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PESTICIDE LEACHING POTENTIAL IN ORD RIVER IRRIGATION AREA, WA

A. H. M. Faisal Anwar[1*] and Lawrence Anak Saing[1]

***Abstract**: Increased use of pesticide in the agricultural fields has become one of the major environmental threats to soil and groundwater. Prediction of leaching potential of such chemicals in the subsurface is an essential prerequisite for their efficient and safe management as well as to establish realistic regulatory controls. In this study, pesticide leaching potential was assessed by computing Vulnerability Index (VI) and Pesticide Impact Rating Index (PIRI) for 24 different pesticides in the Ord River Irrigation Area (ORIA) of Kimberly Region in Western Australia. At first, the grid lines were constructed on the map of the study area and 160 locations were marked on the map to calculate VI and PIRI. Based on VI and PIRI results, 5 pesticides were identified having high leaching potential include ametryn, atrazine, diuron, fenarimol, and isoxaflutole. Calculated indices were ranked by quartiles for very high, high, moderate, low and very low category for all the locations in the study area. Based on this category, most vulnerable sites to pesticide leaching were identified in the vulnerability map. The presence of the pesticides in the groundwater was checked using the available data on pesticide residue in groundwater for the study area. Results revealed that the concentration of Atrazine in the very high vulnerable site exceeds the Australian and New Zealand guidelines (>0.5µg/L). Thus the method of VI or PIRI applied here can be used as important planning tools for early identification of agricultural areas susceptible to groundwater contamination by pesticide leaching.*

***Keywords**: pesticide, irrigation area, leaching potential, vulnerable,*

INTRODUCTION

Pesticide leaching from agricultural fields poses a potential threat for groundwater contamination. Such pollution events have been detected in many countries (Teso et al., 1988; Pionke and Glotfelty, 1989; Kookana et al., 1998). The potentially widespread nature of resulting contamination makes remedial actions difficult because there is no single plume emanating from a point source that can be isolated and controlled. A more prudent approach to prevention or reduction of groundwater contamination by pesticides must be based on understanding of the relationships among chemical properties, soil system properties and the climatic and agronomic variables that combine to induce leaching. Knowledge of these relationships can allow a priori investigation of conditions that lead to problems and appropriate actions can be taken to prevent widespread contamination.

Several investigators have studied the factors contributing to pesticide leaching (Gish et al., 1991; Sichani et al., 1991; Agertved et al., 1992). Their investigations have shown that chemical solubility in water, sorptive properties, pesticide formulation and soil persistence determine pesticide leaching. Similarly, the important environmental and agronomic factors include soil properties,

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climatic conditions, crop type, water management methods and cropping practices. Many of the environmental factors are highly time-variable and soil properties are spatially variable. In short, the hydrological cycle interacts with the chemical properties and characteristics to transform and transport pesticides within and out of the soil profile. Vertical movement out of and below the root zone can result in groundwater contamination. One of the important parts to manage the pesticide leaching in groundwater is the identification of areas susceptible to pesticide contamination. A number of techniques have been developed for assessing the vulnerability of groundwater to leaching contamination by organic contaminants. Some of these methods are based on subjective scoring. A model known as DRASTIC (Aller et al. 1985) involves assigning weightage to various factors influencing leaching. Other qualitative assessment schemes include those of Teso et al. (1988) and Le Seur et al. (1987). Methods that offer a more quantitative assessment of groundwater vulnerability include Rao et al. (1985), Meeks and Dean (1990), Kookana and Aylmore (1994), Di et al. (1995), Kookana et al. (1998), Schlosser et al. (2002) and Kookana et al (2005). Among these studies, it is important to use a relatively simple quantitative approach that uses easily obtainable information to assess the groundwater vulnerability and rank the pesticides based on their leaching potential.

The objective of this study was to assess the pesticide leaching risk in an irrigated area based on the calculation of vulnerability index-VI and Pesticide Impact Rating Index (PIRI). The most commonly used pesticides and the vulnerable areas are ranked together based on their VI and PIRI. The high leaching risk sites were checked for pesticide residues present in groundwater.

