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Delineation of Groundwater Flow within a Coastal Wetlands System using Hydraulic, Geochemical and Stable Isotope Data

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Abstract: Both geochemical and stable isotope data provide important supplemental information to more traditional hydraulic data and unravel the processes that underpin the large variations in chemical and stable isotopic composition within a coastal wetland system. The system studied was the Lake Warden wetlands, located in Esperance, in south coast of Western Australia. The spatial and temporal variations of chemical and isotopic composition of the individual water bodies within the system were measured for an annual cycle. In broad terms, the groundwater levels appear to follow the topography but the distinct higher chloride and isotopic concentrations observed within the wetlands were not reflected in the low lying coastal plain groundwater. The hydraulic analysis of the region surrounding the wetlands suggest that the wetlands are flow-through bodies, however the chemical and isotope information indicates the lakes almost invariably act as discharge points for the surface water flows and the north south groundwater flow. The northeast-southwest groundwater flow is along an observed paleochannel within the wetlands system and in this case the chemical and isotopic evidence are complimentary with the hydraulic study.

Keywords: *Stable Isotope; geochemical; Classic hydraulic; Paleochannel; Coastal wetland system*

1.0 INTRODUCTION

The groundwater inputs to a wetland or lake are considered one of the most difficult components to measure because of the aquifer heterogeneities (Born et al., 1979; Krabbenhoft et al., 1990). In addition, both numerical (Townley et al., 1993) and field (Siegel, 1988) studies have also shown that all wetlands in unconfined aquifers have a complex interrelationship with the surrounding shallow groundwater flow systems. The classical interpretation of the recharge-discharge function of these wetlands is based solely on the hydraulic head elevations of piezometers installed in vertically nested clusters adjacent to the wetland (Toth, 1963; Freeze and Witherspoon, 1967). In this work, both chemical and stable isotope information is used to supplement the classical hydraulic approach taken to delineating the groundwater flow patterns around wetlands. Previous works on utilising isotope and chemical information to delineate flow systems around a wetland (Herczeg et al., 1992; Kehewa et al., 1998; Huddart et al., 1999; Malcolm and Soulsby, 2001) are related mainly to individual or small groups of lakes which have similar chemical and isotopic compositions. Comparatively little is known about systems that have large variations in chemical and stable isotopic composition and complex flow systems. The objectives of this paper are to (1) demonstrate that both chemical and stable isotope data are critical components to constrain flow that are not attainable from limited hydraulic data. (2) Unravel the processes that underpin the wide range of salinity observed in the

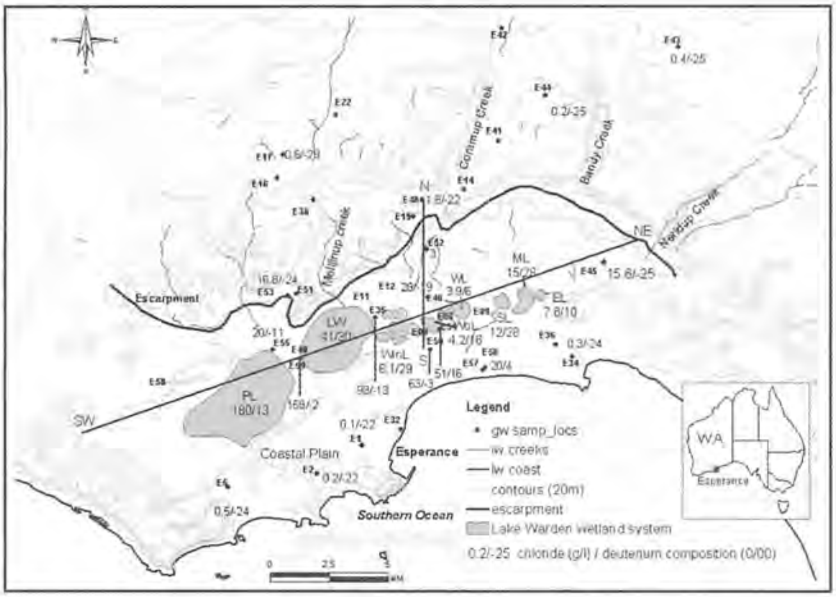


Figure 1: Location map of Lake Warden wetlands system. PL-Pink Lake; LW-Lake Warden; WinL-Windabout Lake; WoL-Woody Lake; WL-Wheatfield Lake; SL-Station Lake; ML-Mullet Lake and EL-Ewans Lake. The chloride and deuterium composition of the water bodies represents Spring 2002 sampling.

surface and subsurface water system.

2.0 SITE DESCRIPTIONS

The study area is located approximately 600 km south east of Perth and near the coastal town of Esperance on the south coast of Western Australia (Figure 1). The climate is Mediterranean, with cool, wet winters and warm to hot, dry summers. The average monthly temperatures for the study area range from 16^{0}C to 26^{0}C during summer (December-February) and from 4^{0}C to 17^{0}C during winter months (June-August). The average annual rainfall is 623 mm, and mainly occurs during winter. Average annual potential evaporation is 1600 mm and is greatest during the summer months of January and February.

The topography of the area is characterized by flat to gently undulating sandplain, rising gradually from sea level to about 150 m Australian Height Datum (AHD). The coastal plain extends up to 10 km inland and includes the wetlands system, which acts as an outlet for Melijinup, Coramup, Bandy and Neridup creeks. A gently curved escarpment, up to 40m high, marks the inland extent of the coastal plain where it merges with the Esperance sandplain that extending approximately 30 to 40 km inland from the coastal plain.

The Lake Warden wetlands system comprising Pink Lake, Lake Warden, Windabout Lake, Woody Lake and Wheatfield Lake as well as Station Lake, Mullet Lake and Ewans Lake in the Bandy Creek watercourse (Figure 1) is situated in infilled basement rock depressions within the coastal plain.

3.0 METHODS

3.1 Physical

The majority of the hydrogeological studies at the study area were performed either to the north or south of the study area. A data gap existed within the wetlands system, and a drilling program was initiated to provide additional information on the lithostratigraphy of the study area. New transects of boreholes were drilled within the Lake Warden wetlands system to collect new geological and hydrogeological data, improve the understanding of regional groundwater flow, and to determine the lake flow characteristics. The boreholes were instrumented with piezometers to determine the groundwater flow, and in addition, nine capacitive water level probes were also installed in selected boreholes and programmed to measure the water level on an hourly basis. All groundwater level measurements were recorded for a

