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**Investigation of Pesticides in Groundwater at
Three Irrigated Sites Near Outlook, Saskatchewan**

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Management Perspective

During the past 15 years, there has been a growing concern about the potential for pesticides to contaminate groundwater. This contamination may lead to associated health risks because of both the inherent toxicity of pesticides at very low concentrations and high dependence of rural residents on groundwater for their drinking water needs (over 90% of rural residents in Canada rely on groundwater). The potential link between groundwater contamination from pesticides and human health has prompted federal and provincial government agencies to assess the fate of pesticides in the subsurface and to enact regulations designed to protect Canada's groundwater from pesticide contamination.

It is generally thought that the meteorological and hydrogeological conditions found in the southern and central Saskatchewan are not conducive to pesticide transport to the water table because the low amount of precipitation combined with high evaporation rates limit the potential for recharge, the water table is often very deep, and the matrix hydraulic conductivity of the dominant surficial deposits of the region (tills and lacustrine sediments) is very low. However, the results of this study indicated that the use of pesticides at three agricultural sites in the Outlook Irrigation District of Saskatchewan has resulted in traces amount of pesticides being detected in some samples collected from piezometers installed in the shallow groundwater regime. It is suspected that the pesticides were able to migrate to the water table through vertical fractures which are commonly found in the underlying tills and silts. When combined with irrigation that is applied at these site, these two factors create a mechanism for the considerable more rapid movement of pesticide and to greater depths of leaching than would occur in unfractured sediments (i.e. intergranular flow) and under typical precipitation conditions.

ABSTRACT

During 1987 and 1988, the pesticides 2,4-D, diclofop-methyl, dicamba, MCPA, triallate, and bromoxynil were detected in shallow groundwaters beneath three irrigated research sites in the Outlook Irrigation District of Saskatchewan. All of the pesticide detections were below the limits set by the Canadian Drinking Water Quality Guidelines. Meteorological and hydrogeological conditions are generally not conducive to pesticide leaching to the water table in this region. However, it is suspected that the pesticides applied at the surface were able to migrate to the water table through the numerous vertical fractures that exist in the tills and silts underlying the fields. When combined with irrigation that is applied at these site, these two factors create a mechanism for the rapid movement of pesticide to a greater depth of leaching than would occur in unfractured soils and with typical precipitation. Further, it is suspected that storage of pesticide in the soil matrix and subsequent desorption during later intense recharge or irrigation events is responsible for observed pesticide detections weeks or months after a pesticide was applied.

INTRODUCTION

Numerous studies have documented the widespread occurrence of groundwater contamination by pesticides in agricultural areas throughout Canada, even when used within recommended application guidelines (Gilles and Walker 1986; Frank et al. 1987a, 1987b, 1990; Jackson et al. 1990; Waite et al. 1992; Liebscher et al. 1992; WCGR et al. 1992). Unlike many regions of Canada, reported incidences of the contamination of groundwater by pesticides are rare in Saskatchewan. Still, given the extensive use of agricultural pesticides in the province, the inadvertent contamination of groundwater supplies may be a potential threat to human health because of the inherent toxicity of pesticides at low concentrations, compounded by the importance of groundwater as the source of drinking water for most rural residents and municipalities (90% of rural residents and 81% of municipalities in Saskatchewan (Hess 1986)).

Studies have shown that meteorological and hydrogeological conditions found in the prairies are not conducive to pesticide transport to the water table (Crowe and Mutch 1992; Pupp et al. 1991). Specifically, the low amount of precipitation combined with high evaporation rates limit the potential for recharge, the water table is often very deep, and the matrix hydraulic conductivity of the dominant surficial deposits of the region (tills and lacustrine sediments) is very low. However, it is recognized that fractures are common in many of these deposits (Grisak and Cherry 1975; Schwartz 1975; Hendry 1982; Keller et al. 1986), and the presence of fractures, occupying a very small percentage of the total volume of the soil profile, can account for the majority of vertical flow (Blake et al. 1973; Beven and Germann 1982; Ewing and Jaynes 1995). The presence of fractures may increase the potential for pesticides to migrate to the water table in Saskatchewan.

The purpose of this paper is to present the results of a study designed to determine if pesticides which are commonly used in agricultural regions of central Saskatchewan will leach to the water table. In addition, possible mechanisms that contribute to pesticide leaching will be discussed. The pesticides evaluated in this study are diclofop-methyl, dicamba, MCPA, bromoxynil, 2,4-D amine, trifluralin, and triallate.

Three irrigated sites, in central Saskatchewan (Figure 1) were selected. These sites are known as (1) the Pederson site, (2) the Saskatchewan Irrigation Development Centre (S.I.D.C.), and (3) the Konst site. The study areas are within the Outlook Irrigation District, which is part of the South Saskatchewan River Irrigation Project.

Regional Setting

The three study sites are situated on the Outlook Plain (Ellis et al. 1968). The topography is nearly level, to gently undulating. The Plain has limited drainage to the South Saskatchewan River and there are no natural year-round drainage courses on or near any of the three study sites.

The Outlook area falls within the arid to semi-arid climatic zone. The mean annual precipitation, over the period 1951-1980, was less than 300 mm (Environment Canada 1986). On average, there are fewer than 100 days per year with measurable precipitation. The mean annual July daily temperature is approximately 18°C; for January is -17.5°C. Evapotranspiration is very high, with of mean annual lake evaporation of 800 mm to 900 mm (Ferguson et al. 1970). The number of growing season degree-days with temperature above 5°C is from 1250 to 1500.

Most agricultural sites in the region are irrigated because of the net annual water deficit. The water used for irrigation at the three sites is pumped from Lake Diefenbaker (Figure 1). The distribution system is operated by the Saskatchewan Water Corporation.

DESCRIPTIONS OF THE THREE STUDY AREAS

The Pederson Site

The Pederson site is irrigated using the flood corrugation method, by which water applied to a sloped parcel of land flows from high to low elevation under gravity, directed by numerous closely spaced shallow furrows cut into the land parallel to the direction of maximum slope. This site has also been investigated for pesticide runoff in irrigation return flow (Nicholaichuk et al. 1986, 1988). The Pederson site is drained artificially, by means of a north-south ditch which cuts across the site (Figure 2). This ditch was placed to intercept excess irrigation water (return flow) flowing either over the surface or through the shallow subsurface from the irrigated field during and following irrigation. The ditch contains water only during irrigation, spring runoff, and heavy precipitation events.

The location of test holes and piezometers used to investigate the stratigraphy of the site, hydrogeological conditions, and monitor for pesticides are shown in Figure 2. Two test holes, 87-01 and 87-02, were drilled to a depth of 18 metres to investigate site stratigraphy.

The site is underlain by poorly permeable glaciolacustrine silts and clayey silts, with some interlayered sands. These are the most widespread surficial deposits in the Outlook area

(Saskatchewan Research Council 1986). A thick glaciofluvial sand unit, encountered by piezometer 87-13 (cross section B-B' in Figure 3), rests unconformably on a silt or silty clay which is found at surface in the other auger holes drilled on the site. This glaciofluvial sand is not evident a short distance to the north (see cross section A-A' in Figure 3). Two till units are encountered beneath the silts, silty clays, and sands. The uppermost unit is a soft, sandy, calcareous brown till which is generally oxidized. This unit is laced with small sand layers of unknown areal extent. In cross section B-B', the similarity of stratigraphy between holes 87-02 and 87-10 indicates that some of these intertill sands may be continuous over the western half of the site. The lower till is harder than the above, olive grey in colour, oxidized, and fractured with gypsum found lining the fractures.

The soil at this site is a chernozemic dark brown soil which developed on medium to fine-textured silty glaciolacustrine deposits belonging to the Elstow Association (Ellis et al. 1968).

The S.I.D.C. Site

The Saskatchewan Irrigation Development Centre (S.I.D.C.) is an irrigation development farm administered by the Saskatchewan Water Corporation (S.W.C.) and the Prairie Farm Rehabilitation Administration (Figure 4). The S.I.D.C. is irrigated using both side roll and centre pivot sprinklers. The S.I.D.C. was originally established in 1949 as the Outlook Predevelopment Farm, to demonstrate the benefits of irrigation in a dryland agricultural environment (Jones and Lebedin 1986). The use of irrigation on the site has been the cause of a progressively worsening soil water logging and salinization problem, which by 1987 had rendered approximately 20 hectares of the land unsuitable for demonstration purposes. As a part of a plan to reduce soil salinity on the site and reclaim the area which has been lost to salinization, a subsurface drainage network was installed in 1986 under Field 11, in the southwest corner of the site (Figure 4). Ten piezometers were installed on the S.I.D.C. site, using a cable tool rig. Their locations are shown in Figure 4.