THEORETICAL CONSIDERATION

Vulnerability Index (VI)

The most common approaches for the assessments of groundwater vulnerability are the statistical/empirical methods and methods based on the solute-transport theory (Rao et al., 1985;, Jury et al., 1987; Meeks and Dean, 1990; Kookana and Aylmore, 1994). These methods are based on the one-dimensional advective-dispersive transport equation for a non-conservative chemical that follows first order decay and linear adsorption in soils. Using simplified assumptions and steady state conditions, Meeks and Dean (1990) derived an indicator for leaching potential of pesticides which is designated as the Leaching Potential Index (LPI):

$$LPI = \frac{1000v}{R\lambda y} \tag{1}$$

where R = retardation factor; v = soil-water velocity (L/T); λ = first order decay rate of the chemical in the soil (T^{-1}); and y = vertical depth (L). Later, Schlosser et al. (2002) presented a modified formulation of Equation (1) for the assessment of aquifer vulnerability based on leachability ratio ($t_{1/2}/k_{oc}$) and site-specific characteristics. This formulation is termed as vulnerability index (VI):

$$VI = \frac{200K\theta_C}{z\rho_b(\%OM)}\left(\frac{t_{1/2}}{k_{oc}}\right)F_{dgw} \tag{2}$$

where ρ_b is the soil bulk density [M/L^3], k_{oc} is pesticide organic carbon partitioning coefficient [L^3/M], θ_C is field capacity moisture content (L^3/L^3), K represents saturated hydraulic conductivity (L/M) and $t_{1/2}$ represents the pesticide half-life (T). The z-term represents the thickness of the shallow zone within which the sorption and biodegradation occurs, this is not the depth of vadose zone, %OM is the percentage organic matter present in the soil and F_{dgw} is the multiplying factor to account for the depth to water table. The multiplying factor of 200 in VI is arbitrarily included to increase the numerical value to yield a range deemed more reasonable. This VI value can be used for identifying the vulnerable areas to pesticide leaching. Higher values of VI indicate a greater vulnerability of groundwater to pesticide leaching.

Pesticide Impact Rating Index (PIRI)

Pesticide Impact Rating Index (PIRI) is a risk indicator which provides the relative risk rating of pesticide leaching to groundwater (Kookana et al., 2005). In PIRI model, the Attenuation factor of Rao et al. (1985) was modified to allow for multiple layers. The movement of pesticide in soil is retarded due to the sorption of pesticide to the soil organic matter which is quantified by the Retardation factor (R in Eq 2):

$$R = 1 + \frac{\rho f_{oc} k_{oc}}{\theta_c} \tag{3}$$

where f_{oc} is the organic carbon content (M/M). The rate of water movement in the soil profile is represented by the recharge rate (q) and θ_C. The fraction of the pesticide that is lost through degradation will depend on the residence time t in the soil and the decomposition rate. The residence time in a soil profile of known depth y is given by:

$$t = \frac{y\theta_c R}{q} \tag{4}$$

The retardation factor and the pesticide half life remain unchanged throughout the soil profile for a particular pesticide but organic carbon content and the microbial activities may decrease significantly with depth (Kookana and Alymore, 1994). This has a significant impact in pesticide leaching and hence it is incorporated in PIRI (Kookana et al., 2005).

STUDY AREA

Ord River Irrigation Area (ORIA) (Kununurra) in the east Kimberly region of Western Australia is selected as the study area (Fig. 1). Kimberly region is located in the northern province of Australia which straddles the border between the Western Australia and Northern Territory. The ORIA is situated on the black soil plains associated with the Ord and Keep Rivers (O'Boy et al., 2001). The Ord River is regulated by two dams, Kununurra Diversion Dam (KDD) and Ord River Dam. The Ord River Dam impounds Lake Argyle which supplies water within the irrigation area and supplies power to the Kununurra town. The climate is tropical monsoon with the wet season occurs from early December to the end of March. The dominant soil in the ORIA consists of cracking clay from the Cununurra and Aquitaine families (Schoknecht and Grose, 1996). The overall soil condition of the area is in favour of various crop productions (ORIA, 1997). The ORIA is made up of Ivanhoe Valley, Packsaddle Plain, Carlton Hill Plain, Mantinea Flat, Weaber Plain, Keep River Plain, Knox Creek and West Ivanhoe Plain from which only Ivanhoe and Packsaddle plains (stage 1 of ORIA) are considered in this study for vulnerability assessment (Fig. 2). Irrigation areas of Ivanhoe Plain and Packsaddle Plain are 13000 ha and 2500 ha repectively. The main crops grown in ORIA are sugarcane, cucurbits, fruits, and hybrid seeds.