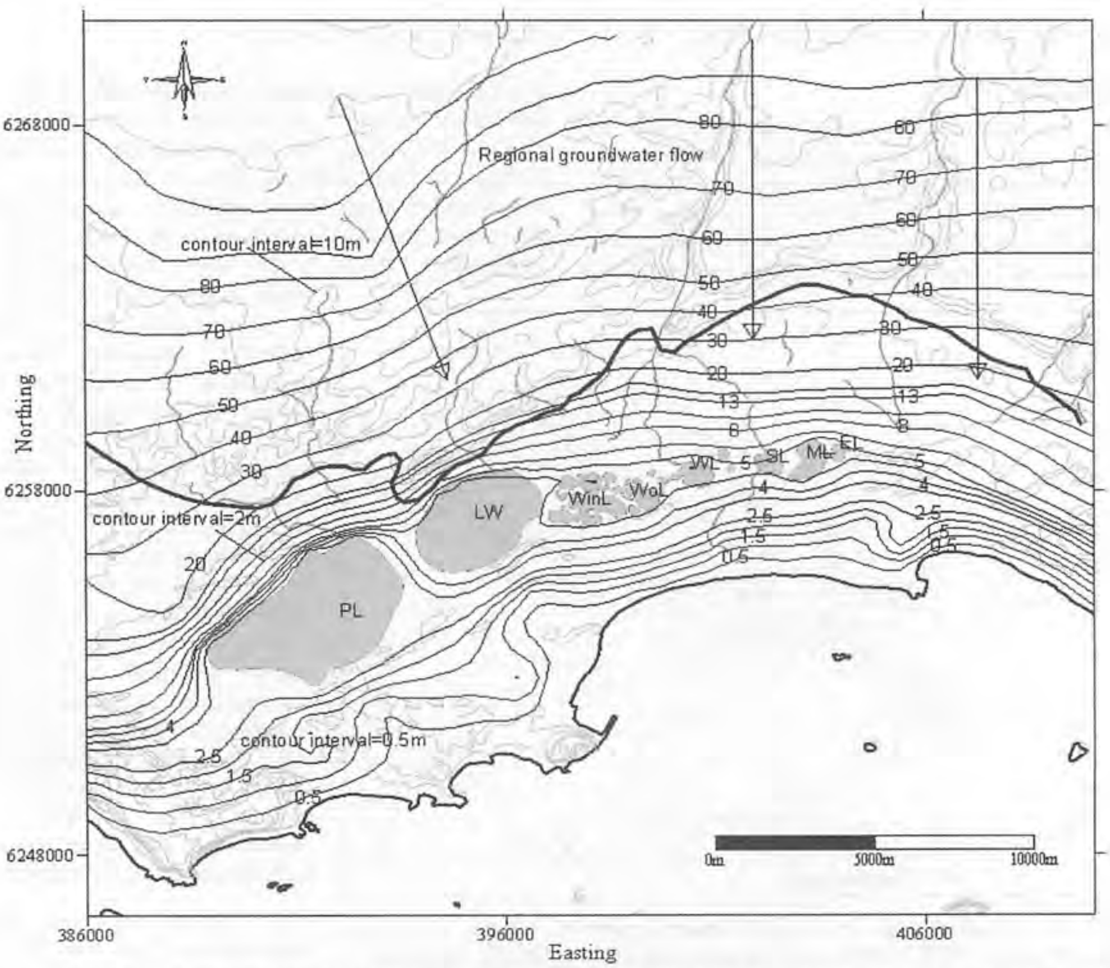


Figure 2: Groundwater contour map of Lake Warden wetlands system. Contour map is derived using limited data. Contour intervals vary between 0.5m, 2m and 10m. Arrows denotes groundwater flow and other symbols are same as in Figure 1.

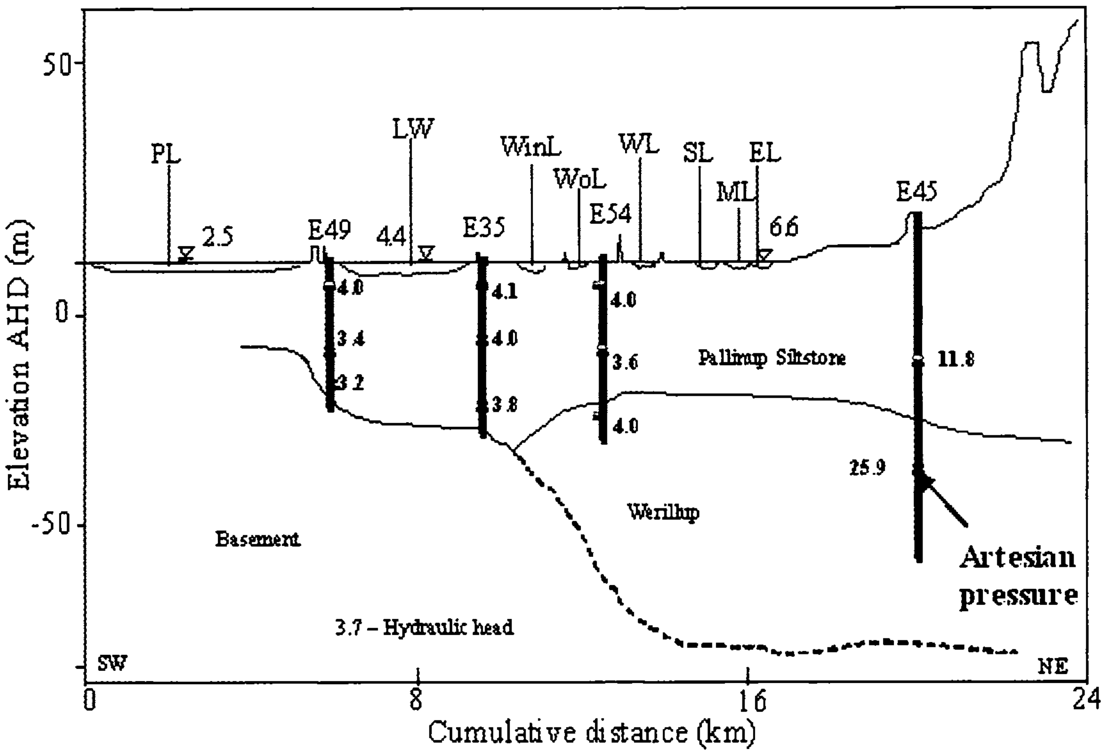


Figure 3: Southwest northeast transect of hydraulic head elevations in the Lake Warden wetlands system (density corrected). AHD- Australian Height Datum. Refer to Figure 1 for transect location and symbols.

period of one annual cycle. All measured hydraulic heads have been converted to fresh water heads (Fetter, 2001).

3.2 Chemical and Stable Isotopes

The temporal and spatial variations of chemical and isotopic composition of a number water bodies in the study area were investigated by seasonal sampling (April 2002 -September 2003). A total of thirty-four groundwater samples from inland, wetland and coastal plain, as well as lake and creek sources were collected (Figure 1). Rain samples were also collected during rainstorm events, and were cumulated to a weekly/monthly basis. In addition, six surface water samples (Lake Warden, Wheatfield and Station lakes, and Coramup and Bandy creeks) were collected on a weekly basis between May 2002 and November 2003.

Physical parameters such as temperature, pH and electrical conductivity (EC) of the water samples were measured in the field. Major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} and S), and anions (HCO_3^- and Cl^-) were measured in the lab. The isotopic composition of ^2H (deuterium) and ^{18}O (oxygen-18) of the water samples were analysed using pyrolis technique and the analytical precision is $3^0/_{00}$ for ^2H and $0.5^0/_{00}$ for ^{18}O while the precision of replicate analysis of the samples is ± 1.5 $^0/_{00}$ for deuterium and ± 0.3 $^0/_{00}$ for oxygen-18. The isotopic compositions of ^{18}O and ^2H are reported as parts per thousand (‰) with respect to V-SMOW (Vienna Standard Mean Ocean Water) using the (δ) notation (Gonfiantini, 1986). The hydrogeochemical models, PHREEQC-2 (Parkhurst and Appelo 1999) and PHRQPITZ (Pitzer 1973) were used to calculate saturation indices of minerals (Marimuthu et al., 2005).