The stratigraphy of the S.I.D.C. site is illustrated by Figure 5. Jones and Lebedin (1986) describe two main hydrostratigraphic units, K1 and K2, at the S.I.D.C. site which were easily delineated in the auger holes drilled for this study. The uppermost (K1) zone consists of silt and silty sand. The underlying K2 zone is a clayey till. The hydraulic conductivities of the K1 and K2 units are about 10^{-5} m/s and 10^{-7} m/s, respectively. Till is encountered beneath the K2 unit. From an interpretation of data available from the present study, it is apparent that the K1 unit is an

unconfined, possibly perched aquifer. This is in agreement with Jones and Lebedin (1986).

Observation well hydrographs indicate that irrigation is responsible for the upward movement of the water table observed since 1981 when monitoring began. The amount of recharge provided by irrigation exceeds the amount of groundwater discharged from the flow system. According to Jones and Lebedin (1986), the primary cause of this is the comparatively low hydraulic conductivity in unit K1, and the lower permeability K2 unit beneath it restricts drainage. A rise in the water table throughout the summer (June to August) was clearly observed in several of the site's piezometers during the summer of 1987.

The soils of the S.I.D.C. area are classified within the Bradwell Association (Ellis et al. 1968), which is a dominantly chernozemic dark brown soil developed on glaciolacustrine parent materials. The lacustrine sediments underlying the soil zone are very fine-grained; consequently the soils have been classified as very fine- to fine-grained sandy loams.

The Konst Site

The Konst site (Figure 6) is irrigated by centre pivot. At the Konst site, approximately 53 ha have undergone increased soil salinization since irrigation began in the late 1960's. A subsurface land drainage system has been installed beneath the salinized area in order to reduce waterlogging and to accelerate the leaching of accumulated salts downward through the unsaturated zone. An additional set of drains was installed in 1987 by the S.W.C. in order to accelerate the movement of groundwater through the soil profile. Ten piezometers were drilled on the Konst site by the S.W.C. in 1985 as part of a soil salinization study. Piezometer locations are shown on Figure 6.

The Konst site is underlain by sandy sediments of glaciofluvial deltaic origin. The deltaic sands form an aquifer, which approaches a thickness of 4 m beneath sections 2 and 3. The sand thins or pinches out completely to the west near SWC-02 (Figure 7). The deltaic sand aquifer receives large amounts of leached irrigation water and conducts this water down-gradient to the west. The thinning of aquifer adjacent to the South Saskatchewan River valley causes an increased gradient between the aquifer and the land surface so that the groundwater essentially flows upward through the overlying silts and gives rise to the development of waterlogging and soil salinity (Figure 6).

The Konst site is underlain by soils of the Asquith and Bradwell Associations (Ellis et al. 1968). The Asquith Association soils are orthic to calcareous dark brown soils developed on

hummocky disintegration moraine, with limited external drainage. The Bradwell Association soils are chernozemic or orthic dark brown fine to very fine sandy loams developed on a gently sloping glaciolacustrine plain.

GROUNDWATER SAMPLING METHODOLOGY

Upon completion of drilling and installation, a peristaltic pump was used to remove several casing volumes of groundwater from each piezometer in order to develop the intake zone and to remove any traces of contamination which may have been present from the drilling operations. In low yield piezometers this was done by repeatedly pumping the piezometer dry and allowing the water level to rise again in the interim.

Pesticide samples were collected using a peristaltic pump and dedicated Teflon hose placed in each piezometer to avoid cross-contamination between piezometers. Before sampling, each piezometer was pumped to remove several casing volumes of water. Because of slight turbidity, all samples were filtered through 0.45 micron Millipore filter paper in the field. Samples consisted of approximately 0.6 L of groundwater collected in 1-litre glass bottles which had been washed and rinsed with pesticide grade acetone and hexane and autoclaved for 8 hours at 300°C. The bottle caps were lined with solvent-rinsed and autoclaved aluminum foil. Samples were placed in a cooler and kept at approximately 4°C in the field until they could be brought back to the National Hydrology Research Institute, where they were put into a cold room at -50°C. The bottles were not filled completely making it possible to freeze the samples without breakage. Samples were stored for up to four months before analysis.

The samples were submitted to the Saskatchewan Research Council laboratory for analyses of major ions, nutrients (nitrogen and phosphorus species), hardness, alkalinity, pH, iron, manganese, and organic carbon. During the 1987 sampling period, samples were also submitted to Environment Canada's Water Quality Branch Laboratory for analysis of nutrients.

RESULTS

The Pederson Site

Table 1 presents the crop management and water sampling schedule at the Pederson site over the course of the 1987 and 1988 field seasons. Two irrigations were performed in 1987 and four during 1988. The 1987 application of the herbicide diclofop-methyl (Hoe-grass) occurred on June 8, 1987. A mixture of dicamba and MCPA (Dyvel) was applied on June 17, 1987. A mixture of diclofop-methyl and bromoxynil (Hoe-grass-II) was applied on June 9, 1988, followed by 2,4-D amine about 5 days later. The application rate of each pesticide is given in Table 1.

Samples collected during the 1987 field season were analyzed for dicamba, MCPA, and diclofop-methyl. The 1988 samples were analyzed for bromoxynil, 2,4-D, and diclofop-methyl. Analytical results from the samples collected are presented in Tables 2. All of the pesticide concentrations were well below the maximum acceptable concentrations (MAC's) established by the Canadian Drinking Water Guidelines (Health and Welfare Canada 1993) for pesticides.

Diclofop-methyl

During 1987, traces of diclofop-methyl were detected in piezometers adjacent to the drainage ditch (87-04, 87-05), at the eastern edge of the site (87-08, 87-09), and at the western end of the site (87-11). Traces of diclofop-methyl were not detected in the piezometers located in the centre of the fields (87-12, 87-07, 87-13), in some of the piezometers near the drainage ditch (87-06, 87-03, SIDC), or at one of the piezometers at the western edge of the site (87-10). The maximum concentration detected during 1987 was 0.54 µg/L, on June 11 at piezometer 87-05.

During 1988, diclofop-methyl residues were detected in five piezometers, as was the case during 1987. However, of the five piezometers exhibiting trace amounts of diclofop-methyl during 1988 (87-03, 87-05, 87-06, 87-07, 87-12), only one piezometer, 87-05, had detections during both 1987 and 1988. In piezometer 87-03, a detection of diclofop-methyl occurred on the date of application and another during the first irrigation of the summer (June 9, 1988). Early detection of diclofop-methyl was not observed in 87-05, but samples collected later in the summer contained detectable amounts, and these may be related to the four irrigations during the course of the summer. The only detection of diclofop-methyl from 87-07 was in a sample taken on May 19, 1988, and this

occurred before the application of Hoegrass-II and the first irrigation on June 9, 1988. There were multiple detections of diclofop-methyl in piezometers 87-03, 87-05, 87-06, and 87-12, and in each case the concentration of diclofop-methyl increased during the sampling period.

The spatial distribution of piezometers exhibiting diclofop-methyl detections does not show a definite pattern in either 1987 or 1988 that could correlate surface features (e.g., the drainage ditch) or piezometer location. Diclofop-methyl also was detected in a sample of irrigation water collected on June 10, 1988.

Dicamba

Dicamba was applied on June 17, 1987. Dicamba was detected in the S.I.D.C. piezometer in the sample collected on July 7, 1987. It was not detected in any subsequent sample in 1987 or 1988. The only other detection of dicamba during 1987 and 1988 was 0.44 µg/L in piezometer 87-04 on June 11, 1987; 6 days before its application on the field. It was not detected in any other sample in 1987 or 1988, or at any piezometer other than 87-04. It is not possible that the application of irrigation water containing trace amounts of dicamba on this field infiltrated to the water table because the first irrigation did not occur until June 23, 1987, or 12 days after its detection in piezometer 87-04. Although both piezometers 87-04 and S.I.D.C. are adjacent to the drainage ditch, it is unlikely that water from the drainage ditch is the source of this dicamba because traces of dicamba were not found in other the piezometers near the drainage ditch (Figure 2) even though these other piezometers respond rapidly to irrigation. It is suspected that dicamba was carried over from a previous year's application. Dicamba was not applied to the site nor analyzed during 1988, and hence this can not be confirmed.

MCPA

MCPA was applied at the site only on June 17, 1987, and was not applied during 1988. Of the twelve piezometers sampled at the Pederson Site, only three piezometers 87-03, 87-10, 87-12, did not exhibit traces of MCPA. The maximum concentration found was 0.53 µg/L in piezometer 87-09 on July 9, 1987. Piezometers 87-07, 87-08, and 87-09 had detectable levels of MCPA in both the June and July samples. Detections in piezometers 87-05, 87-06, 87-08 and 87-11 from the June 10 and 11, 1987 sampling episodes predate the June 17, 1987 application of MCPA on the field.