The groundwater levels beneath ORIA (Ivanhoe Plain and Packsaddle Plain) are in the range of 1m – 8m (Ali and Salama, 2003). Because of the increased irrigated agriculture, pesticide use in the area has also been increased. Thus, the shallow groundwater table in ORIA is likely to be threatened by pesticide contamination.

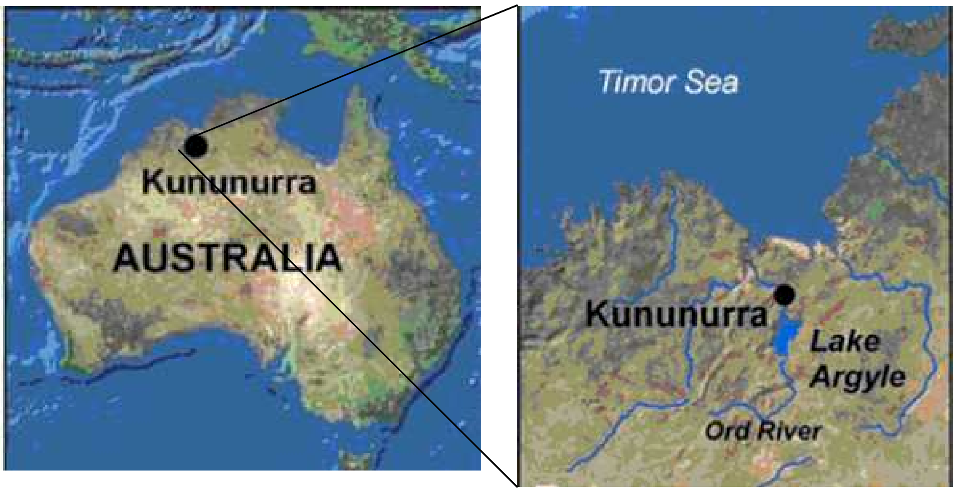


Fig. 1 Location map of the study area

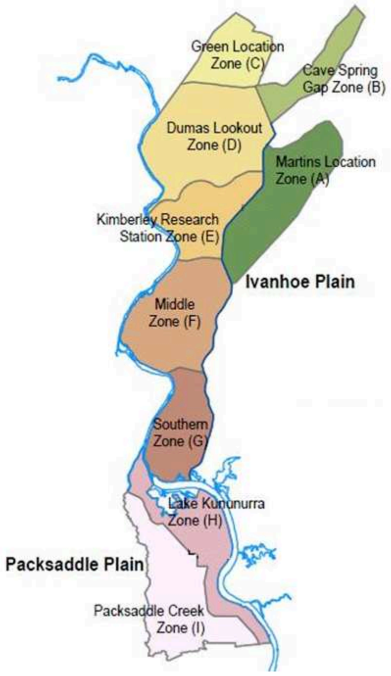


Fig. 2 Different zones in ORIA- Stage 1(Ali and Salama, 2003)

DATA COLLECTION

At first, the grid lines were constructed on the map of the study area at 1.25 kilometre intervals running from north to south and from west to east for ease of reference to the locations selected for