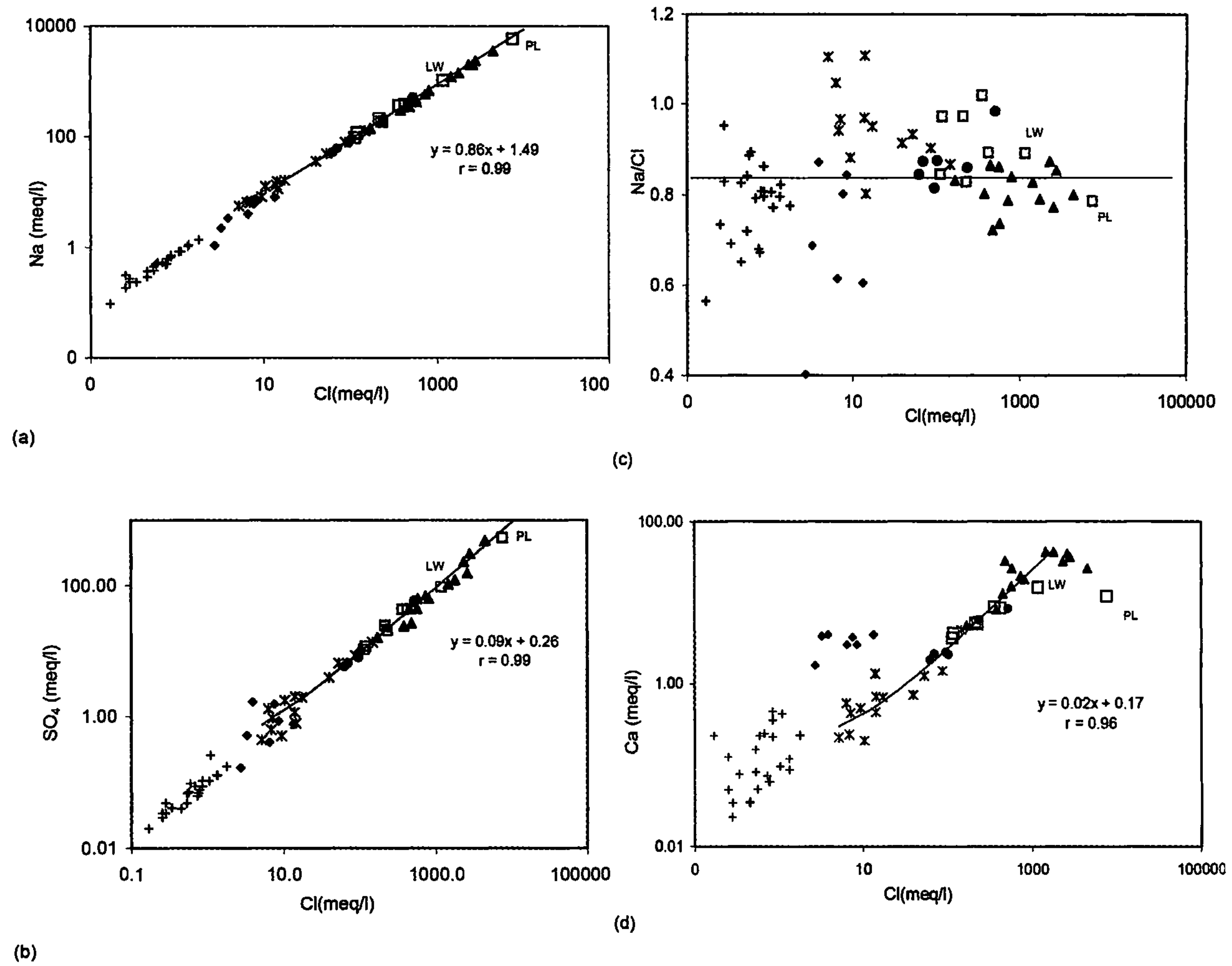
4.0 RESULTS

4.1 Hydraulics

The groundwater hydraulic heads follow the topography (Figure 2), exhibiting the highest values in the escarpment and lowest in the coastal plain. Flow is indicated as being predominantly north to south, with west to east components in the coastal plains south of Pink Lake. The perception of "global" north to south groundwater movement is contradicted by the results from the nested piezometers within the wetlands system (NE-SW transect, Figure 1) which indicate a mixture of downward and upward discharge (Figure 3) as well as a significant component of northeast to southwest flow.

The time-averaged lake levels of Station, Mullet and Ewans lakes on the eastern part of the wetland system are generally lower than the regional groundwater table (lake recharge scenario), while the levels of Wheatfield, Windabout and Woody lakes are generally higher than the adjacent groundwater table (lake discharge scenario). The relationship between time-averaged water levels in the lakes and the water table in their vicinity is spatially consistent for all lakes with the exception of Lake Warden, which has a lake recharge configuration to the east and a lake discharge configuration to the west.

The lake levels and local water tables were found to vary in phase (data not shown), although it was observed that heavy rainfall events affect the lakes more rapidly than the groundwater. The lake levels and groundwater



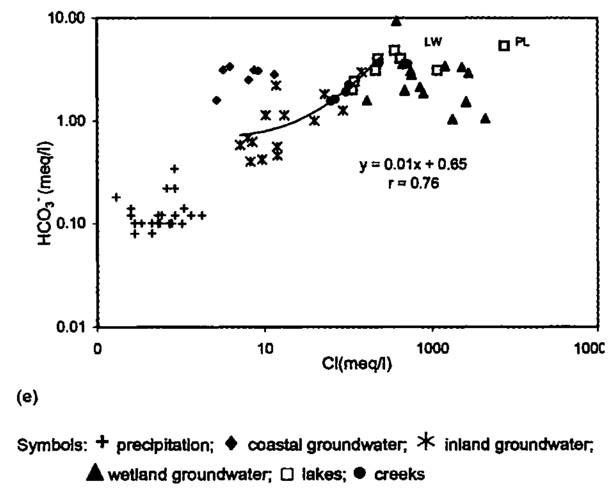


Figure 4: Chemical plots for the Lake Warden Wetlands system (Spring samples). (a) Na versus Cl, (b) SO_4 versus Cl, (c) Na/Cl versus Cl (d) Ca versus Cl, and (e) HCO_3 versus Cl . PL, Pink Lake and LW, Lake Warden.

table are highest in June-September after the winter rainfall and lowest in February-April at the end of summer. The large fluctuations in hydraulic head in the shallow aquifer (observation well) often correspond to the fluctuation in deeper aquifers and were also mimicked by fluctuations in the lake level.

4.2 Hydrochemistry

The physical and chemical parameters of the water samples taken during the spring 2002 sampling session are presented in Table 1. All surface and groundwater samples were found to have Na and Cl as dominant ions. As a general rule, the creek and lake samples are mildly alkaline with most pH values ranging from 7.9 to 9, while groundwater samples tend to be more acidic with pH ranging from 5.8 to 7.8. Small seasonal variations were observed in the surface water pH while groundwater samples showed little seasonal variation. Hydrochemical analysis of the groundwater samples revealed three distinct groundwater environments; coastal plain, inland, and wetland.

Groundwater from the coastal plain is the freshest water body in the region with chloride concentrations ranging from 0.1 to 0.5 gL^{-1} (Figure 1). The dominant ions are chloride and sodium followed by bicarbonate and calcium + magnesium. The groundwater from inland is more saline (0.1-5.5 gL^{-1}) and shows marginally higher SO_4^{2-} and lower HCO_3^- (Figure 4b and 4e) and than the coastal plain. Groundwater within the boundaries of the wetlands is saline to hypersaline (6 to 158 gL^{-1}) and characterised by dominant Na^+, Cl^-, SO_4^{2-} and Mg^{2+} ions. The dissolved solute concentrations in the groundwater increase significantly along the northeast to southwest flow path (the existence of which was inferred from the hydraulic data) from Ewans to Pink Lake. The largest dissolved solute concentration gradients occur in the vicinity of Lake Warden, and in most cases the gradient is increasing along the flow path. In contrast to the dissolved solute trend, HCO_3^- ion decreases along the flow path and pH does not change appreciably.

