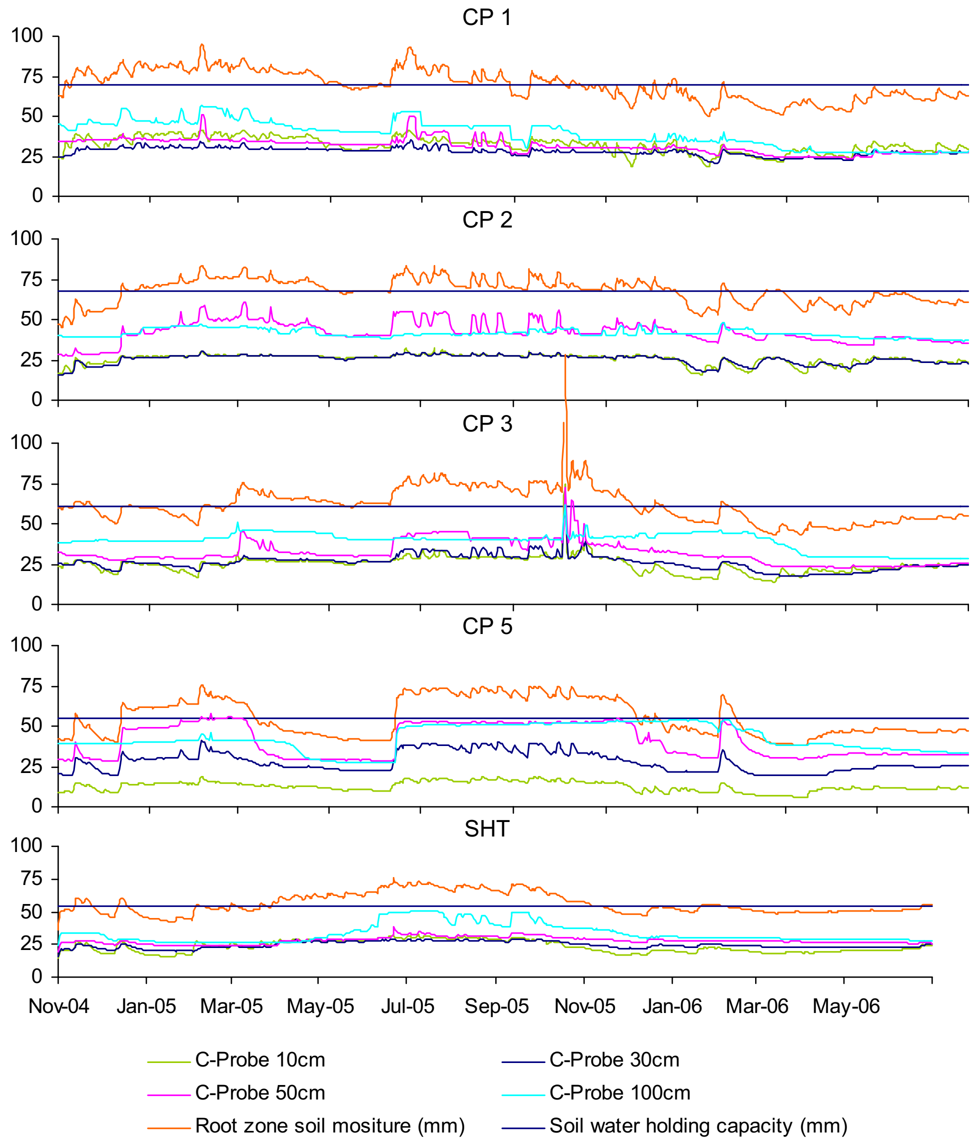

Fig. 4. Temporal behaviour of soil moisture at different depths in the root zone observed during November 2004–June 2006; where C-Probe 10 cm, C-Probe 30 cm, C-Probe 50 cm and C-Probe 100 cm represents the observed volumetric moisture content at 10, 30, 50 and 100 cm depths of soil profile, respectively.

4.2. Effluent quality

Effluent quality monitoring was conducted to achieve irrigation applications to meet Australian EPA licence requirement (Table 6). Treated wastewater samples were collected and analysed on a quarterly basis for oil and grease, pH, total N, total P, BOD and total suspended solids. Fig. 5 presents the wastewater quality data observed from June 2001 till June 2005. Generally, the EPA licence pollutant concentration limits were achieved, occasionally the oil and grease levels exceeded EPA limits. However, these oil and grease levels are still low (20 mg/L) enough to avoid danger according to DEC (2004), which considered effluent of high strength (where irrigation rates and practices must be managed to ensure soil and vegetation are not damaged) if it carries more than 1500 mg/L of oil and grease.