VI and PIRI computation and 160 locations were marked on the map. Required soil data for VI and PIRI calculation were collected from Australian Soil Resource Information System (ASRIS), climatic data from Bureau of Meteorology-Australian Government, and pesticide data were collected from the literatures. Twenty-four pesticides were selected which are most commonly used in the different crops such as, sugar, hybrid seeds, mangoes and melons. The pesticides half-life and organic carbon partitioning coefficient were taken from Oliver and Kookana (2005-06). Soil parameters such as, soil bulk density, soil organic matter, topsoil thickness, and hydraulic conductivity were extracted from ASRIS. The moisture content remains constant at 1m depth which was taken as the field capacity throughout the irrigation period. The F_{DGW} is based on the vadose-zone thickness of aquifer in ORIA. The thicker the vadose-zone, the smaller the multiplying factors are assigned to the VI model because the thickness of vadose-zone directly influences the amount of pesticides that reaches the groundwater. In Schlosser et al. (2002), the best multiplying factors are listed for four 5m intervals (0-5; 6-10; 11-15 and >15) thickness. These factors are 3, 2.5, 2 and 1 for each 5m intervals. These groupings were done by trial-and error calibration with the pesticide data. Due to the unavailability of the pesticide concentration history in the study area, these factors were used in this study. The groundwater levels data were taken from Department of Water (DoW), Government of Western Australia. The groundwater recharge rate is needed for the calculation of PIRI and a conservative value of recharge rate for different soil types (clay, clay loam and sandy clay loam) were assumed for all land-use types. The pesticide data (sorption, persistence, application rate and frequency of application) were obtained from Oliver and Kookana (2005-06).

DATA ANALYSIS AND DISCUSSION

Vulnerability Index (VI)

The pesticides were first ranked to different leaching class based on the leachability ratio ($t_{1/2}/k_{oc}$) (Schlosser et al. 2002). Pesticide with leachability ratios <0.01 were assigned to the low leachability class; pesticides with ratios ≥0.01 and <0.1 were placed in the moderately leachable class; and pesticides with ratios greater than or equal to 0.1 were assigned to the high leachability class. These classifications were made similar to Schlosser et al. (2002) where breaks of these groups occurred at the 30th percentile and 63rd percentile on a cumulative frequency diagram for 340 pesticides. Based on the calculated VI, vulnerability maps were produced for low, moderate and high leachabilty class as shown in Fig. 3.

Vulnerability maps show that the pesticide with high leachability is more vulnerable to leaching. Again, variability of soil organic matter and hydraulic conductivity in the area might produce significant variation in leaching. It should be noted that the hydraulic conductivity is higher along the east of Ord River in Ivanhoe plain and the soil organic carbon is higher in the Packsaddle plain which are more susceptible to leaching than the other areas. Vulnerability index in Eq. 2 depends on the hydrologic factors and pesticide properties. The hydrologic factors may be constant for a particular well location. For this reason, VI should be calculated for each of the leachability classes. The vulnerability for two different pesticides may be different in one location because of the difference in hydrophobicity and biodegradibility of pesticides (Schlosser et al. 2002). Pesticide vulnerability to leaching was done by ranking the numerical VI value by quartiles in Excel into very low, low, moderate, high and very high risk categories to identify the most vulnerable areas as given in Table 1. This categorization provides the spatial distribution of VI in the study area. The results revealed that the pesticide vulnerability based on VI value strongly depends on the leachability class but do not necessarily have any correlation with it. Low leachabilty class have very low risk, medium leachabilty has low and moderate risk and high leachabilty has high and very high risk of pesticide leaching.