Creeks feeding into the wetlands are brackish (2-8 gL^{-1}) while the lake system itself is brackish to hypersaline (2.8 to 180 gL^{-1}). The surface water samples from the study area are characterised by higher Na^+, Mg^{2+}, Cl^- and SO_4^{2-} concentrations than the inland or coastal groundwater, and slightly lower concentrations than in the wetland groundwater with the exception of Pink Lake. The lakes in the study area are too shallow to develop stratification, and in addition the region also experiences strong windy conditions throughout the year resulting in good mixing.

Initially, the relationship between different water bodies and the processes influencing their chemical composition was investigated through the use of major ions concentrations versus Cl^- concentration (indicative of concentration/ evaporation). Plots of Na^+, SO_4^{2-}, K^+, and Mg^{2+} vs. Cl^- for the overall system show a trend along the evaporation line of inland groundwater (Figures 4a & b). A deviation from this line indicates addition or removal of solutes as result of chemical reactions, such as mineral dissolution or precipitation. Coastal and inland groundwater samples in the Na^+ versus Cl^- plot (Figure 4a) are clustered on the lower end of the inland groundwater evaporation line except for a few samples which were collected closer to the wetlands and are clustered with the creeks and the less saline lake samples. Lake Warden and Pink Lake seem to be isolated from the latter cluster (Figure 4a & b). It is very important to note that the groundwater samples from the wetlands system are bounded along the evaporation line between the regional groundwater (inland) and Pink Lake.

Figure 4c presents the Na^+ to Cl^- concentration ratio as a function of the Cl^- concentration. The observed Na/Cl ratios of the inland groundwater shows a wide range from 0.8 to 1.2 while the coastal groundwater shows a similar ratio to the precipitation (0.6 to 0.9) being mainly depleted in Na^+ compared to the inland groundwater. The ratios for creeks and lakes show a slightly narrower range (0.8 to 1.00), while groundwater from the wetlands is nearly constant (0.7 to 0.9).

Figure 4d-e presents the relationship between Ca^{2+} and HCO_3^- concentrations to Cl^- concentration. The relationship for Ca^{2+} of inland groundwater, creeks and less saline lake samples is generally positive with increasing concentration of Cl^- and plots along the inland groundwater evaporation line (Figure 4d). The Ca^{2+} concentrations of the coastal groundwater are higher than the inland groundwater, while the Ca^{2+} concentrations of the groundwater from the wetlands and lakes also increases with increasing concentration of Cl^- . Groundwater samples from the Lake Warden region (E35b, E35c, E49a and E49b) show a decreasing Ca^{2+} trend which is also observed at Pink Lake.

Similarly, the HCO_3^- concentration of inland groundwater, creeks and less saline lakes samples are generally increasing with increasing concentration of Cl^- and plot along the inland groundwater evaporation line, while the HCO_3^- concentration of the coastal groundwater samples is relatively high with respect to inland groundwater and plots above the evaporation line (Figure 4e). The bicarbonate concentrations of lake water increase with increasing Cl^- concentration with the exception of Lake Warden and Pink Lake which plot below the evaporation line. The HCO_3^- concentrations of the groundwater from the wetland plots are much more scattered with most of them depleted in HCO_3^- with respect to the evaporation line (with the exception of E54b). This bore is placed in the Spongolite facies of the Pallinup Siltstone.

4.3 Stable isotopes

The isotopic composition of the weekly/monthly precipitation collected for the Esperance region (from May 2002 to Nov 2003) ranged from -54 ‰ to +0 ‰ and -10.2 ‰ to –1.7 ‰ for δ^2H and $\delta^{18}O$ respectively. These values define the LMWL as: $\delta^2H = 7.1\pm0.8\delta^{18}O + 18.1\pm1.7$ (Figure 5). The measured spring 2002 sampling stable isotope data are presented in Table 1. The isotopic composition of the inland groundwater falls within a very narrow range, -6.8 to -4.7 ‰ and to -32 to –22 ‰ for $\delta^{18}O$ and δ^2H respectively. The isotopic composition of the coastal groundwater is similar, and ranges from -6.7 to -4.9 ‰ and -30 to -22 ‰ for $\delta^{18}O$ and δ^2H, respectively. In general, both the isotopic values of the

Table 1: Physical, Chemical and isotopic composition of the water samples in Lake Warden wetlands system (Spring samples)

	pH	Temp	Ca	Mg	Na	K	Cl	HCO_3	SO_4	δ^2H	$\delta^{18}O$	Corrected for salt		SI_C	SI_d	SI_g	SI_h	P_{CO2}	
		^0C	(g/L)							VSMOW		δ^2H_a	$\delta^{18}O_a$						Remarks
Groundwater(coastal)																			
E1	7.1	19.6	74	29	140	5	269	190	74	-25	-5.3	-24	-5.3	-0.3	-0.9	-1.8	-6.0	-1.9	Coastal Plain
E2	7.2	18.6	60	24	92	2	232	154	20	-26	-5.7	-26	-5.7	-0.3	-1.0	-2.4	-6.2	-2.1	Coastal Plain
E5	7.1	20.2	79	47	186	4	473	172	37	-22	-6.0	-22	-6.0	-0.3	-0.7	-2.1	-5.7	-1.9	Coastal Plain
E32	7.6	19.8	80	28	78	5	138	206	80	-26	-3.7	-26	-3.7	0.3	0.3	-1.7	-6.6	-2.4	Coastal Plain
E34	7.8	19.7	33	16	25	1	96	98	8	-25	-5.0	-25	-5.0	-0.1	-0.4	-2.9	-7.2	-2.9	Coastal Plain
E36	7.2	18.7	59	43	165	2	301	187	41	-30	-5.8	-30	-5.8	-0.3	-0.6	-2.2	-5.9	-2.0	Coastal Plain
E58	7.1	18.7	76	18	51	2	115	190	25	-21	-6.0	-21	-6.0	-0.3	-1.0	-2.2	-6.8	-2.1	Coastal Plain
Groundwater(inland)																			
E14	5.8	21.8	9	20	361	8	502	34	97	-24	-5.1	-24	-5.1	-3.2	-6.0	-2.6	-5.4	-1.3	Pallinup Siltstone
E16	6.9	22.7	14	27	377	12	612	70	95	-25	-5.2	-25	-5.2	-1.6	-2.8	-2.4	-5.3	-2.1	Basement rock
E17B	5.6	21.9	9	20	159	6	254	38	45	-28	-5.9	-28	-5.9	-3.3	-6.1	-2.8	-6.0	-1.1	Basement rock
E19	5.8	20.3	15	50	830	22	1400	61	188	-30	-6.2	-30	-6.2	-2.8	-5.2	-2.3	-4.6	-1.1	Basement rock
E22	6.0	20.8	5	10	149	4	243	24	30	-28	-5.9	-28	-5.9	-3.3	-6.3	-3.2	-6.0	-1.7	Pallinup Siltstone
E38A	5.9	18.1	11	11	153	15	225	41	63	-22	-4.7	-22	-4.7	-2.9	-5.8	-2.6	-6.0	-1.3	Pallinup Siltstone
E38B	6.5	18.5	91	247	2917	56	5184	182	648	-26	-5.1	-26	-5.1	-1.2	-1.8	-1.4	-3.6	-1.4	Werillup Formation
E41A	6.4	21.3	10	12	190	5	332	26	25	-25	-5.2	-25	-5.2	-2.6	-5.1	-3.0	-5.8	-2.0	Pallinup Siltstone
E42	6.7	22.5	14	22	266	9	510	28	38	-28	-5.6	-28	-5.6	-2.2	-4.0	-2.8	-5.5	-2.3	Pallinup Siltstone
E43	6.6	19.3	4	5	292	6	366	70	84	-27	-5.9	-27	-5.9	-2.5	-4.7	-2.9	-5.6	-1.8	Pallinup Siltstone
E44	7.1	21.6	4	9	131	4	183	35	21	-27	-5.9	-27	-5.9	-2.2	-3.8	-3.4	-6.2	-2.6	Pallinup Siltstone
E48	6.4	21.2	25	80	1133	28	1871	111	310	-22	-5.7	-22	-5.7	-1.9	-3.1	-2.0	-4.4	-1.5	Pallinup Siltstone
E51	6.4	21.3	26	37	310	15	493	135	56	-23	-5.9	-23	-5.9	-1.6	-3.3	-2.4	-5.4	-1.6	Basement rock
E52	6.1	19.9	29	109	1809	38	3088	77	404	-23	-5.8	-23	-5.8	-2.3	-4.0	-1.9	-4.0	-1.3	Pallinup Siltstone