4.2.1. Nutrients loadings

Nutrients in effluent such as nitrogen and phosphorus are beneficial to plant growth, provided their concentrations do not exceed plant requirements. The average concentration of nitrogen and phosphorus monitored from October 2001 till May 2006 was around 3.3 and 2.4 mg/L, respectively. These concentrations correspond to average annual nitrogen and phosphorus loadings of around 17.6 and 12.8 kg/ha (Table 7). However, annual uptakes of nitrogen and phosphorus by a perennial pasture are around 200–280 and 20–50 kg/ha, respectively. Therefore, there

Table 5
Summary of water balance for different paddocks during November 2004–June 2006

Paddocks	Wastewater applications (ML)	Rainfall (ML)	Evapotranspiration (ML)	Deep percolation (ML)	Change in soil moisture storage (ML)	Runoff (ML)
November 2004–June 2005 (9 months)						
CP 1	191	143	191	122	−5	27
CP 2	81	61	86	52	−3	7
CP 3	105	130	72	152	−4	15
CP 4	62	84	46			
CP 5	79	52	71	49	−3	13
SHT	69	66	93	26	−4	20
July 2005–June 2006 (12 months)						
CP 1	182	94	320	−77	5	28
CP 2	81	40	137	−29	2	12
CP 3	55	86	148	−27	5	14
CP 4	104	55	165			
CP 5	65	34	115	−29	2	10
SHT	26	41	141	−82	2	7

Table 6
Australian EPA licence pollutant concentration limits for the wastewater applications to the effluent reuse areas

Pollutant (waters)	50%	90%	100% concentration limit
Oil and grease (mg/L)			5
pH			5.5–9.5
Total N (mg/L)			20
Total P (mg/L)			5
BOD (mg/L)	15	20	40
Total suspended solids (mg/L)	20	30	45

will be no danger of a build up of nutrient levels in the soil under a pasture cropping.

4.2.2. Organic loadings

In an effluent irrigation application scheme, if organic matter is applied at a rate greater than the soil's ability to assimilate it, then soil pores can become clogged and anaerobic condition may result in odours. Effluent with high organic loading will require more irrigation area to match soil's ability to assimilate the organic loading, as compared to effluent with low organic loading. Minimum irrigation area required based on organic loading can be estimated (DEC, 2004):

$$\text{Minimum irrigation area (ha)} = \text{BOD(mg/L)} \times \frac{\text{Average effluent application rate(ML/month)}}{\text{Critical organic loading rate(kg/ha/month)}}$$

The critical organic loading rate for most soils is around 1500 kg/ha/month. The average BOD monitored from October 2001 till May 2006 was around 5.0 mg/L, however maximum BOD of 1100 mg/L was also once monitored during the first month of effluent reuse operations, due to a malfunction of wastewater treatment plant. Therefore, using this maximum BOD value, minimum irrigation area that was required is compared with the actual paddock-wise irrigation areas (Table 8). All the paddocks were having around 67% additional area than it was required to assimilate organic loading, as high as with BOD of 1100 mg/L, in the effluent used for irrigation applications. Observed organic loadings in the effluent being used for irrigation applications do not present any adverse impact risk on the soil and crop health.

4.2.3. Salts loadings

As a general guide, irrigation water quality less than 0.65 dS/m (or 650 μS/cm) is classified as very low salinity rating suitable to irrigate salt sensitive plants (DEC, 2004). The average salinity of the effluent was observed from October 2001 till June 2006 at around 0.34 dS/m (217 mg/L). Table 9 presents total, average annual and average monthly salts loadings observed from October 2001 till June 2006 on different effluent re-use paddocks at the farm. Average monthly salts loadings of 97 kg/ha was observed, which is very low by any irrigation water salinity ratings. For 0.65 dS/m salinity of irrigation water, the average monthly salts loadings would have been around 186 kg/ha. Therefore, salinity of effluent being used at the farm does not present any risk to the soil or crop health.

4.3. Soil environment

Fig. 6 presents the temporal behaviour of environment indices observed during July 2000–June 2006 in the top soil (0–15 cm) under all the paddocks.

4.3.1. Soil salinity

Soil salinity refers to the amount of dissolved salts in the soil solution. Effluent or the combined effect of effluent and fertilisers may raise soluble salt levels to the extent that