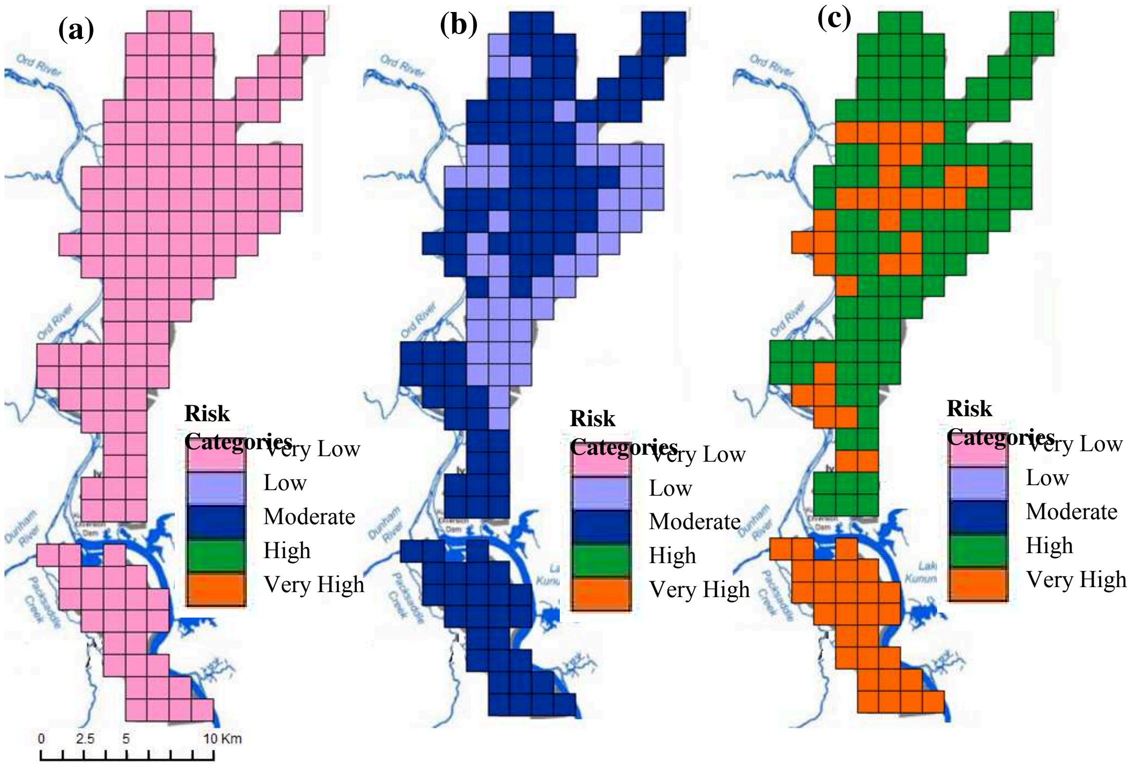


Fig. 3 Vulnerability map based on VI for the (a) low, (b) medium and (c) high leachability class

Table 1: Spatial distribution of VI in the study area for different leachability class

Risk categories	Quartile Range	VI Rank	Leachability class					
			Low		Medium		High	
			Number of sections	% of study area,	Number of sections	% of study area,	Number of sections	% of study area,
Very Low	≤24	<1	160	100	-	-	-	-
Low	25-49	2 – 7	-	-	47	29	-	-
Moderate	50-74	8 – 19	-	-	113	71	-	-
High	75-89	20 – 49	-	-	-	-	100	63
Very High	≥90	>50	-	-	-	-	60	37

Again, pesticides were also classified by quartiles in the same way into very low, low, moderate, high and very high risk leaching category for all the pesticides for all 160 sites. Each of the 24 pesticides was ranked based on these classifications with respect to their predicted VI which is given in Table 2. The groundwater depth do not varied considerably in Ord River irrigation area and thus it has relatively little influence on the defining factor for the depth to groundwater as well as its predicted vulnerability. Table 2 shows that 7 pesticides were found in very high and high risk categories.

Table 2 Pesticide ranking based on their leaching potential

Risk categories	Quartile Range	VI Rank	Pesticides
Very Low	≤24	<1	Beta Cyfluthrin; Chlorothalonil; Chlorpyrifos; Cypermethrin; Endosulfan; Glyphosate; Imidacloprid; Mancozeb; Pendimethalin; Thiodicarb; Trifluralin
Low	25-49	2 – 7	Carbaryl; Propiconazole
Moderate	50-74	8 – 19	2, 4-D; Ametryn; Fipronil; Fluroxypyr
High	75-99	20 – 49	Atrazine; Bupirimate; Diuron; Methomyl
Very High	100	>50	Fenarimol; Isoxaflutole; Trichlorfon

Pesticide Impact Rating Index (PIRI)