Infiltration of water containing dissolved MCPA prior to this date is not suspected because none of the other piezometers adjacent to the irrigation ditch exhibited pesticide detections. It is suspected that there is some carry-over from previous years. However, there were no detections of MCPA during the 1988 sampling program. Detections in piezometers 87-07, 87-08, and 87-09 occurred in both the July 7, 1987, and July 17, 1987 samples, with concentrations decreasing from the first sampling to the second. The S.I.D.C. piezometer and 87-13 showed detectable MCPA on July 7, 1987, but no further detections over the summer. There were no detections of MCPA in 87-03 or 87-10 even though these piezometers are within a few metres of the S.I.D.C. piezometer and 87-11, respectively (both of which exhibited detections of MCPA), and were drilled to similar depths.

Bromoxynil

Bromoxynil, which with diclofop-methyl is an active ingredient of Hoegrass-II, was applied on June 9, 1988 as the N-octanoic ester. Bromoxynil was detected in piezometers 87-05, and 87-03 on June 22 and July 4, 1988, respectively. These are both shallow piezometers (less than 5 m depth), located at the low end of the irrigated field, where considerable ponding of water is observed during each flood irrigation event. Bromoxynil was not detected in piezometer 87-06, situated only about 10 m from 87-05, during the summer of 1988, but was detected several months later during the December 7, 1988, sampling. Piezometer 87-06 is 7-8 m deeper than 87-05, and hence it may have taken longer for the pesticide to leach to this depth. It is suspected that the bromoxynil detected in piezometers 87-03, 87-05 and 87-06 originates from water in the drainage ditch because these three piezometers are located adjacent to the drainage ditch and bromoxynil was not detected in any of the piezometers located away from the drainage ditch.

2,4-D

2,4-D amine was applied to the study area on June 14, 1988, or about five days after the first irrigation. It was not detected in any of the groundwater samples collected during the 1988 summer field season, but was found in two samples from piezometers 87-03 and 87-05 during December, 1988. The 2,4-D may have originated from contaminated water in the drainage ditch infiltrating to the water table, because the only two piezometers in which 2,4-D was detected are adjacent to the drainage ditch.

The S.I.D.C. Site

During the summer of 1987, samples were collected from piezometers SIDC-02, SIDC-06, SIDC-07, SIDC-09, and SIDC-10. In addition to the groundwater samples, a sample was collected from each of the two outlets from the drains installed in the southwest corner of the site (field 11). Samples were not collected in 1988.

Because the S.I.D.C. site is used by many different researchers, is broken into many small plots, and is used for different crop experiments, a detailed land use schedule for 1987 is not available, nor are the precise irrigation dates known for the S.I.D.C. site. However, Figure 4 shows the location and types of pesticides used on each plot. They include: Buctril M (Bromoxynil and MCPA), Hoegrass II (diclofop-methyl and bromoxynil), Treflan (trifluralin), Fusilade (fluazifop-butyl), Round-up (glyphosate), Sencor (metribuzin), and Tilt (propiconazole). From Figure 4, it is evident that the most common pesticides used are diclofop-methyl, bromoxynil, and trifluralin. The fungicide propiconazole, metribuzin, and triallate were only used over a very small portion of field 7. Thirteen groundwater samples were analyzed for trifluralin, triallate, dicamba, bromoxynil, 2,4-D, and diclofop-methyl (Table 3). Groundwater samples were not analyzed for glyphosate. Only triallate, 2,4-D and diclofop-methyl were detected during the sampling program and only these three pesticides will be discussed below. None of the pesticide concentrations exceeded the MAC's of the Canadian Drinking Water Guidelines (Health and Welfare Canada 1993).

Diclofop-methyl

Diclofop-methyl was detected only in piezometers SIDC-01 on July 28, 1987, and SIDC-02 on June 25, 1987. These detections probably occurred after a spring application of diclofop-methyl and irrigation, although land use data are not available to verify this. The absence of diclofop-methyl in subsequent samples indicates that it either flushed through the groundwater system or degraded rapidly enough to prevent detectable amounts from reaching the water table later in the summer.

2,4-D

2,4-D was detected in one sample each from piezometers SIDC-01 and SIDC-09. Because 2,4-D was not used on fields 2 or 3 during 1987, these detections are attributed to carry over of leached chemical from previous years or from 2,4-D dissolved in the irrigation supply water. No

analysis of the supply water is available from the S.I.D.C. site, although it is notable that supply water at the Konst site contained detectable concentrations of 2,4-D (see below).

Triallate

Triallate was detected in piezometer SIDC-10 which is screened from 3 to 4 m below ground surface (Figure 4). The source of triallate detected in this piezometer may be a small experimental plot in field 7 where a number of broadleaf and grassy herbicides were used. Triallate was also detected in SIDC-01. The detection of triallate in SIDC-01 is problematical because it was neither used on the field in which SIDC-01 is located, nor used on any nearby fields. It may be possible that the detection originated from contaminated irrigation water applied to the field.

The Konst Site

The Konst site was sampled only during 1987. Samples were collected from piezometers SWC-01, and SWC-04 through SWC-09. Samples were also collected from the tile drain outlet located on the west edge of the site and from the irrigation supply canal near piezometers SWC-06 and SWC-07 (Figure 6). Pesticides used on sections 2 and 3 include Buctril M (bromoxynil and MCPA), Hoegrass (diclofop-methyl), Poast (sethoxydim), Fusilade (fluazifop-butyl), and MCPA. Fifteen groundwater samples and four irrigation supply samples from the Konst site were analyzed for trifluralin, triallate, dicamba, bromoxynil, 2,4-D, and diclofop-methyl. The analytical results are shown in Table 4. The only pesticide residues detected were for diclofop-methyl, 2,4-D and triallate. All pesticide concentrations of groundwater the samples are well below the MAC's stated in the Canadian Drinking Water Guidelines (Health and Welfare Canada 1993).

Diclofop-methyl

Diclofop-methyl was detected in three out of four of the irrigation supply water samples collected from the canal and in four groundwater samples from SWC-04, SWC-08, and SWC-09 (two samples). Diclofop-methyl was not used on the Konst site during 1986 or 1987. Therefore, it is suspected that diclofop-methyl in the groundwaters is due to its presence in the irrigation supply.

Triallate

Triallate was detected in low concentrations in piezometers SWC-01, SWC-06, SWC-07, and SWC-08 (all located next to the irrigation water supply canal), as well as in two samples from the irrigation supply canal running past the site. Triallate was not detected in any groundwater sample obtained from piezometers located away from the irrigation canal. Triallate is not used on the Konst site and therefore, it is suspected that the triallate detections originated during infiltration of the irrigation water from the irrigation supply canal. It is possible that the sandy glaciofluvial sediments beneath the site are conducive to the rapid movement of triallate through the saturated zone from land to the east of the Konst site. However, if triallate is persistent enough to remain in the groundwater as it flows under the site from the east, then it should appear in more than only one of two samples each collected during the summer of 1987 in each of the three piezometers. It did not.

2,4-D

2,4-D was detected in all four irrigation supply samples from the canal and in six of the seven piezometers (not detected in SWC-09). Because 2,4-D was not applied to the site, there are two possible mechanisms to explain the detections of 2,4-D; leakage from the irrigation supply canal or from groundwater entering the site from the topographically higher farming areas to the east of the site. Because 2,4-D was detected in all four irrigation water samples, it is suspected that this is the source of the 2,4-D in the groundwater. Alternatively, if 2,4-D did originate to the east of the site then it should appear in most of the piezometers and samples collected during the summer of 1987. Because 6 of the 7 piezometers and 12 of 19 samples exhibited 2,4-D detections, this could also be a possible source of the 2,4-D in the groundwater. There is insufficient evidence to conclusively support either alternative.

POSSIBLE MECHANISMS CONTRIBUTING TO PESTICIDE LEACHING

It is suspected that the principal factor contributing to the detection of pesticides in the groundwater is the presence of the numerous vertical fractures which exist in the silts and tills. As noted previously, vertical fractures are commonly reported in fine grained sediments. Detailed water level measurements were taken at the Pederson site during the summers of 1987 and 1988 to determine if fractures are an important feature of these sediments. Based on an analyses of the

hydrographs from the piezometers at the Pederson site, infiltration through the unsaturated zone to the water table occurs as both intergranular flow and fracture flow. In permeable soils, such as the sands and gravels, infiltration occurs as intergranular flow. Intergranular flow is much slower than fracture dominated flow, and the nature of a porous media will cause the water to disperse over a larger area. Hence, an observed water level response in a piezometer would exhibit a very gradual, or negligible, rise and fall in the water level in response to irrigation (Figure 8). This response is seen in piezometers 87-07, 87-10, and 87-13.

In till, clay or silt, infiltration is preferential channelled through vertical fractures causing a rapid downward movement of water. As water moves downward through, or is stored within, the fractures, water will slowly move into the adjacent porous media. A typical response of the water level observed in piezometers intersecting vertical fractures is a very rapid increase in the water level occurring a few hours after each irrigation event, due to saturation of these fractures, followed by a subsequent gradual drop in water levels over the following weeks as the water stored in the fractures is drained into intergranular storage adjacent to the fractures (Figure 8). This type of response is seen at piezometers 87-03, 87-05, and 87-12.