Table 1 (continued)

	pH	Temp °C	Ca (g/L)	Mg	Na	K	Cl	HCO_3	SO_4	δ^2H VSMOW	$\delta^{18}O$	Corrected for salt δ^2H_a	$\delta^{18}O_a$	SI_C	SI_d	SI_g	SI_h	P_{CO2}	Remarks
Groundwater(wetlands)																			
E35b	6.1	19.2	631	5432	54680	813	83600	178	12679	-13	-2.3	-6	-2.5	-1.0	-0.5	-0.2	-1.0	-1.3	Pallinup Siltstone
E35c	6.2	19.8	650	5594	46450	652	81948	203	11252	-12	-2.3	-6	-2.5	-0.8	-0.1	-0.2	-1.1	-1.3	Basement rock
E40	6.0	21.6	385	1433	15467	163	28382	113	3035	-19	-3.9	-17	-3.9	-1.5	-2.2	-0.7	-2.2	-1.2	Pallinup Siltstone
E45A	6.0	20.7	103	341	3227	59	5974	96	771	-25	-5.7	-24	-5.7	-1.9	-2.8	-1.3	-3.5	-1.2	Pallinup Siltstone
E45B	6.5	21.2	258	903	8874	130	15798	218	2098	-24	-5.2	-22	-5.3	-0.8	-1.0	-0.8	-2.7	-1.4	Werillup Formation
E49A	5.8	19.6	529	15216	81890	1491	157722	65	23658	1	-1.8	13	-2.3	-1.2	-0.2	0.2	-0.2	-1.5	Pallinup Siltstone
E49B	5.8	19.5	800	8104	45835	762	91455	94	7490	-5	-2.0	2	-2.2	-1.3	-1.1	-0.3	-1.0	-1.2	Basement rock
E50	5.7	19.9	838	3501	32281	473	62915	63	5852	-3	-2.4	1	-2.5	-1.8	-2.4	-0.3	-1.5	-1.2	Pallinup Siltstone
E53	6.4	18.6	656	1086	7891	114	16830	122	1288	-24	-5.6	-23	-5.6	-0.8	-1.2	-0.7	-2.7	-1.6	Basement rock
E54A	6.7	19.8	164	740	6974	192	13390	569	1160	16	0.0	17	0.0	-0.6	-0.4	-1.2	-1.6	-1.3	Pallinup Siltstone
E54B	6.3	20.6	850	3310	27567	436	51298	209	5090	-10	-3.3	-6	-3.4	-0.7	-0.2	-0.3	-1.6	-1.3	Werillup Formation
E55	6.4	21.2	529	1654	9750	118	20371	172	3017	-11	-3.2	-10	-3.3	-0.8	-0.9	-0.5	-2.5	-1.4	Pallinup Siltstone
E56	7.0	18.6	422	1588	13189	363	25789	131	3310	4	-1.8	5	-1.9	-0.4	-0.1	-0.6	-2.3	-2.2	Pallinup Siltstone
E57	7.0	18.5	317	1052	11176	180	19981	187	2111	0	-2.5	1	-2.5	-0.4	0.0	-0.8	-2.5	-2.0	Pallinup Siltstone
Creeks																			
E9	8.3	25.8	39	121	1204	28	2195	95	276	-18	-3.7	-18	-3.7	0.2	1.0	-1.9	-4.3	-3.4	Coramup Creek(down stream)
E10	7.9	22.8	45	177	2066	38	3638	137	479	-21	-4.3	-21	-4.3	-0.1	0.5	-1.7	-3.9	-2.9	Bandy Creek(down stream)
E11	8.2	27.3	168	1161	11646	179	18231	220	2851	-9	-2.0	-7	-2.0	0.7	2.4	-1.0	-2.5	-3.1	Bandy Creek(upstream)
E12	8.8	29.9	49	172	1779	38	3364	117	379	-18	-3.9	-18	-3.9	0.7	2.3	-1.8	-4.0	-3.9	Coramup Creek(upstream)
E13	8.2	25.8	120	441	4636	80	8302	224	1083	10	0.6	10	0.6	0.7	2.1	-1.3	-3.2	-3.0	Bandy Creek (outflow)
E39	9.0	27.2	47	136	1392	31	2457	99	312	-10	-2.7	-9	-2.7	0.8	2.3	-1.8	-4.2	-4.3	Coramup Creek(down stream)
Lakes																			
E23	8.6	25.8	73	223	2189	50	3986	123	505	6	-0.6	6	-0.6	0.7	2.1	-1.6	-3.8	-3.7	Lake Wheatfield
E24	8.1	26.3	177	838	8419	155	12729	295	2078	28	3.4	29	3.4	0.8	2.4	-1.0	-2.8	-2.9	Station Lake
E25	8.3	23.7	171	834	8690	146	14995	246	2129	27	3.4	28	3.3	0.8	2.5	-1.0	-2.7	-3.2	Mullet Lake
E26	8.6	25.1	112	430	4781	79	7567	190	1172	10	1.0	11	0.9	0.9	2.6	-1.2	-3.2	-3.6	Ewans Lake
E28	8.0	25.6	82	278	2654	53	4203	148	558	16	1.6	16	1.5	0.3	1.3	-1.5	-3.7	-3.0	Woody Lake
E29	8.5	26.4	108	479	4350	94	8082	246	988	29	3.2	30	3.2	0.9	2.7	-1.3	-3.2	-3.4	Windabout Lake
E30	7.1	25.4	228	12955	133941	2855	242000	327	26267	13	3.1	25	2.7	0.6	3.9	0.5	0.8	-3.0	Pink Lake
E46	8.4	26.9	307	2164	23862	509	41218	190	4590	30	1.9	33	1.8	0.9	3.0	-0.8	-1.8	-3.4	Lake Warden

coastal and inland groundwater are similar to the weighted average isotopic composition of winter precipitation with some minor deviations. In contrast to the groundwater samples from locations outside the wetlands, the groundwater samples from within the wetlands system tend to have a highly enriched isotopic composition (Figure 6).