The leaching of pollutants to the groundwater is influenced by many variables such as, meteorological parameters (eg. rainfall and temperature), soil properties (soil texture and organic carbon content) and pesticide properties (Meeks and Dean 1990). The two key parameters such as, recharge rate and organic carbon content are needed in PIRI calculation. Due to the heterogeneous nature of the soil and the variable infiltration rate, pesticide in soil may have slow degradation and provide faster downward movement. For this reason, three soil types such as, clay, clay loam and sandy clay loam; and two organic carbon content of 0.5% and 1.1% were considered in PIRI simulation. PIRI simulations were performed for four main land-uses such as, cucurbits, hybrid seeds, sugarcane, and fruits. One of the PIRI output for sugarcane is presented in Fig. 4. Five pesticides, out of 24, used in 4 land-use types were found having high leaching risk include: atrazine, fenarimol, diuron, isoxaflutole, and ametryn. It is to be noted here that all of these pesticides were ranked as high leaching class in VI except ametryn. However, the high pesticide leaching risks was found in sandy clay loam and clay loam soil with low soil organic carbon content. Results showed that changing the soil types would have significant impact to the leaching potential of pesticide. Sandy clay loam soil has the highest recharge rate and followed by clay loam soil, while clay soil has the lowest recharge rate. Results revealed that the higher recharge rate and lower soil organic matter increased the risk of pesticide leaching to the groundwater.

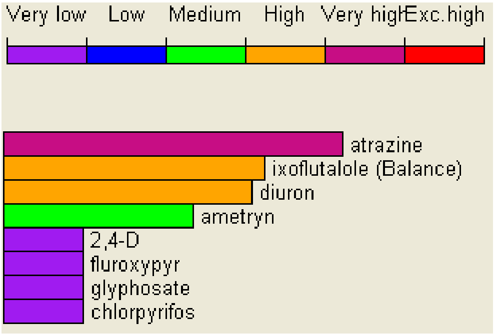


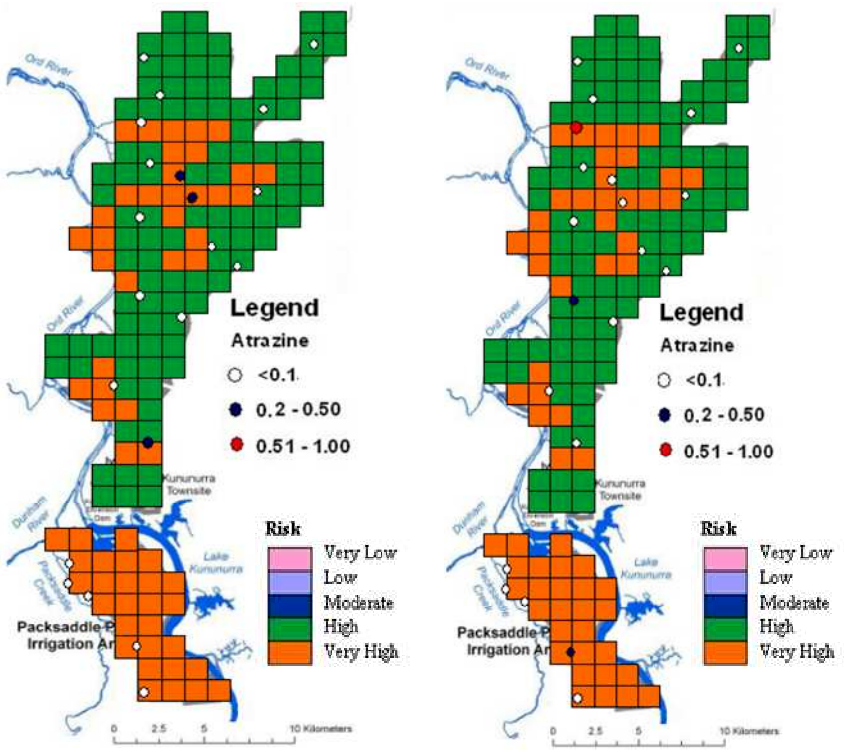
Fig. 4 PIRI results for sugarcane in sandy clay loam