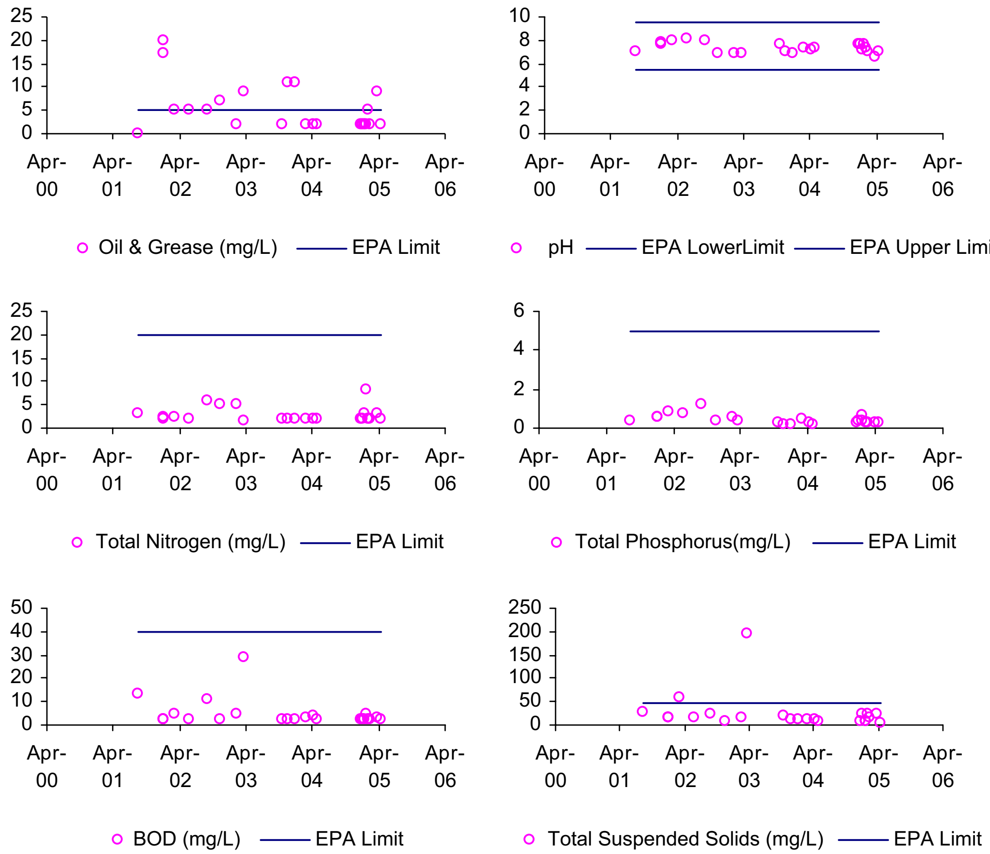

Fig. 5. Temporal observations of the treated wastewater quality for irrigation applications.

Table 7
Annual nutrients loadings on different effluent re-use paddocks

	Irrigation application rate (ML/ha)		Annual nutrient loadings (kg/ha)	
	October 2001–May 2006	Annual applications	Nitrogen	Phosphorus
CP 1	27.32	5.85	19.32	14.05
CP 2	28.76	6.16	20.34	14.79
CP 3	22.45	4.81	15.87	11.54
CP 4	27.35	5.86	19.34	14.06
CP 5	32.80	7.03	23.20	16.87
SHT	11.66	2.50	8.24	6.00

Table 8
Comparison of actual irrigation areas with the minimum areas required based on organic loadings with BOD of 1100 mg/L

	Effluent application rate (ML/month)	Minimum area (ha) required based on maximum observed organic loadings	Actual area (ha)
CP 1	13.79	10.11	28.27
CP 2	6.19	4.54	12.06
CP 3	10.30	7.55	25.70
CP 4	8.11	5.94	16.60
CP 5	5.96	4.37	10.18
SHT	3.71	2.72	17.50

they impede plant growth. However, the concentration in the soil at which salt is hazardous varies with soil texture and plant species. An indicator of soil salinity is the electrical conductivity of a water-saturated soil paste (EC_e). According to DEC (2004), where the EC_e of a soil is less than 2 dS/m, effects on plants are mostly negligible; between 2 and 4 dS/m, yields of sensitive plants become restricted. At present, there was no soil salinity threat under any of the paddock (Fig. 6), as the EC_e values present soil salinity conditions that are even suitable for salinity sensitive crops.

Table 9
Salts loadings on different effluent re-use paddocks

	Irrigation application rate (ML/ha)			Salts loadings (kg/ha)		
	Total	Annual	Monthly	Total	Annual	Monthly
CP 1	27.32	5.85	0.49	5929	1270	106
CP 2	28.76	6.16	0.51	6241	1337	111
CP 3	22.45	4.81	0.40	4871	1044	87
CP 4	27.35	5.86	0.49	5934	1272	106
CP 5	32.80	7.03	0.59	7118	1525	127
SHT	11.66	2.50	0.21	2530	542	46