The isotopic composition of the creek samples for both Bandy and Coramup creeks showed some spatial and temporal variations. Creek samples collected upstream have relatively enriched isotopic values compared to the samples collected in middle and down stream reach (Table 1). The isotopic composition of the Bandy Creek outflow to the ocean, however, showed some enrichment of ^{18}O (-1.9 to +0.6 $^{0}/_{00}$) and ^{2}H (-6 to +10 $^{0}/_{00}$). The lake s amples display a broad range of isotopic values and vary substantially on a seasonal basis (Figure 6).

In most hydrological systems, evaporation from open water bodies is the principal fractionation mechanism and the evaporative isotopic enrichment and the variation in the $\delta^{18}O$ and $\delta^{2}H$ of that system is strongly influenced by temperature, salinity and relative humidity. The line that passes through evaporated water is referred as an evaporation line and also differs from place to place. The isotopic composition of all the creeks samples were used to define the Evaporation Line (EL) of the study area is $\delta^{2}H = 5.7\pm0.23\delta^{18}O + 6.2\pm0.89$ (Figure 5), which intersects the LMWL at $\delta^{2}H$ -46$^{0}/_{00}$ and $\delta^{18}O$ -8.2$^{0}/_{00}$.

All the creeks and inland groundwater samples tend to fall on this evaporation line while the less saline lakes and wetlands groundwater samples tend to fall in between the LMWL and the EL. Pink Lake samples tend to fall on the LMWL, and the isotopic composition of Pink Lake is also not as enriched as would be expected in a shallow and ephemeral lake under evaporation. This is due to the high dissolved salt concentration which decreases the thermodynamic activity of the water and its evaporation rate (Clark and Fritz, 1997).

5.0 DISCUSSION

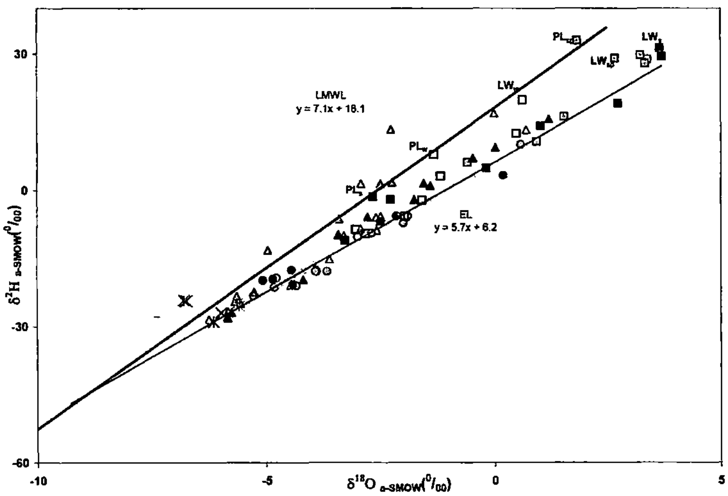
5.1 Hydraulic Delineation

The Lake Warden wetlands system is in hydraulic connection with the regional groundwater flow system and is in a dynamic balance between topography, geology and climatic factors. The piezometric surface to the north (inland) exhibits moderate to large gradients (Figure 2), however previous investigations found that the north-south flow is constrained by irregular topography, lateral differences in the hydraulic conductivity and generally altered or deflected flow conditions around areas of shallow basement (Johnson and Baddock, 1998; Short 2000). The present study has observed sub artesian flows in the escarpment (E19 and E53) and an elevated water table between the escarpment and the wetlands system. All regional hydraulic information points to the wetlands as being a minor component of the overall flow system acting as a sink for the north south flow.

The extensive drilling and instrumentation in the vicinity of the wetlands, however, indicated complex spatial and temporal variations in the local groundwater flow system. On the eastern side of the wetlands system, the hydraulic heads in the Werillup Formation and in the Pallinup Siltstone (E45a and E45b) indicate that the lakes are acting as groundwater discharge lakes. Conversely, the lake levels of Wheatfield, Woody and Windabout lakes which are at similar elevations in the middle part of the wetland system are generally higher than the adjacent groundwater levels in winter and spring, hence act as groundwater recharge lakes. A reversal occurs in summer, however, as evapotranspiration lower the Wheatfield, Woody and Windabout Lake levels below the groundwater levels, resulting in groundwater discharge to the lakes (groundwater discharge lakes).

Local hydraulic head measurements also indicate a flow divide between the eastern lakes and Lake Warden (Figure 7) and as a result, local groundwater recharge is occurring in this zone. The flow divide is coincident with the transition zone within the Pallinup Siltstone from the Spongolite facies to the Siltstone facies. This flow divide also results in Lake Warden being classified as a flow through lake, with groundwater discharge on its eastern edge and groundwater recharge on its western edge.

The groundwater flow patterns within the western reaches of the wetlands (in areas where the Werillup



Symbols: - precipitation; × mean coastal groundwater; ✳ mean inland groundwater; ▲ wetland groundwater; □ lakes; ● creeks

Figure 5: A plot of $\delta^{18}O_a$ versus $\delta^{2}H_a$ (a-isotope activity ratios) for the Lake Warden wetlands system for winter (w), spring(sp) and summer(s) (2002-2003) samples. Coastal and inland are represented by mean values for respective seasons. Key: unshaded, grey and black colours denote winter, spring and summer samples respectively. PL-Pink Lake and LW-Lake Warden.

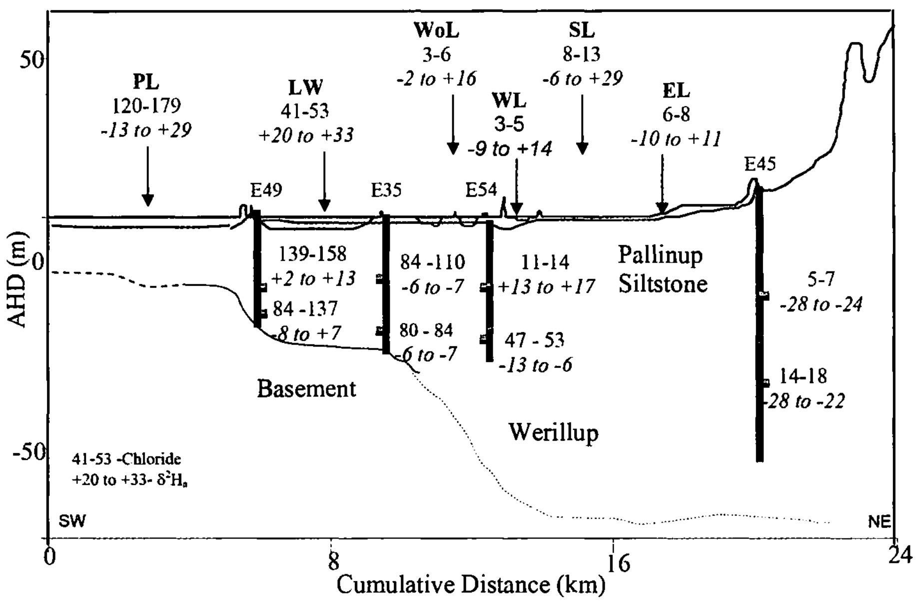


Figure 6: Southwest-northeast transect of chloride concentration (gL-1) and deuterium composition ($^0/_{00}$) in the Lake Warden wetlands system. The values for chloride and deuterium are the range for 2002-2003 seasonal sampling. Symbols are same as in Figure 1.

formation is not present) are further complicated by the existence of changes in the direction of the vertical gradients. The hydraulic head within the basement aquifers beneath Lake Warden and east is lower than the lake levels and the elevated hydraulic head of the upper aquifers suggests downward groundwater discharge in this region (Figure 3). The observed hydraulic head elevations in the Pink Lake agree well with the results of limited drilling records in Pink Lake (Hurle and Associates, 1986), and both suggest upward groundwater flow in this area.