In soils where the density and the connectivity of vertical fractures is much lower, and where the hydraulic conductivity of the intergranular material has a sufficiently high specific storage to allow for retention of irrigation water in the unsaturated zone, the observed water levels will exhibit characteristics of both fracture flow and intergranular flow. Water levels rise rapidly after irrigation, due to infilling of, and flow through, vertical fractures, then decline very gradual or negligible during the following weeks due to the slow release of water from matrix storage into the fracture (Figure 8). These water level responses were observed in piezometers 87-04, 87-06, and 87-09.

Water level measurements in the piezometers at the S.I.D.C. and Konst sites were not measured at a sufficiently small time interval (measurements taken daily to monthly) to clearly show the response of the water table to irrigation events. However, these data do show that the water table rises in response to irrigation and it is suspected that fine-grained sediments (silts, tills, clays) contain vertical fractures which control flow through the unsaturated zone.

The vertical fractures enable the water to infiltrate to the water table from both water that has accumulated in the irrigation drainage ditches and directly from water applied to the field. Because of the rapid and essentially direct downward movement of the pesticide, the pesticide will pass much

of the upper portion of the soil horizon which is the most biologically active zone and region containing the highest amounts of organic carbon. Thus, the amount of pesticide that would have been degraded or absorbed by passing through the soil matrix as intergranular flow will be much lower, and hence concentrations at the water table will be relatively higher. In addition, the seemingly erratic pattern of pesticide detections in the fields could be due to the variation in fracture density, depth of penetration of the vertical fractures and the number of fractures intersecting each of the piezometers.

At the Pederson site, groundwater analyses from piezometers 87-07, 87-10, and 87-13, which were completed in sand (unfractured media) appear to show fewer detections of pesticides (except for 87-07) than the piezometers exhibiting fracture dominated flow. For example, dicamba, 2,4-D and bromoxynil were not detected in these piezometers, but were detected in at least one groundwater sample from all the piezometers exhibiting fracture-flow characteristics. Also, diclofop-methyl, which was detected in only one sample from piezometers exhibiting intergranular flow, was detected in all eight of the piezometers at which fracture flow dominates.

It was quite common for pesticide to be detected either several days before the pesticide was applied, or during a year in which the pesticide was not applied to the field. The suspected mechanisms that may account for this at the three sites include the infiltration of contaminated irrigation water, and carry over of pesticide from a previous years application through storage in the unsaturated zone and subsequent release. The probability of contaminated surface runoff or groundwater flow from an adjacent field to which the pesticide was applied is very low. Nicholaichuk et al. (1986) reported that only 0.18% of applied diclofop-methyl was lost to surface drainage at the Pederson site.

There is a strong correlation between pesticide detections in the irrigation water and the groundwater at the Konst site; triallate, 2,4-D and diclofop-methyl were detected in both irrigation water and groundwater, and there were no detections of trifluralin, dicamba and bromoxynil in either the irrigation water or groundwater. However, it is unlikely to be the principal source of contamination at the Pederson Site because of not only the lack of a correlation between pesticide detections in the irrigation water and groundwater, and but there was only one detection of a pesticide, diclofop-methyl, in the irrigation water.

It is suspected that the carry over of a pesticide from a previous year's application is the most

feasible mechanism to account for most of the observed detections. The infiltration of water from the fractures into the surrounding soil matrix or into dead-end fractures, causes the pesticide to also move into these areas where it is retained (sorption) long after the fractures have drained. Subsequent major infiltration or irrigation events will cause the pesticide to be desorbed and flushed from storage in the matrix material or dead-end fractures, hence resulting in detections from the original pesticide application weeks to years after the original application and detection. This process, leading to the contamination of groundwater from pesticides, has been observed at other sites in which flow through the unsaturated zone is dominated by the vertical fractures (Jackson et al. 1990, Ewing and Jaynes 1995).

Carry over or long-term retention of pesticide appears to be more frequent in samples obtained from piezometers exhibiting fracture flow characteristics than intergranular flow characteristics. For example, dicamba and MCPA were found in groundwater samples collected on June 11, 1987 in piezometers 87-04 (dicamba), and 87-05, 87-06, 87-11 (MCPA) which was several days prior to the application of these pesticides on June 17, 1987. Bromoxynil and 2,4-D were detected in groundwater samples on December 7, 1988 in piezometers 87-03, and 87-05 which was several months after the pesticide was applied on June 9, and June 14, 1988, respectively.

The impact of irrigation runoff, containing traces of pesticide, ponding in the drainage ditch and subsequently infiltrating to the water table through vertical fractures is uncertain. At the Pederson site, the only detections of 2,4-D, dicamba and bromoxynil were in piezometers located adjacent to the drainage ditch. MCPA and diclofop-methyl were also found in all piezometers located along the drainage ditch, as well as most of the other piezometers at the Pederson site. However, not all piezometers along the drainage ditch exhibited the same frequency of pesticide detections. For example, diclofop-methyl was found in piezometers 87-04 and 87-05, but not in 87-06, 87-03 and S.I.D.C. during 1987, and during 1988, it was detected in 87-03, 87-05, and 87-06, but not 87-04 and S.I.D.C.

The results of this study indicate that these commonly used pesticides can migrate to the water table under typical agricultural conditions found in central Saskatchewan. It is suspected that the primary factors contributing to contamination of the shallow groundwater regime are the presence of vertical fractures in the overburden which provide a path for rapid downward migration, and the application of irrigation which increases the infiltration rate through the unsaturated zone.

However, the precise mechanism controlling pesticide migration, retention and subsequent desorption are poorly understood, and further research is required to quantify the importance of these two factors.

CONCLUSIONS

It is generally thought that the meteorological and hydrogeological conditions found in the southern and central Saskatchewan are not conducive to pesticide transport to the water table because the low amount of precipitation combined with high evaporation rates limit the potential for recharge, the water table is often very deep, and the matrix hydraulic conductivity of the dominant surficial deposits of the region (tills and lacustrine sediments) is very low. However, the use of pesticides at three agricultural sites in the Outlook Irrigation District of Saskatchewan has resulted in traces amount of pesticides being detected in some samples collected from piezometers installed in the shallow groundwater regime.

The herbicides diclofop-methyl, MCPA, bromoxynil, dicamba and 2,4-D were detected in the groundwater at the Pederson site. At the S.I.D.C. site, a few detections of the pesticides triallate, 2,4-D and diclofop-methyl were found. Triallate, 2,4-D and diclofop-methyl were detected in groundwater samples at the Konst site. In all cases, the concentrations of pesticides detected are below the maximum acceptable concentrations as established by the Canadian Drinking Water Guidelines (Health and Welfare Canada 1993).

It is suspected that the pesticides were able to migrate to the water table through vertical fractures which are commonly found in the underlying tills and silts. When combined with irrigation that is applied at these site, these two factors create a mechanism for the considerable more rapid movement of pesticide and to greater depths of leaching than would occur in unfractured sediments (i.e. intergranular flow) and under typical precipitation conditions. All the piezometers which exhibited detections of pesticides were located in or adjacent to fields that were irrigated.

Ponding of irrigation runoff in drainage ditches may also contributed to ability of pesticides to migrate to the water table at these sites. At the Pederson site, the piezometers exhibiting the greatest number of detections and the largest number of pesticide detections were located adjacent to the irrigation drainage ditches where ponding of irrigation runoff was observed.

It is also suspected that contaminated irrigation water may also cause contamination of the shallow groundwater. At the Konst site, the irrigation supply water that was used here had detectable concentrations of 2,4-D, diclofop-methyl, and triallate, and these same pesticides (and only these pesticides) were found in the groundwater samples. However, this pattern was not observed at the Pederson site.

Not all the pesticide detections occurred immediately following the application of the pesticide and a subsequent irrigation. It is suspected that the pesticide detection that occurred several weeks or months after its application could be attributed to storage of the pesticide in the unsaturated zone due to diffusion from a saturated fracture into the soil matrix, and later desorption through flushing of the soil matrix into a fracture during subsequent major infiltration events.

The results of this study indicates that pesticides which are commonly used in typical agricultural regions of central Saskatchewan can migrate to the water table. Although it is suspected that the primary factors contributing to contamination of the shallow groundwater regime are the presence of vertical fractures in the overburden and the application of irrigation, further research is required to verify the suspected mechanisms described here and to quantify the precise mechanism controlling pesticide migration, retention and subsequent desorption.

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Table 1. Event summary at the Pederson site during the 1987-1988 field seasons.