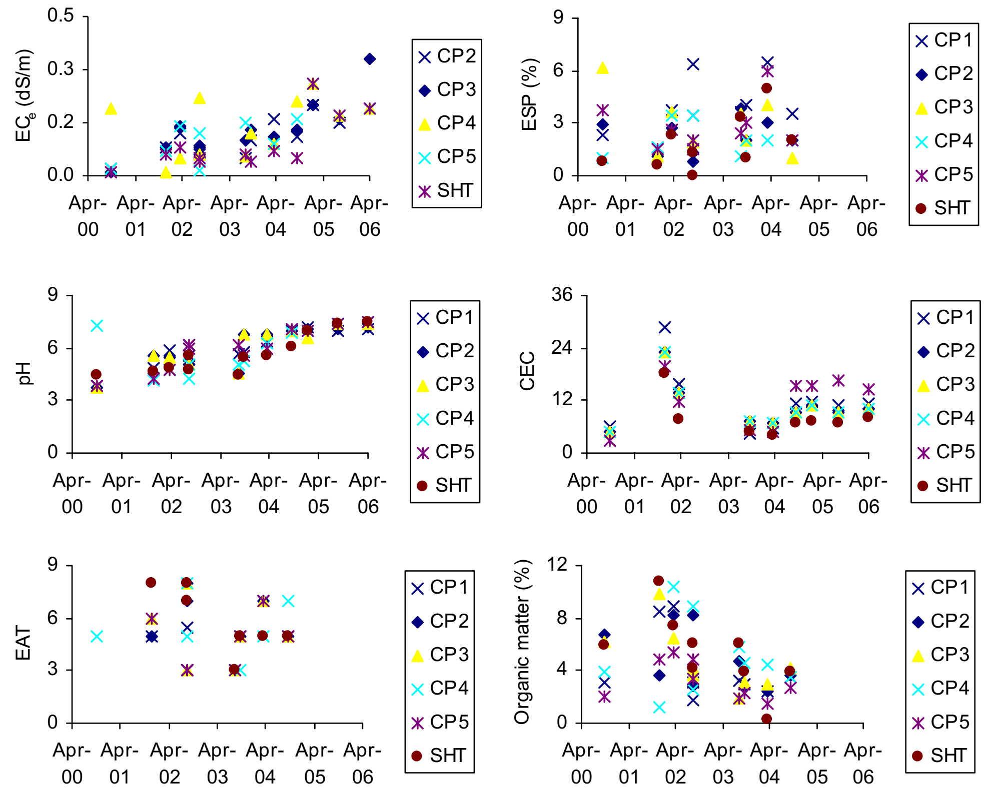

Fig. 6. Temporal behaviour of environment indices observed during July 2000–June 2006 in the top soil (0–15 cm) under all the paddocks; where EC_e, ESP, CEC, EAT represents EC of a water-saturated soil paste (in dS/m, where 1 dS/m = 1000 μS/cm), exchangeable sodium percentage, cation exchange capacity, Emerson Aggregate Test, respectively.

4.3.2. *Soil sodicity*

Soil sodicity refers to the amount of exchangeable sodium (Na) cations relative to other cations in the soil and is expressed in terms of ESP. Exchangeable sodium acts as a mechanism for weakening the bonds of soil aggregates creating a soil with poor structure that can impede water and plant root movement into and through the soil. Generally, soils with an ESP of greater than 5 are at risk of showing the adverse structural impacts associated with sodicity (DEC, 2004). Results indicated that there was no sodicity threat under any of the paddocks; as at present most paddocks show ESP less than 5 (Fig. 6).

An estimation of sodicity levels in irrigation water can be predicted using the sodium adsorption ratio (SAR). Effluent with an SAR of greater than 6 is likely to raise ESP in non-sodic soils, whereas effluent with a SAR of less than 3 may lower ESP in sodic soils (DEC, 2004). Since the commissioning of irrigation operations at the farm, the average SAR of wastewater applications was estimated around 2.3. At this SAR, such effluent may even lower the soil ESP.

4.3.3. *Soil pH*

Soil pH is a measure of the concentration of hydrogen ions in the soil. It is known to be related to the availability of plant macro and micronutrients. According to DEC (2004), for most plants a pH range of between 6 and 7.5 (measured in calcium chloride) maximises the availability of plant nutrients and hence the potential for plant growth. Measurements of pH will vary depending on the field or laboratory technique used. It is advisable to measure pH in calcium chloride to ensure a consistent interpretation of results. Under all the paddocks, the soil pH in the root zone remained closed to the range suitable for plant growth (Fig. 6).

4.3.4. *Cation exchange capacity*

The CEC is a useful indicator of soil fertility because it shows the soil's ability to supply three important plant nutrients: calcium, magnesium and potassium. Addition of organic matter (which typically has a high CEC) or the incorporation of a green manure crop (which will also increase the soils organic matter content) may improve soils with a low CEC. According to DEC (2004), CEC is considered low if it ranges from 6 to 12, and as moderate if it ranges between 12 and 25. Under all the paddocks, CEC has improved from low to moderate because of growing green manuring crops like ryegrass, oats and lucerne (Fig. 6).

4.3.5. *Soil structural stability*

The EAT results were used to measure the structural stability of the wastewater reuse soils. Soils with an EAT of 1 are likely to have the least stable structure (aggregates will slake and disperse when wetted). Stable aggregates will usually have an EAT of between 4 and 7. An EAT of 8 means that the soil is so dense that it cannot be penetrated by plant roots. Over the period, all the paddock samples show stable aggregate situations (Fig. 6), which are suitable for proper root growth.

4.3.6. Organic matter

Soils with a reasonably high level of organic matter (i.e. at least 2% by weight) are desirable for effluent irrigation schemes. Organic matter encourages soil microbial activity and increases cation exchange and water holding capacity thereby buffering the potential adverse impacts associated with overloading the soil temporarily with nutrients, contaminants or water. Soil organic matter can be increased by incorporating green crops or by adding manures, composts or bio-solids directly to the soil (taking into account any addition to the nutrient budget for the site). All the paddocks have very high levels of organic matter in the 0–15 cm top soil profile (Fig. 6).