The compilation and contouring the available data of the regional hydraulic information indicates that the main groundwater flow in the region is north south and the wetlands act as flow-through bodies (Figure 2). Conversely, the analysis within the wetlands system reveal a localized groundwater flow system that predominantly trends northeast southwest with the ultimate discharge point being Pink Lake. The groundwater flow is along an observed paleochannel. The deeper formations in the stratigraphy are recharging the surficial formations to the east of the wetlands, and the wetlands are, variously, acting as groundwater recharge, groundwater discharge, or neutral elements. The compilation of the localized hydraulic information leads to the conceptual model for the groundwater flow within the wetlands system (Figure 7). The total volume of groundwater flow is expected to be small however, due to the low hydraulic gradient and the low permeability of the siltstone facies which dominates the Lake Warden-Pink Lake area.

Despite the significant drilling and instrumentation that took place in this study, a conceptual model based on hydraulic information alone may be inadequate for fully understanding the interaction of flows in the wetlands. The conclusions drawn from the hydraulic data, therefore, will be tested with the chemical and isotope data.

5.2 Hydrochemistry

The coastal waters in the region are dominated by the chemistry of rainfall as is evidenced by similar Na/Cl ratios (Figure 4c) and absolute concentrations (Figure 4a). The inland groundwater in the Pallinup siltstone and the weathered basement rock aquifers generally shows slightly higher Na/Cl ratio than those found in precipitation. This is likely due to rock weathering in addition to sodium directly associated with chloride (Eugster and Jones, 1979; Drever, 1982; Herczeg and Edmunds, 1999).

The dissolved chloride concentration in the wetland groundwater samples increases along the northeast-southwest transect through the wetlands system (Figure 6), with groundwater samples well distributed along the evaporation line between the regional groundwater and lake end members (Figure 5). The highest dissolved chloride concentration was observed beneath Lake Warden (E49). Given the indication of a groundwater flow line along this transect by the hydraulic data, the increased concentrations are also impacted by the high concentration surface water recharge. This mechanism will be further explored in the next section with the stable isotope results.

The ratio of Na/Cl of the wetlands groundwater is nearly constant around 0.8 (Figure 4c) as the salinity increases. The increased concentration of Na^+ and Cl^- would have been contributed by the sea spray, diffusion loading from halite evaporates (NaCl) deposited in the underlying formation (Pallinup Siltstone) and/or solutes discharge from lakes as suggested by the downward discharge from the lakes within the wetland system (Figure 3). The constant Na/Cl ratio at high salinity is due to evapoconcentration and buffering of sodium by slow reactions involving mature clay silicate minerals with concentrated aqueous solution (Herczeg and Edmunds, 1999).

Utilization of other dissolved anion/cation data to further the development or refinement of the conceptual model is complicated by various factors. The coastal groundwater shows relatively higher calcium and bicarbonate compared with that expected from evaporation. Saturation with respect to calcite and dolomite in coastal groundwater samples suggests these evolve through dissolution of carbonate minerals. The increase in the concentration of Ca^{2+} of inland groundwater, creek and less saline lakes and some of the wetland groundwater can

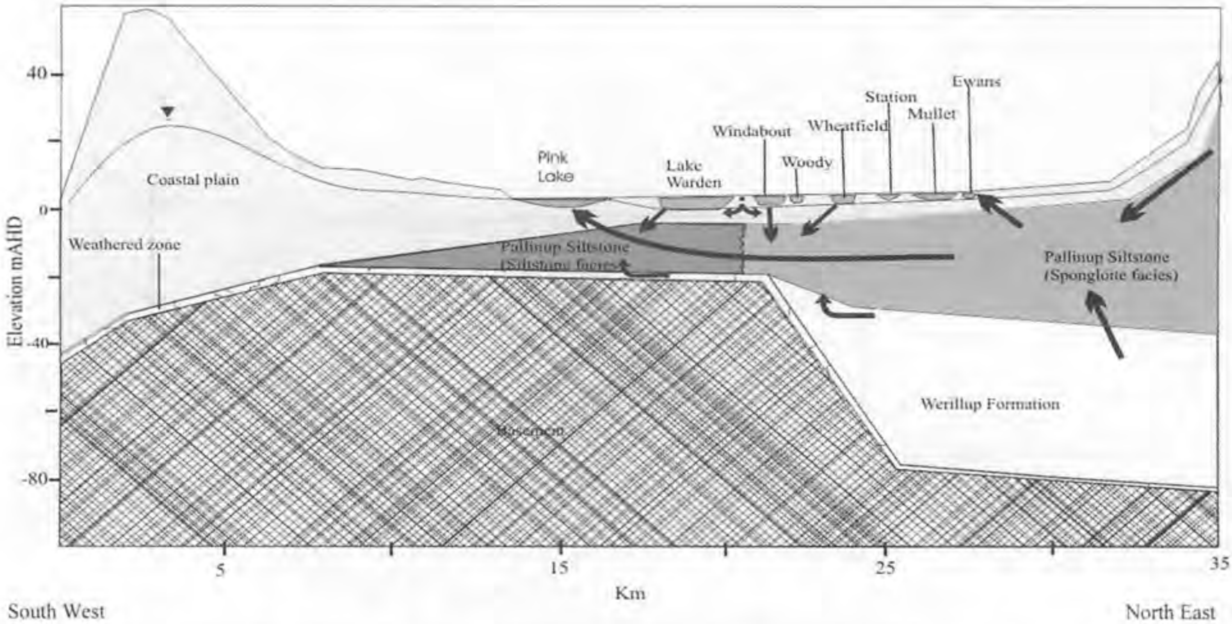


Figure 7: Conceptual model of the interaction between the regional groundwater and groundwater discharge zone. Arrows denote groundwater flow. Refer to Figure 1 for transect location.

be explained by conservative evapoconcentration and the concept of chemical divides (Hardie and Eugster, 1970). The decrease in HCO_3^- concentration and increase in the Ca^{2+} of the wetland groundwater samples and lakes at higher salinity suggest continued precipitation of carbonate minerals (Eugster and Jones, 1979).

The composition of the wetlands groundwater evolves along the evaporation line between the least saline groundwater and the brine (E49 and Pink Lake), and subsequent evaporative concentration leads to the successive precipitation of carbonate, gypsum and halite minerals. This down gradient evolution of groundwater chemistry can be used to indicate a flow path, and is in agreement with the hydraulic data. In addition to the evapoconcentration of the regional groundwater, past and present lake leakage may also contribute to the small solute concentration along the flow path as shown in the three-end mixing plot (Figure 8). From a geochemical standpoint, the composition and halite saturation index of the wetland groundwater beneath Lake Warden (E49) is similar to the composition of Pink Lake.

All the hydrochemical evidence suggests that Pink Lake is the discharge point for the regional groundwater flow system where evaporation gives rise to accumulation of brine and evaporite minerals. Interpretation of geochemical data in complex heterogeneous environments is a difficult task in isolation and in the final analysis has simply supported the processes hypothesized in the conceptual model derived from hydraulic data. The geochemical data, when utilized in combination with the stable isotope data, however, allowed for significant improvements to and verification of the conceptual model.