1987: (from Nicholaichuk et al. 1988)

May 1	fertilizer applied
May 11	seeding (wheat) and fertilization
May 22-29	piezometers installed
June 8	Hoegrass (diclofop-methyl) applied
June 10	groundwater sampling
June 17	Dyvel (dicamba + bromoxynil) applied
June 23-26	first irrigation
July 7	groundwater sampling
July 26	groundwater sampling
August 5-7	second irrigation
August 14	groundwater sampling
Sept. 30	groundwater sampling

1988:

May 18-19	sampled groundwater from piezometers 87-09, 87-08, 87-12
May 20	sampled piezometers 87-03, 87-06, 87-05
May 24	sampled piezometer 87-06 and 87-04, water foul and anoxic in 87-04
June 3	installation of suction lysimeters
June 9	Hoegrass II (diclofop-methyl + bromoxynil) applied; start of first irrigation at 10:00; sampled 87-03
June 10	sampled piezometers 87-07, 87-05, 87-03 and irrigation pipe; collected field blank
June 12	sampled piezometers 87-12, 87-13
June 14	2,4-D applied (approximate date)
June 17	site reseeded
June 18	site recorruigated
June 22	start of second irrigation; sampled 87-12 and 87-13
June 23	sampled piezometers 87-12, 87-13, 87-05, 87-06, 87-03; collected demin. blank; sampled lysimeters at site of 87-13; lysimeters at site of 87-12 were dry
June 28	evacuated lysimeters
July 4	sampled lysimeters 1,2, and 3 (site of piezometer 87-13); lysimeters at site of 87-12 dry, but still under vacuum; sampled piezometers 87-04, 87-05, 87-06
July 13	third irrigation started; re-evacuated lysimeters 4, 5, 6; sampled piezometers 87-13, 87-06, 87-03
July 15	re-evacuated lysimeters; sampled piezometer 87-12, 87-13, 87-05, 87-03
July 18	sampled lysimeters 4, 5, and 6 (near site of piezometer 87-13)
July 26	sampled piezometers 87-12, 87-13, 87-03, 87-06, 87-05
July 27	fourth irrigation begun at 12:45; lysimeters re-evacuated
July 28	sampled lysimeters 4, and 5; re-evacuated remainder
July 29	lysimeters dry; could not sample
August 3	sampled piezometers 87-06, 87-05, 87-03 (one sample spiked with diclofop-methyl), 87-12, 87-13; sampled lysimeters 4 and 5 (near piezometer 87-13)
Sept. 13	conducted response tests in all piezometers
Sept. 23	conducted response tests in all piezometers
Dec. 7	sampled piezometers 87-12, 87-13, 87-05, 87-03, 87-06.

Table 2. Pesticide analyses from the Pederson site during the 1987 and 1988 field seasons.

Piezometer	Date	Sample No.	Dicamba ($\mu\text{g/L}$)	MCPA ($\mu\text{g/L}$)	Diclofop-methyl ($\mu\text{g/L}$)	2,4-D ($\mu\text{g/L}$)	Bromoxynil ($\mu\text{g/L}$)
87-03	26-June-87	113	<0.1	<0.1	<0.1	NA	NA
87-03	20-May-88	1	<0.1	<0.1	ND	ND	<0.1
87-03	9-June-88	2	NA	NA	0.299*	ND	<0.1
87-03	10-June-88	3	NA	NA	0.313*	ND	<0.1
87-03	22-June-88	4	NA	NA	ND	ND	<0.1
87-03	23-June-88	5	NA	NA	0.134*	<0.1	<0.1
87-03	4-July-88	6	NA	NA	<0.1	ND	0.105*
87-03	13-July-88	7	NA	NA	<0.1	ND	<0.1
87-03	15-July-88	8	NA	NA	ND	ND	<0.1
87-03	26-July-88	9	NA	NA	ND	ND	<0.1
87-03	3-Aug-88	10	NA	NA	0.439*	<0.1	<0.1
87-03	7-Dec-88	57	NA	NA	<0.1	0.188*	<0.1
87-04	11-June-87	102	0.44	<0.1	0.42	NA	NA
87-04	7-July-87	118	<0.1	<0.1	<0.1	NA	NA
87-04	17-July-87	129	<0.1	0.12	<0.1	NA	NA
87-04	24-May-88	11	NA	NA	ND	<0.1	<0.1
87-05	11-June-87	103	<0.1	0.23	0.54	NA	NA
87-05	26-June-87	114	<0.1	<0.1	<0.1	NA	NA
87-05	7-July-87	119	<0.1	<0.1	<0.1	NA	NA
87-05	17-July-87	130	<0.1	<0.1	<0.1	NA	NA
87-05	20-May-88	12	NA	NA	ND	ND	<0.1
87-05	9-June-88	13	NA	NA	<0.1	ND	<0.1
87-05	10-June-88	14	NA	NA	<0.1	ND	<0.1
87-05	22-June-88	15	NA	NA	<0.1	<0.1	0.167*
87-05	23-June-88	16	NA	NA	<0.1	ND	<0.1
87-05	4-July-88	17	NA	NA	0.134*	ND	<0.1
87-05	15-July-88	18	NA	NA	0.129*	ND	<0.1
87-05	26-July-88	19	NA	NA	0.135*	<0.1	<0.1
87-05	3-Aug-88	20	NA	NA	0.170*	<0.1	<0.1
87-05	7-Dec-88	58	NA	NA	<0.044	0.141*	<0.1
87-06	10-June-87	104	<0.1	0.31	<0.1	NA	NA
87-06	7-July-87	120	<0.1	<0.1	<0.1	NA	NA
87-06	16-July-87	131	<0.1	<0.1	<0.1	NA	NA
87-06	24-May-88	21	NA	NA	ND	ND	<0.1
87-06	9-June-88	22	NA	NA	ND	ND	<0.1
87-06	10-June-88	23	NA	NA	ND	ND	<0.1
87-06	22-June-88	24	NA	NA	ND	ND	<0.1
87-06	23-June-88	25	NA	NA	<0.1	<0.1	<0.1
87-06	4-July-88	26	NA	NA	0.163*	<0.1	<0.1
87-06	13-July-88	27	NA	NA	0.177*	<0.1	<0.1
87-06	15-July-88	28	NA	NA	<0.1	<0.1	<0.1
87-06	26-July-88	29	NA	NA	<0.1	<0.1	<0.1
87-06	3-Aug-88	30	NA	NA	<0.1	<0.1	<0.1
87-06	7-Dec-88	59	NA	NA	<0.1	<0.1	0.200*
87-07	11-June-87	105	<0.1	<0.1	<0.1	NA	NA
87-07	7-July-87	121	<0.1	0.38	<0.1	NA	NA
87-07	17-July-87	132	<0.1	0.15	<0.1	NA	NA
87-07	19-May-88	31	NA	NA	0.147*	ND	<0.1

Table 2. continued...

87-08	11-June-87	106	<0.1	0.11	<0.1	NA	NA
87-08	7-July-87	122	<0.1	0.23*	0.27*	NA	NA
87-08	17-July-87	133	<0.1	0.22	<0.1	NA	NA
87-08	19-May-88	32	NA	NA	ND	<0.1	<0.1
87-09	11-June-87	107	<0.1	<0.1	<0.1	NA	NA
87-09	7-July-87	123	<0.1	0.53	0.12	NA	NA
87-09	17-July-87	134	<0.1	0.17	<0.1	NA	NA
87-09	19-May-88	33	NA	NA	ND	<0.1	<0.1
87-10	10-June-87	108	<0.1	<0.1	<0.1	NA	NA
87-10	6-July-87	124	<0.1	<0.1	<0.1	NA	NA
87-10	16-July-87	135	<0.1	<0.1	<0.1	NA	NA
87-10	18-May-88	34	NA	NA	ND	ND	<0.1
87-11	11-June-87	109	<0.1	0.25	0.17	NA	NA
87-11	7-July-87	125	<0.1	<0.1	<0.1	NA	NA
87-11	17-July-87	136	<0.1	<0.1	<0.1	NA	NA
87-11	18-May-88	35	NA	NA	ND	<0.1	<0.1
87-12	11-June-87	110	<0.1	<0.1	<0.1	NA	NA
87-12	7-July-87	126	<0.1	<0.1	<0.1	NA	NA
87-12	17-July-87	137	<0.1	<0.1	<0.1	NA	NA
87-12	24-May-88	36	NA	NA	ND	ND	<0.1
87-12	11-June-88	37	NA	NA	0.107*	0.1	<0.1
87-12	22-June-88	38	NA	NA	0.189*	ND	<0.1
87-12	23-June-88	39	NA	NA	ND	ND	<0.1
87-12	4-July-88	40	NA	NA	ND	ND	<0.1
87-12	13-July-88	41	NA	NA	0.167*	ND	<0.1
87-12	15-July-88	42	NA	NA	ND	ND	<0.1
87-12	26-July-88	43	NA	NA	ND	ND	<0.1
87-12	3-Aug-88	44	NA	NA	ND	ND	<0.1
87-12	7-Dec-88	60	NA	NA	<0.1	<0.1	<0.1
87-13	11-June-87	111	<0.1	<0.1	<0.1	NA	NA
87-13	7-July-87	127	<0.1	0.15	<0.1	NA	NA
87-13	17-July-87	138	<0.1	<0.1	<0.1	NA	NA
87-13	24-May-88	45	NA	NA	ND	ND	<0.1
87-13	11-June-88	46	NA	NA	ND	ND	<0.1
87-13	22-June-88	47	NA	NA	ND	ND	<0.1
87-13	23-June-88	48	NA	NA	ND	ND	<0.1
87-13	4-July-88	49	NA	NA	ND	ND	<0.1
87-13	13-July-88	50	NA	NA	ND	<0.1	<0.1
87-13	15-July-88	51	NA	NA	ND	ND	<0.1
87-13	26-July-88	52	NA	NA	ND	ND	<0.1
87-13	3-Aug-88	53	NA	NA	ND	ND	<0.1
87-13	7-Dec-88	61	NA	NA	<0.1	<0.1	<0.1
IRR.	24-June-87	116	<0.1	<0.1	<0.1	NA	NA
IRR.	10-June-88	56	NA	NA	0.127*	<0.1	<0.1
IRR.	24-June-87	115	<0.1	<0.1	<0.1	NA	NA
SIDC	11-June-87	101	<0.1	<0.1	<0.1	NA	NA
SIDC	26-June-87	112	<0.1	<0.1	<0.1	NA	NA
SIDC	7-July-87	117	0.14	0.44	<0.1	NA	NA
SIDC	17-July-87	128	<0.1	<0.1	<0.1	NA	NA