4.4. Heavy metals and trace elements

4.4.1. Winter storage dam, surface runoff dams, irrigation effluent and creek flows

According to DEC (2004), the trigger values of irrigation effluent for long term use on all soil types (up to 100 year) regarding arsenic, cadmium, chromium, copper, lead, mercury, nickel, manganese and zinc are 0.1, 0.01, 0.1, 0.2, 2.0, 0.002, 0.2, 0.2 and 2.0 mg/L, respectively.

The concentration levels of all the heavy metals and trace elements in water from the winter storage dam as well as from surface runoff dams were below the detectable limit, except for zinc. However, zinc concentration values were also significantly lower than the trigger values for long-term use on all soil types (up to 100 year). As maximum zinc concentration observed in water stored in winter storage dam and all the surface runoff dams was 0.046 and 0.019 mg/L.

Fig. 7 presents concentrations of both zinc and manganese in wastewater used in this study, and the results indicate that both zinc and manganese in irrigation effluent is below the trigger value for long-term use on all soil types (up to 100 year).

Fig. 8 presents variations in zinc and manganese concentrations in creek flows observed at different monitoring locations. Zinc concentrations are significantly lower than the trigger value for long-term use on all soil types (up to 100 year). However, manganese concentration at SW 1 is lower than SW 2 where it becomes even higher than the trigger value. Inflows from another farm, observed at SW4 upstream of the winter storage dam, were affecting the concentration levels at SW 5 and SW 2.

4.4.2. Top soil profile

According to DEC (2004), the maximum permissible values of arsenic, cadmium, chromium, copper, lead,

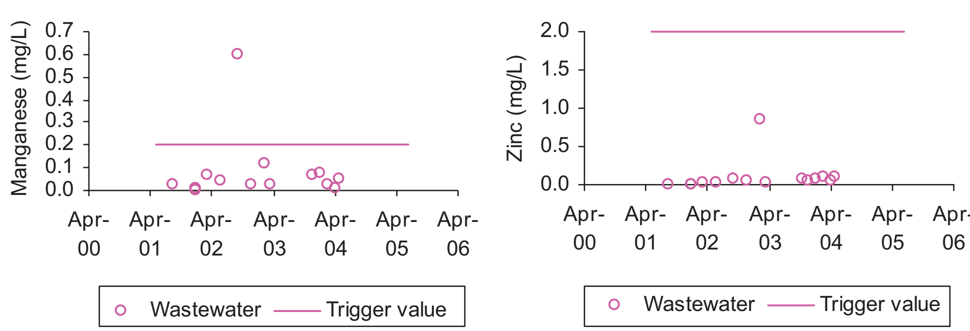

Fig. 7. Status of zinc and manganese concentrations in effluent irrigation.

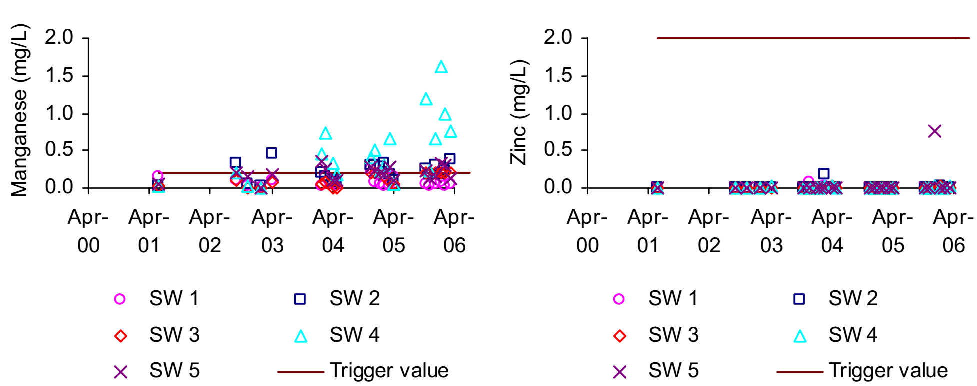

Fig. 8. Status of zinc and manganese concentrations at different locations on the creek.

mercury, nickel and zinc are 20, 1.0, 100, 100, 150, 1.0, 60 and 200 mg/kg, respectively. To estimate heavy metals and trace elements levels in the top soil profile (0–15 cm), soil samples were collected periodically from December 2001 to April 2006 from all irrigation paddocks. The concentration levels of all the heavy metals and trace elements in the top soil profile were below the detectable limit, except for chromium, copper, lead and zinc (Table 10); however, the concentration values of these heavy metals were also significantly lower than the trigger values for long term use (up to 100 year) on all soil types (DEC, 2004).