Presence of Pesticide Residues in Groundwater

It was revealed in PIRI results that atrazine is the highest leaching potential pesticide in ORIA. The 160 locations in ORIA were classified based on the pesticide leaching risk for different pesticides based on the VI value. The most susceptible atrazine leaching zone was identified in the vulnerability map. Total 23 sampling sites of Department of Water, Government of Western Australia were found in ORIA where the groundwater samples are analyzed for three pesticides (atrazine, chlorpyrifos and endosulfan) residues. The last pesticide residues analysis was conducted in June 2006 and November 2006 respectively for these sites. The atrazine concentration in groundwater is shown in the vulnerability maps given in Fig. 6. Atrazine concentration was detected in three locations falling in the very high leaching potential zone. In one of the site, atrazine concentration exceeded the Australia and New Zealand guidelines of 0.5μg/L (ANZECC and ARMCANZ, 2000) in November 2006. Again in this location, atrazine concentration did not exceed the permissible limit in June of the same year. The concentration of atrazine was found low in some sites of the high vulnerable areas as predicted by VI. This is because of that the pesticide leaching potential is sensitive to a number of factors, particularly the soil factors and land management practices. In VI model, these factors are omitted that could be associated with the soil conditions (eg. preferential flow path, low permeability layer) and land management practices (Schlosser et al., 2002). On the other hand, chlorpyrifos and endosulphan were predicted as low leaching category pesticides and hence, there was no detection in any of the groundwater samples of the area.

CONCLUSION

Vulnerability Index (VI) and Pesticide Impact Rating Index (PIRI) were used to evaluate the risk of pesticide leaching to groundwater in the Ord River Irrigation Area (ORIA) in Western Australia. These methods are simple screening tools to predict the contamination potential of pesticide using chemical, hydro-geological and land management data. Twenty-four pesticides were first classified into three leachability class based on the leachability ratio ($t_{1/2}/k_{oc}$). Calculated VI was ranked by quartiles into very low, low, moderate, high and very high category to rank different pesticides in one location or one pesticide in different locations. Higher VI represents higher vulnerability to pesticide leaching. A semi-quantitative assessment is performed in PIRI which provides relative risk rating of pesticides among different land-use settings. In this analysis, pesticides are ranked in term of their potential behavior in the environment. Atrazine was found as the most critical pesticide that might have significant leaching in the area. The most vulnerable sites for atrazine leaching, as identified by VI, were checked for atrazine residues in groundwater. Examining the available groundwater quality data in the area, it was found that atrazine concentration exceeds the permissible limit of 0. 5μg/L in one of the most vulnerable sites. However, atrazine was not found in all the high leaching areas because of the heterogeneous nature of the porous media and the simplified assumptions used in developing the models. But both the methods, used herein, provide a relative ranking of pesticides based on their leaching potential. This ranking may be used to determine the pesticide in concern which may serve as a basis on selection/substitution of the pesticides for agricultural land management practices.



(a) (b)

Fig. 6 Atrazine detection (µg/L) in groundwater sampled in (a) June 2006 (b) November 2006.

REFERENCES

Agertved, J., Rugge, K. and Barker, J.F. 1992. Transformation of the herbicide MCPP and atrazine under natural aquifer conditions, *Groundwater*, **30**(4): 500-506.

Ali, R., and Salama, R.B. 2003. Groundwater quality in the Ord irrigation area, its suitability for irrigation and prediction of salinity and sodicity hazards. CSIRO Land and Water, Perth, Technical Report No 7/03, June.

Aller, L.T., Lehr, J.H. and Petty, R.J. 1985. DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeologic settings, U.S. EPA (600/2-85/0180).

ANZECC and ARMCANZ 2000. "Australian and New Zealand Guidelines for Fresh and Marine Water Quality, Volume 1, The guidelines", Australian and New Zealand Environment and Conservation Council, Agriculture and Resource Management Council of Australia and New Zealand, Canberra.

Australian Soil Resource Information System (ASRIS) – the database. CSIRO Land and Water, available at http://www.asris.csiro.au.