note: * confirmed by GC/MS NA - not analyzed ND - not detected

Table 3. Pesticide analyses from the S.I.D.C. site during 1987.

Piezometer	Date	Trifluralin (µg/L)	Triallate (µg/L)	Dicamba (µg/L)	Bromoxynil (µg/L)	2,4-D (µg/L)	Diclofop (µg/L)
SIDC-01	28-July-87	<0.1	0.13	<0.1	<0.1	0.21*	0.10
SIDC-02	25-June-87	<0.1	<0.1	<0.1	<0.1	<0.1	0.24*
SIDC-02	28-July-87	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SIDC-04	6-Aug-87	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SIDC-05	28-July-87	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SIDC-06	26-June-87	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SIDC-06	28-July-87	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SIDC-07	25-June-87	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SIDC-07	25-July-87	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SIDC-09	25-June-87	<0.1	<0.1	<0.1	<0.1	0.66*	<0.1
SIDC-09	28-July-87	<0.1	<0.1	<0.1	<0.1	0.10	<0.1
SIDC-10	26-June-87	<0.1	0.17*	<0.1	<0.1	<0.1	<0.1
SIDC-10	6-Aug-87	<0.1	0.39*	<0.1	<0.1	<0.1	<0.1

note: * confirmed by GS/MS

Table 4. Pesticide analyses from the Konst site during 1987.

Piezometer	Date	Trifluralin ($\mu\text{g/L}$)	Trillate ($\mu\text{g/L}$)	Dicamba ($\mu\text{g/L}$)	Bromoxynil ($\mu\text{g/L}$)	2,4-D ($\mu\text{g/L}$)	Diclofop ($\mu\text{g/L}$)
SWC-01	9-July-87	<0.10	0.13	<0.10	<0.10	0.12*	0.22*
SWC-01	28-July-87	<0.10	<0.10	<0.10	<0.10	0.10	<0.10
SWC-04	24-June-87	<0.10	<0.10	<0.10	<0.10	<0.10	0.23*
SWC-04	28-July-87	<0.10	<0.10	<0.10	<0.10	0.12*	<0.10
SWC-05	25-June-87	<0.10	<0.10	<0.10	<0.10	0.11*	<0.10
SWC-06	9-July-87	<0.10	0.14*	<0.10	<0.10	<0.10	<0.10
SWC-06	27-July-87	<0.10	<0.10	<0.10	<0.10	0.14*	<0.10
SWC-06	27-Aug-87	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
SWC-07	9-July-87	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
SWC-07	14-Aug-87	<0.10	0.13*	<0.10	<0.10	<0.10	<0.10
SWC-07	27-Aug-87	<0.10	<0.10	<0.10	<0.10	0.11*	<0.10
SWC-08	9-July-87	<0.10	<0.10	<0.10	<0.10	0.12*	<0.10
SWC-08	27-Sep-87	<0.10	0.13*	<0.10	<0.10	0.15*	0.13*
SWC-09	24-June-87	<0.10	<0.10	<0.10	<0.10	<0.10	0.17*
SWC-09	28-July-87	<0.10	<0.10	<0.10	<0.10	<0.10	0.12*
Irr Canal SWC06*	24-June-87	<0.10	<0.10	<0.10	<0.10	0.57*	0.15*
Irr Canal SWC06*	27-July-87	<0.10	0.14*	<0.10	<0.10	0.18*	0.21*
Irr Canal SWC07*	9-July-87	<0.10	<0.10	<0.10	<0.10	1.65*	0.24*
Irr Canal SWC07*	27-July-87	<0.10	0.15*	<0.10	<0.10	0.17*	<0.10

note: * confirmed by GS/MS * sample from the irrigation canal near piezometer SWC-0n

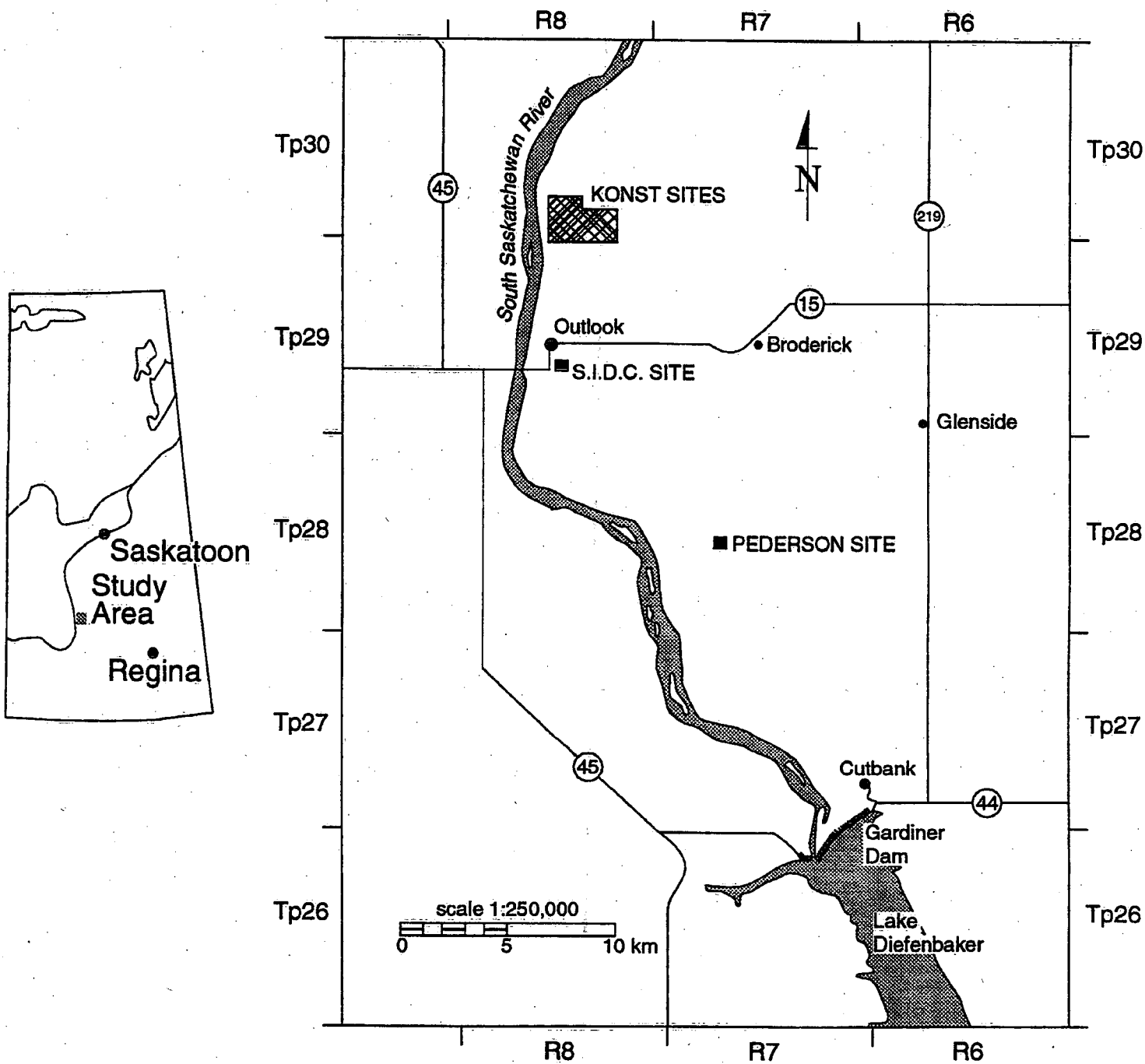


Figure 1. Location of the study sites.