4.4.3. Groundwater

From the majority of the piezometers installed at the farm, the concentration values of heavy metals and trace elements concentration levels were available from April 2001 till May 2006. All the heavy metals and trace elements in groundwater collected from these piezometers were below the detectable limit, except for zinc. However, the maximum zinc concentration of 0.33 mg/L observed, is also significantly lower than the trigger values for long-term use (up to 100 year) on all soil types (DEC, 2004).

4.5. Groundwater dynamics

Fig. 9 presents temporal behaviour of depth to water-table in areas outside the effluent reuse paddocks observed during July 2001–June 2006. For the location of piezometers please see Fig. 2. Groundwater fluctuates seasonally, increasing during summer and falling during winter.

In piezometers BH1, BH2 and BH3, which are located outside the effluent reuse paddocks at south-east side of the farm, the groundwater fluctuates between 2 and 3 m but at a depth greater than 3 m from the soil surface (Fig. 9). The corresponding salinity fluctuations were also recorded, which indicate minor variations between: (i) 0.40–0.55 dS/m at BH1, (ii) 0.33–0.44 dS/m in case of BH2, and (iii) 0.12–0.23 dS/m at BH3.

At the north-west side of the farm, piezometer BH15s (shallow) and BH15d (deep) are located outside the effluent

Table 10
Chromium, copper, lead and zinc concentrations in top soil profile under all the effluent reuse paddocks at the farm

Date	CP 1				CP 2			
	Chromium	Copper	Lead	Zinc	Chromium	Copper	Lead	Zinc
Oct-2000	–	–	–	–	–	–	–	–
Dec-2001	10.6	7.0	<1.0	20.3	9.9	6.0	<1.0	13.3
Apr-2002	6.0	3.0	1.0	26.0	3.0	3.0	<1.0	11.0
Oct-2003	2.0	5.0	<1.0	6.0	<2.0	1.0	<1.0	7.0
Apr-2004	1.4	7.9	2.0	9.5	13.3	2.5	<1.0	13.2
Oct-2004	3.0	8.1	2.0	10.8	2.0	3.1	<1.0	14.4
Feb-2005	1.4	5.8	2.0	7.2	0.9	2.9	1.0	6.1
Sep-2005	0.4	14.9	5.0	17.3	<0.4	8.4	<4	11.1
Apr-2006	12.2	<0.8	7.7	11.6	3.7	<0.8	4.6	10.0
Apr-2006	34.2	6.1	10.3	18.9	12.6	1.2	7.2	17.2
	CP 3				CP 4			
Oct-2000	–	–	–	–	–	–	–	–
Dec-2001	11.9	5.0	1.0	22.4	7.2	4.0	<1.0	10.4
Apr-2002	6.0	5.0	<1	19.0	5.0	7.0	1.0	19.0
Oct-2003	3.0	5.0	<1.0	14.0	2.0	2.0	<1.0	29.0
Apr-2004	8.2	9.0	2.0	11.4	1.6	4.7	2.0	6.0
Oct-2004	4.0	9.4	2.0	12.3	2.6	6.8	2.0	6.7
Feb-2005	<5.0	12.0	<5.0	12.0	<5.0	6.0	<5.0	6.0
Sep-2005	15.6	15.7	5.0	18.2	<0.4	11.5	4.0	13.6
Apr-2006	9.2	<0.8	9.5	12.9	6.3	<0.8	10.2	9.1
Apr-2006	28.5	5.7	11.8	16.0	22.8	2.5	4.7	11.3
	CP 5				SHT			
Oct-2000	–	–	–	–	-	–	–	–
Dec-2001	11.7	12.0	<1.0	15.0	10.5	14.0	<1.0	13.9
Apr-2002	4.0	8.0	<1.0	13.0	2.0	5.0	<1.0	6.0
Oct-2003	3.0	5.0	<1.0	11.0	2.0	5.0	<1.0	6.0
Apr-2004	1.7	5.4	1.0	11.2	1.8	7.5	3.0	6.5
Oct-2004	4.1	7.8	2.0	15.1	3.7	7.2	2.0	7.7
Feb-2005	2.4	5.5	2.0	10.7	<5.0	12.0	<5.0	9.0
Sep-2005	1.6	14.3	5.0	25.9	1.2	11.0	5.0	20.8
Apr-2006	8.0	<0.8	13.6	18.8	6.8	<0.8	5.8	9.1
Apr-2006	20.0	0.9	7.5	15.0	31.4	4.7	10.6	17.6