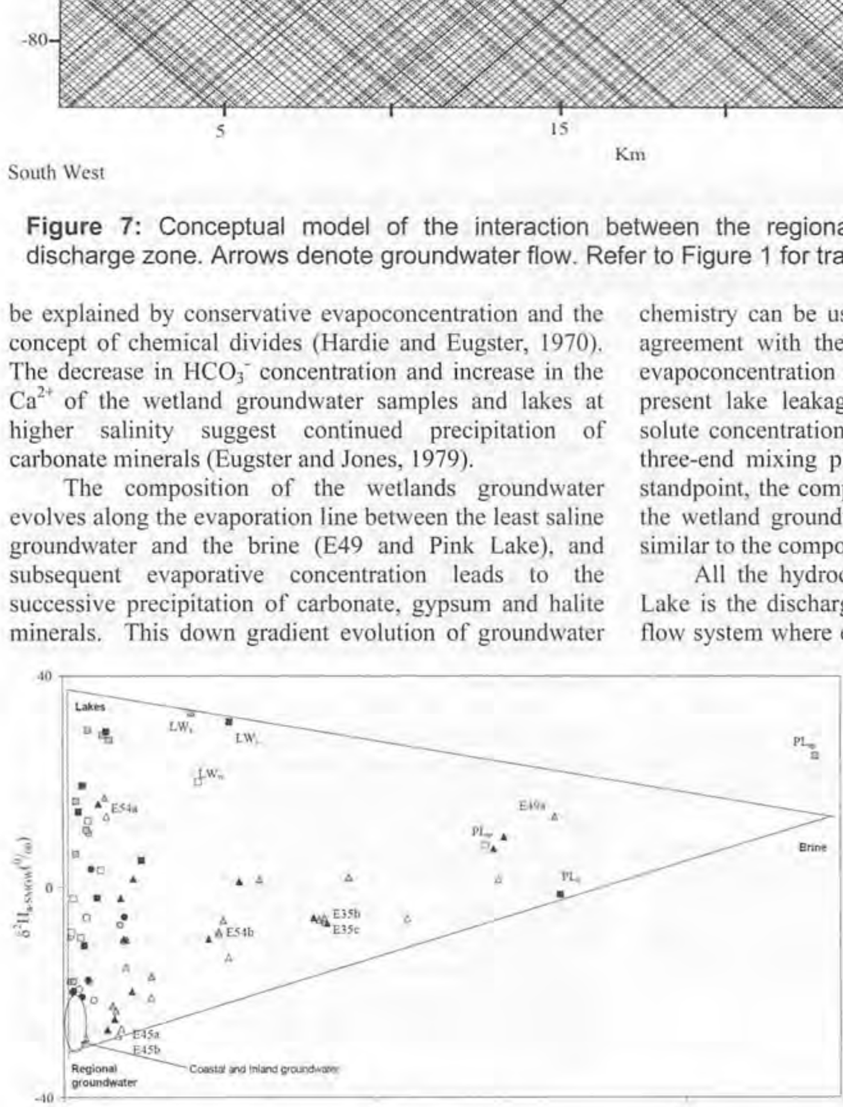


Figure 8: δ^2H_a versus chloride for the Lake Warden wetlands for winter (w), spring (sp) and summer (s) (2002-2003). E 45, E54, E35 and E 49 denote groundwater from wetlands along northeast-southwest transect. The triangle depict three-end member mixing between the regional groundwater, lakes and brine (E49 and Pink Lake). Symbols are same as in Figure 5.

5.3 Stable isotopes

The stable isotope measurements conducted during this study support the developed conceptual model in some key areas. The groundwater sampled from inland and the coastal plain boreholes cluster as a group in Figure 5, slightly below the LMWL, following the general EL which intersects the LMWL at δ^2H -46‰ and $\delta^{18}O$ -8.2‰. This isotopic composition is close to the weighted average composition of the winter depleted precipitation, indicating that the groundwater is recharged by depleted winter precipitation, which may have been modified by some degree of evaporation during or prior to recharge.

The mixing processes that were hinted at by the hydraulic data, and supported by the hydrochemical data, are defined in great detail when the stable isotope data are examined. Stable isotope measurements along the northeast southwest transect within the wetlands system all display intermediate isotopic characteristics between the regional groundwater and lake water (Figure 6). The isotopic composition from piezometer E45 located on the east (upgradient) side of the wetlands system, however, is very similar to that of inland groundwater. The continual enrichment of isotopic concentrations is quite visible along the transect towards Lake Warden (Figure 6). The stable isotope measurements allow for a better definition of the mixing beneath the lakes in the wetlands, and may indicate the presence of mixing "cells" which are more active beneath the lakes at the terminal (Warden and Pink) and starting (Station and Wheatfield) ends of the transect. In most locations beneath the wetlands lakes the isotopic composition of the groundwater from the intermediate aquifer (Pallinup Siltstone) is highly enriched relative to the deeper aquifer (Werillup Formation). The exception to this is in the location of borehole E35, where the isotopic signatures are identical in the intermediate and deep aquifers. The enrichment of the deeper aquifer is continuous along the transect, whereas the enrichment in isotope signatures in the intermediate aquifer is not. This discontinuity in the Pallinup siltstone aquifer is an indication of mixing cells, a process that could not be identified with the hydraulic or geochemical data.

The opposite situation, where the deeper aquifer is enriched relative to the intermediate aquifer, was found northeast of Pink Lake (E55 and E49B). These results suggest that regional basement flow along the northeast-southwest transect is mixed with the regional basement flow from the escarpment to a much more significant degree in this area. The isotopic composition of the groundwater from the escarpment ranges from -5.8 to –5.5 ‰ and -27 to –23 ‰ for $\delta^{18}O$ and δ^2H respectively. The groundwater sample (E58) collected on the eastern side of the Pink Lake is less enriched in isotopic composition and is similar to the coastal groundwater samples. Hurle and associates (1986) have also noted that the chloride content of the boreholes drilled in Pink Lake (123-157 gL^{-1}) is very much higher compared to the chloride content of E55. These findings, coupled with the chemical and hydraulic elevation data, support the hypothesis that Pink Lake is acting as a sink/terminal lake.

The isotopic signature data collected during this study also provided detailed information on the origin of the water entering the wetlands through the major creeks and streams. The isotopic compositions of creek water in the middle and downstream reaches of the creeks are significantly less enriched with respect to the upstream reaches and the isotopic values show some similarities to the average isotopic composition of inland groundwater. This would tend to indicate that there is preferential discharge of groundwater into the creeks along their lengths, followed by evaporation. The relative contributions of inland groundwater to the middle reaches of Coramup and Bandy Creeks were estimated using a two-end, mass-balance mixing model with $\delta^{18}O$ (Marimuthu et al 2005). The results suggest that groundwater is a predominant source for the creeks contributing between 50 to 70% of the creek flow.

The isotope data collected in this study proved invaluable in confirming the flow pathways and processes which were identified in a preliminary manner from the hydraulic and geochemical studies. The largest use of stable isotope techniques for this study, however, was an attempt to tie the temporal evolution of the surface waters in the wetlands system, to the evolution of the subsurface waters.

6.0 CONCLUSIONS

The spatial and temporal chemical and isotopic characterization of wetland groundwater has served to trace its movement clearly in the wetland, providing details not attainable from limited boreholes. For example, the north-south groundwater flow appears to follow the topography but the distinct higher chloride and isotopic concentration of the groundwater within the wetlands system did not reflect in the coastal plain groundwater. Similarly, the hydraulic elevation data within the wetlands only provides a point measurement and without the aid of the hydrochemistry and stable isotopes, many spatially distributed hydraulic head measurements would be required to determine the fine scale flow details in the system.

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