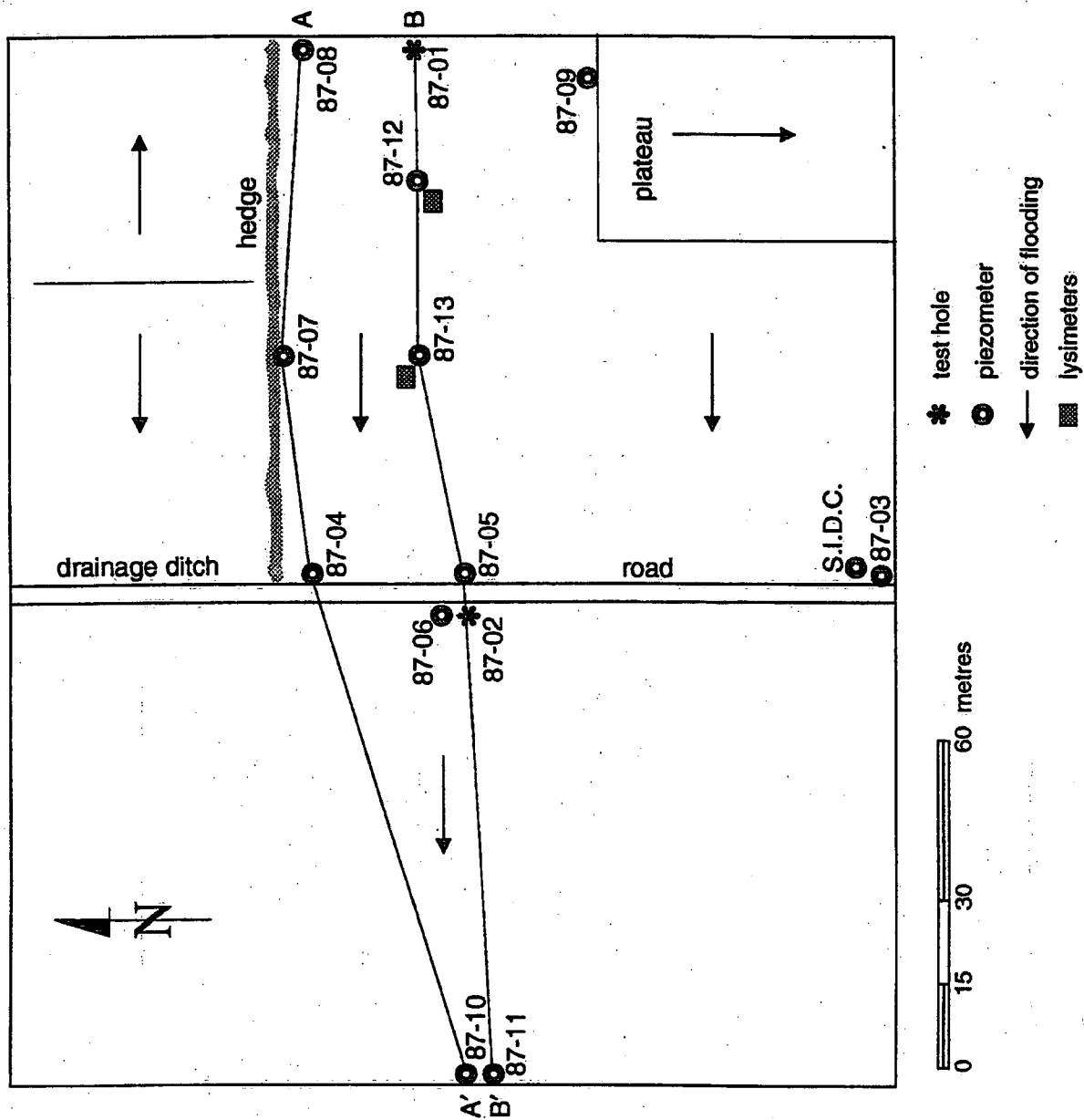


Figure 2. Map of the Pederson site.

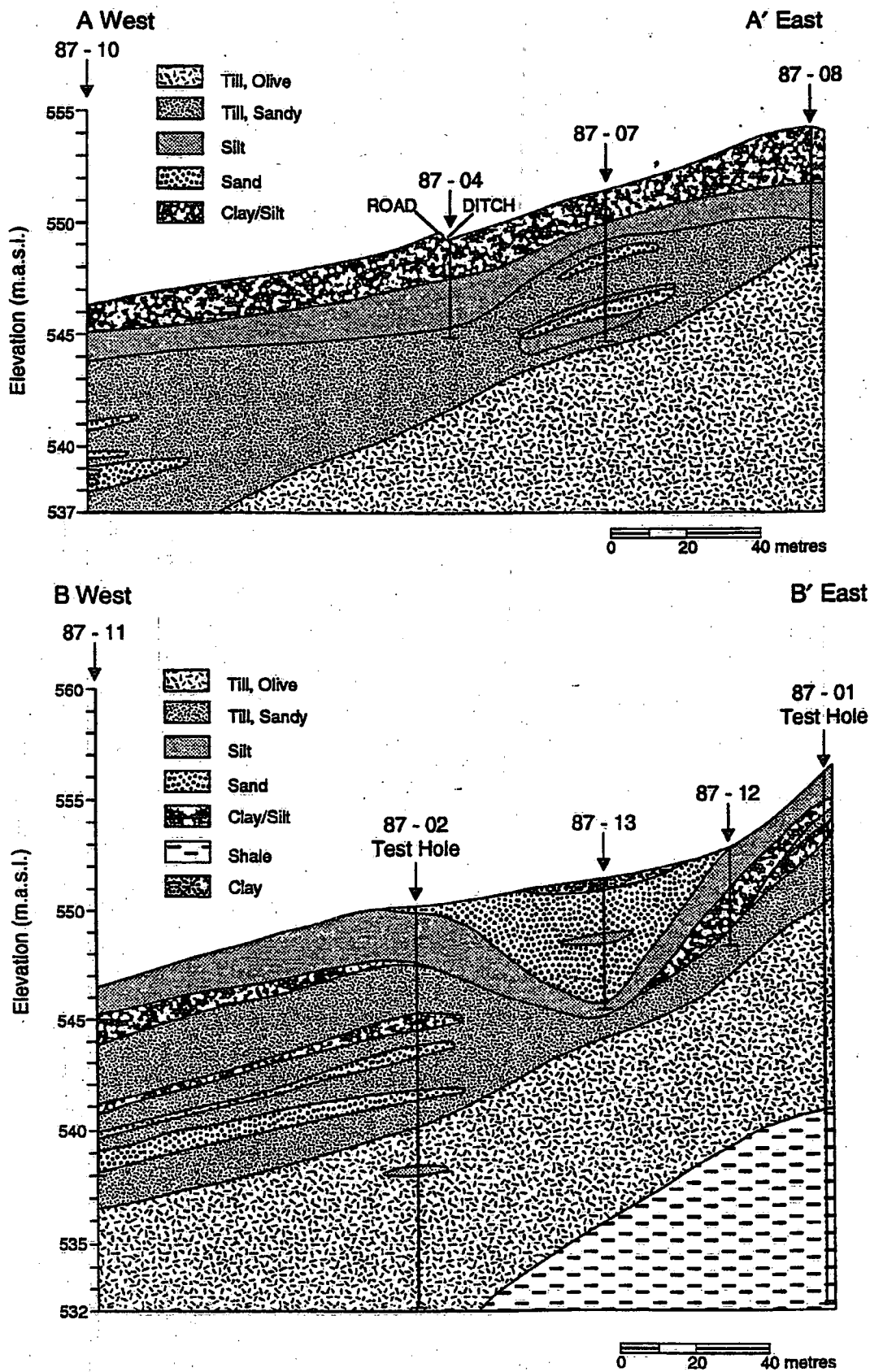


Figure 3. Stratigraphic cross-sections through the Pederson site.