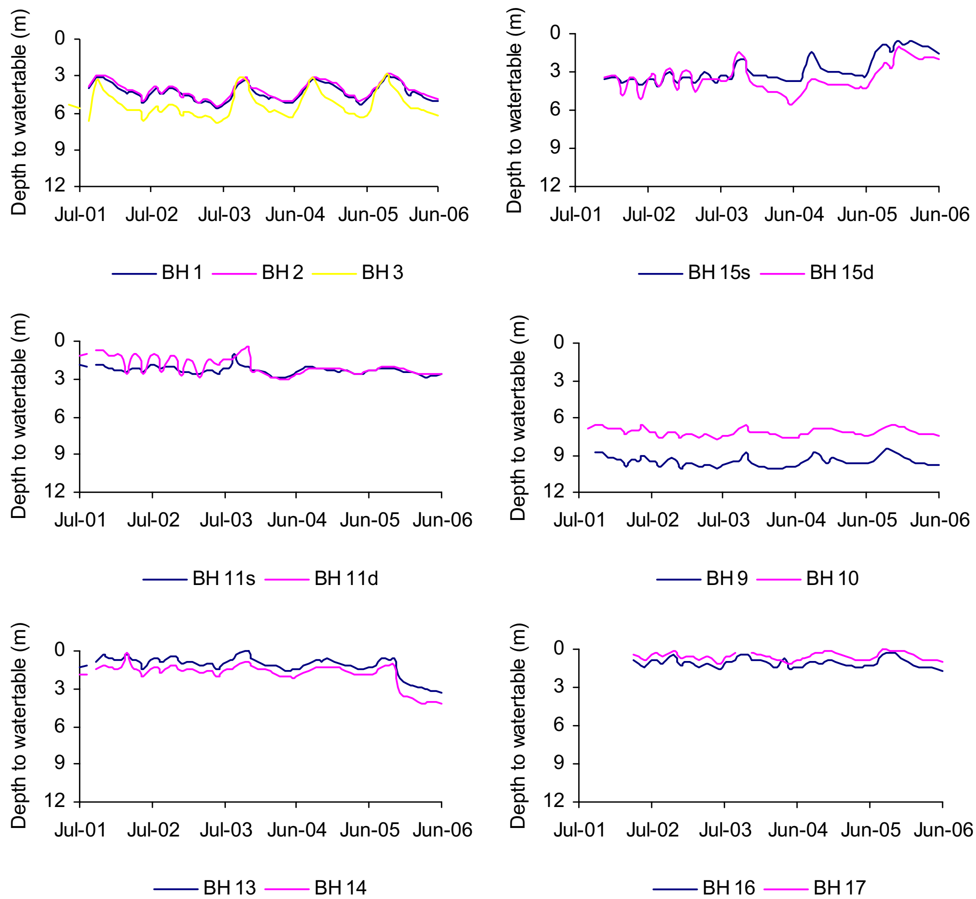

Fig. 9. Temporal behaviour of depth to watertable in areas outside the effluent reuse paddocks during July 2001–June 2006.

reuse paddocks. Both the piezometers show overall rising trends with seasonal groundwater fluctuations between 1 and 3.5 m depth from the soil surface (Fig. 9). However, groundwater salinity has decreased slightly from 0.59 to 0.47 dS/m and from 0.50 to 0.36 dS/m in case of BH15s and BH15d, respectively.

An inspection of piezometer BH11s and BH11d, which are located outside the effluent reuse paddocks at the south-west side of the farm, indicates an overall decrease in the shallow and deep groundwater levels from July 2001 to June 2006, but it fluctuates between 0.5 and 3.0 m depths from the soil surface (Fig. 9). In case of BH11 s, groundwater salinity levels have decreased substantially from 1.30 to 0.88 dS/m during this period. Similarly, for BH11d, groundwater salinity has also decreased from 1.10 to 0.76 dS/m.

Piezometers BH9 and BH10 are next to the creek at the north-east side of the farm. An inspection of piezometric levels at these locations shows very little fluctuations, which also remained around 7 and 10 m from the soil surface at BH9 and BH10, respectively (Fig. 9). Groundwater salinity varied between 0.61 and 0.72 at BH9 and between 0.43 and 0.55 dS/m at borehole BH10.

To observe the groundwater dynamics around the vicinity of winter storage dam, a number of piezometers were installed. An inspection of piezometers BH13, BH14, BH16 and BH17, installed downstream of the winter storage dam, shows seasonal fluctuations between 0 and 2 m in the depth to watertable from the soil surface (Fig. 9). Groundwater salinity of these piezometers shows a decreasing trend: BH13 (from 1.10 to 0.96 dS/m), BH16 (from 2.40 to 1.78 dS/m), and BH17 (from 1.60 to 1.01 dS/m); except BH14 (from 0.78 to 0.88 dS/m).

Thus, groundwater dynamics (both in terms of changes in depth to watertable and its salinity), observed from July 2001 till June 2006 does not result in any negative environmental impacts on the areas outside the effluent reuse paddocks at the farm.