Australian Bureau of Meteorology (BOM). "Monthly climate statistic for Kununurra". Western Australia. http://www.bom.gov.au/.

Di, H.J., Kookana, R.S. and Aylmore, L.A.G. 1995. Application of a simple model to assess the groundwater contamination potential of pesticides, *Aust. J. Soil Res.*, **33**, 1031-1040.

Gish, T.J., Isensce, A.R., Nash, R.G., and Helling, C.S. 1991. Impact of Pesticides on

Shallow Groundwater Quality, Soil and Water Division, *Transactions of the ASAE*, **34**(4): 1745-1753.

Jury, W.A., Focht, D.D. and Farmer, W.J. 1987. Evaluation of pesticide ground water pollution from standard indices of soil-chemical adsorption and biodegradation, *J. Environ. Qual.* **16**(4): 422-428.

Kookana, R.S., and Aylmore, L.A.G. 1994. Estimating the pollution potential of pesticides to groundwater. *Aust. J. of Soil Res.* **32**, 1141-1155.

Kookana, R. S., Baskaran, S. and Naidu, R. 1998. Pesticide fate and behavior in Australian soils in relation to contamination and management of soil and water: A review. *Aust. J. of Soil Res.* 36, 715-764.

Kookana, R.S., Correll, R.L. and Miller, R.B. 2005. Pesticide impact rating index: A pesticide risk indicator for water quality. *Water, Air, & Soil Pollution: Focus* **5**: 45-65.

Le Seur, L.P., Wehrmann, H.C., Schock, S.C., and Shafer, J.M. 1987. Prioritizing Areas for State-wide Groundwater Monitoring, *J. of Water Resour. Plan. & Management,* **113**(2):204-215.

Meeks, Y.J., and Dean, J.G. 1990. Evaluating groundwater vulnerability to pesticides. *J. of Water Resour. Plan. & Management* **116**(5): 693-707.

O'Boy, C. A., Tickell, S. J., Yestertener, D. P., Commander, D.P., Jolly, P. and Laws, A.T. 2001. Hydrogeology of the Ord River Irrigation Area, Water and Rivers Commission, Western Australia. Hydrogeological Record Series Report HG7.

Oliver, D., and Kookana, R. 2005. Pesticide use in the Ord River Irrigation Area, Western Australia, and risk assessment of off-site impact using Pesticide Impact Rating Index (PIRI). CSIRO Land and Water Technical Report No 10/05, July.

Oliver, D., and Kookana, R. 2006. Minimising the off-side impact of pesticides in the Ord River Irrigation Area (ORIA), Final summary report 2006. CSIRO Land and Water Science Report No 12/06, June.

Ord River irrigation area: Kununurra Western Australia. 1997. 5th ed. Agriculture Western Australia.

Pionke, H.B. and Glotfelty, D.E. 1989. Nature and extent of groundwater contamination by pesticides in an Agricultural Watershed", *Water Res.*, **23**(8): 1031-1037.

Rao, P.S.C., Hornby, A.G. and Jessup, R.R. 1985. Indices for ranking the potential for pesticide contamination of groundwater. *Proceedings Soil and Crop Science Society of Florida* **44**: 1-8.

Schlosser, S.A., McCray, J. E., Murray, K. E., and Austin, B. 2002. A subregional-scale method to assess aquifer vulnerability to pesticides. *Groundwater* **40**(4): 361-367.

Schoknecht, N. and Grose, C. 1996. Soils of the Ivanhoe west bank East Kimberly Western Australia. Western Australia: Department of Agriculture, Resource Management Technical Report 155.

Sichani, S.A., Engel, B.A., Monke, E.J., and Kladivko, E.J. 1991. Validating GLEAMS with Pesticide Field Data on a Clermont Silt Loam Soil, *Transactions of the ASAE*, **34**(4): 1732- 1737.

Teso, R. R., Younglove, T., Peterson, M.R., Sheeks, D.L. and Gallavan, R.E. 1988. Soil Taxonomy and Surveys: Classification of Areal Sensitivity to Pesticide Contamination of Groundwater, *J.of Soil and Water Conservation.*, **43**(4):348-352.