4.6. Quality of creek flows

Monitoring of the water quality in the creek was conducted on a monthly basis to determine any impact the irrigation activities were having on surface water quality. As there is no EPA licence condition for assessing the water quality in a creek; Australian and New Zealand guidelines for fresh and marine water quality (ANZECC, 2000) were used. According to these guidelines, the best water quality being 'very low' is considered if the EC is less than 0.65 dS/m; whereas 'low' irrigation

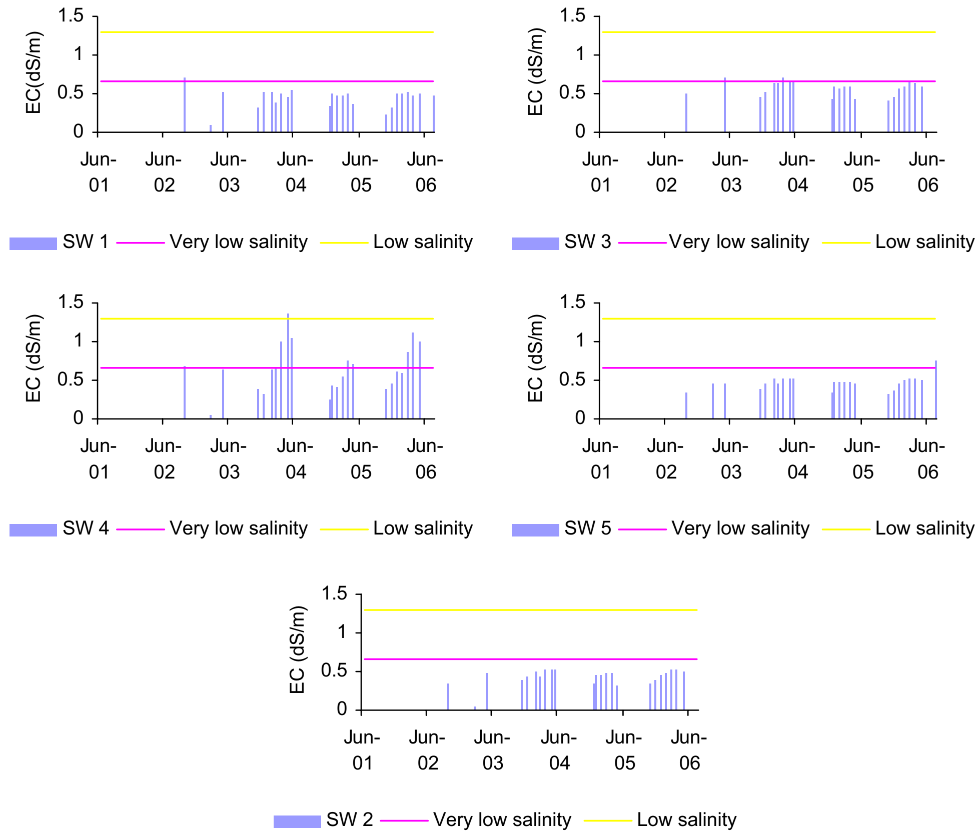

Fig. 10. Temporal behaviour of surface water quality at different locations in the creek (all values are in dS/m; 1 dS/m = 1000 μS/cm).

salinity rating is described when EC ranges from 0.65 to 1.3 dS/m.

Fig. 10 presents the temporal observations of EC (dS/m) of creek flows at all the monitoring points. Overall, the EC of water in the creek where it enters and leaves the farm were less than the 'very low' and 'low' irrigation water quality criteria set by the ANZECC (2000), which means that the existing effluent reuse practices have no environmental impacts on the surface water quality.

However, dilution observed in the EC levels of stream water; being the higher EC levels at SW 1 (and SW 3) and the lower EC levels at SW 2. This dilution effect is usually greater between SW 1 (and SW 3) and SW 5, as compared to the reach between SW 5 and SW 2. This dilution is attributed to: (i) rainfall runoff that enters the creek just before SW5, and (ii) groundwater flows from the farm towards the creek.

On the other hand, downstream of the winter storage dam (i.e., at SW 5) shows relatively lower EC than at SW 4, which is in a wetland upstream of winter storage dam. This wetland receives surface water runoff from neighbouring farmland. The water from this wetland does not enter to the winter storage dam, but is diverted under the winter storage dam through subsurface drains to a manhole and via 225 mm diameter pipe to the creek.

5. Conclusions and recommendations

At the beginning of irrigation operations, irrigation practices were based on water supply (using soil-based irrigation schedules) to reuse as much as pulp and paper mill effluent as possible before winter. However, demand based irrigation applications (using soil moisture depletion in the root zone), which are being currently employed at the farm, offer a better effluent reuse scenario aimed at managing salinity in the root zone as well as in the groundwater.

To accurately assess the soil water status, there is a need for additional calibration of C-probes to represent spatial soil moisture status for the respective paddocks. Once calibrated, the soil moisture deficit estimated from these probes can be used to properly define the wastewater applications on any particular day; otherwise improper wastewater applications would not only endanger the soil and water environment at the farm but may also affect the flows in the creek (WHO, 1989). The proper use of C-probes data would also help in maximising the benefits of rainfall.

The effluent irrigation applications and winter storage dam operations were having no negative environmental impact on the soil receiving surface and ground water under the effluent irrigated area or on the adjacent creek. However, social attitudes to the use of crops that have been irrigated with recycled waters and the resulting impact on market value of the produce could be a consideration.

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