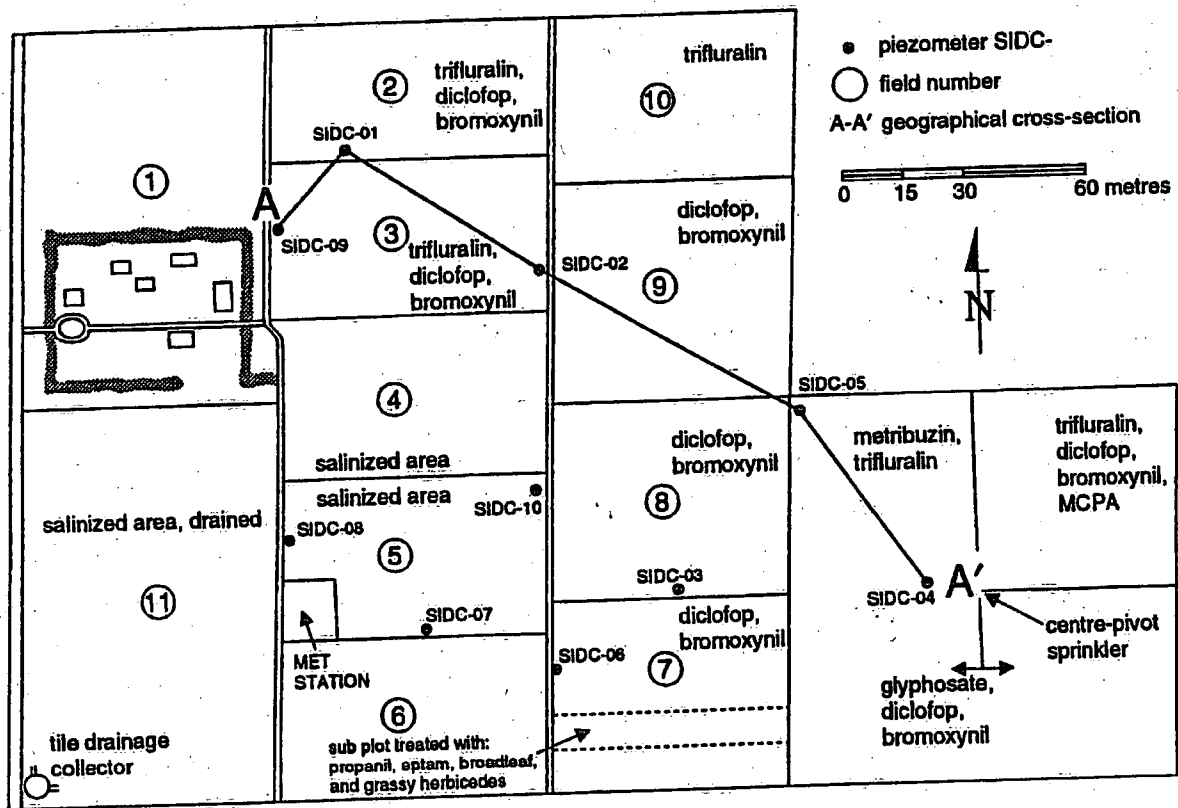


Figure 4. Map of the S.I.D.C. site.

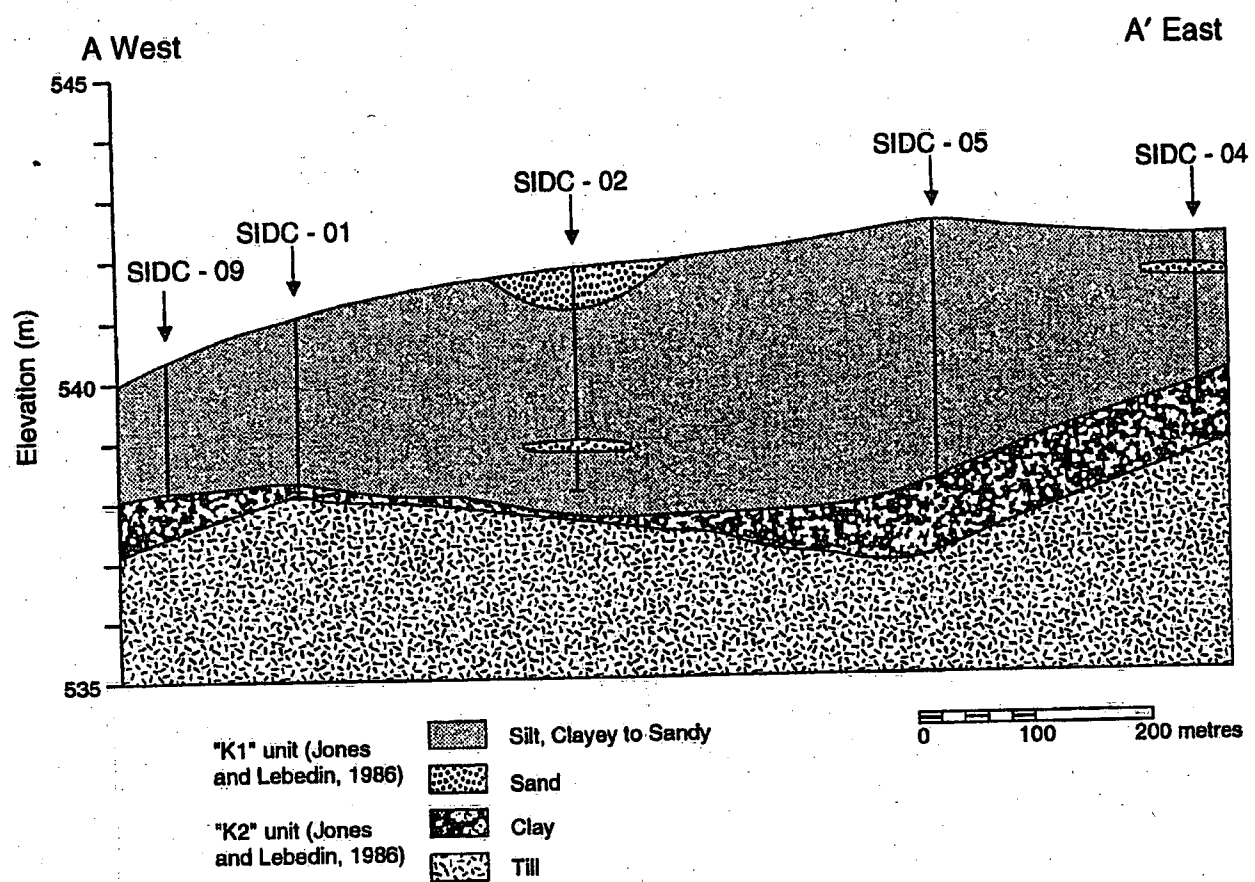


Figure 5. Stratigraphic cross-section through the S.I.D.C. site..

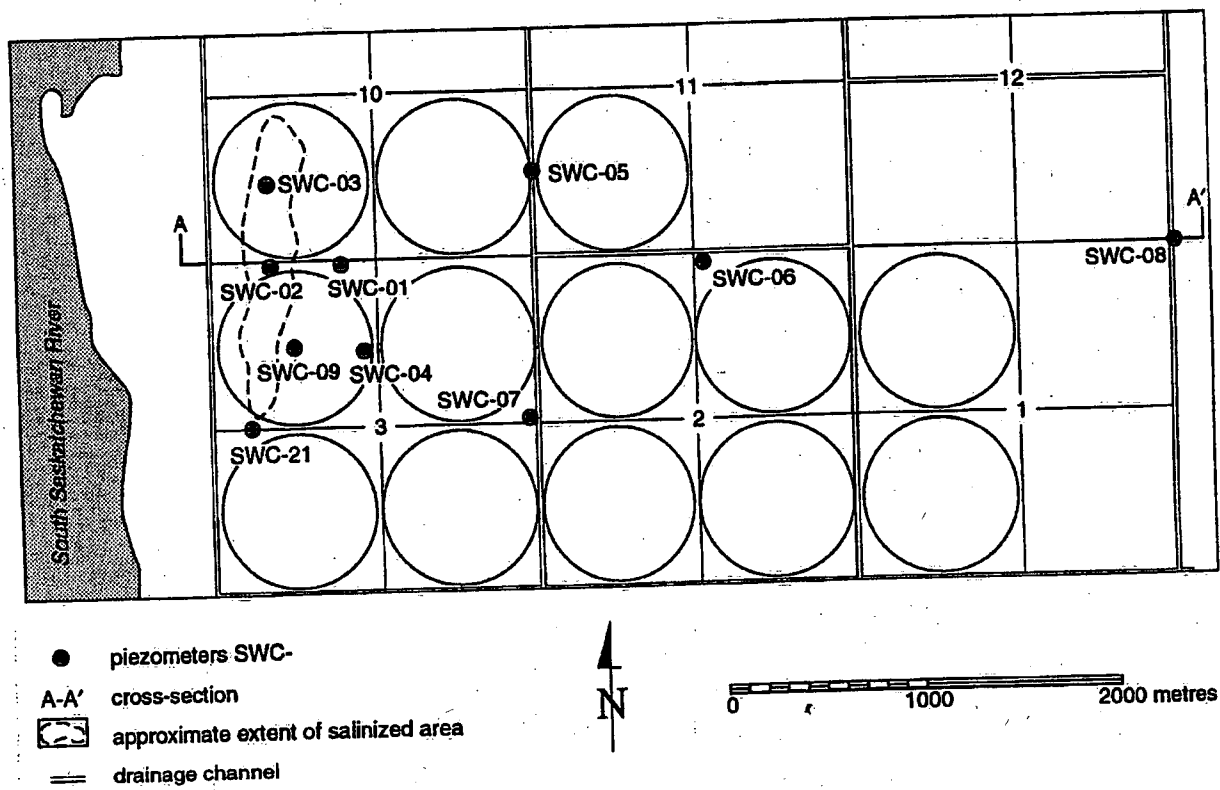


Figure 6. Map of the Konst site.

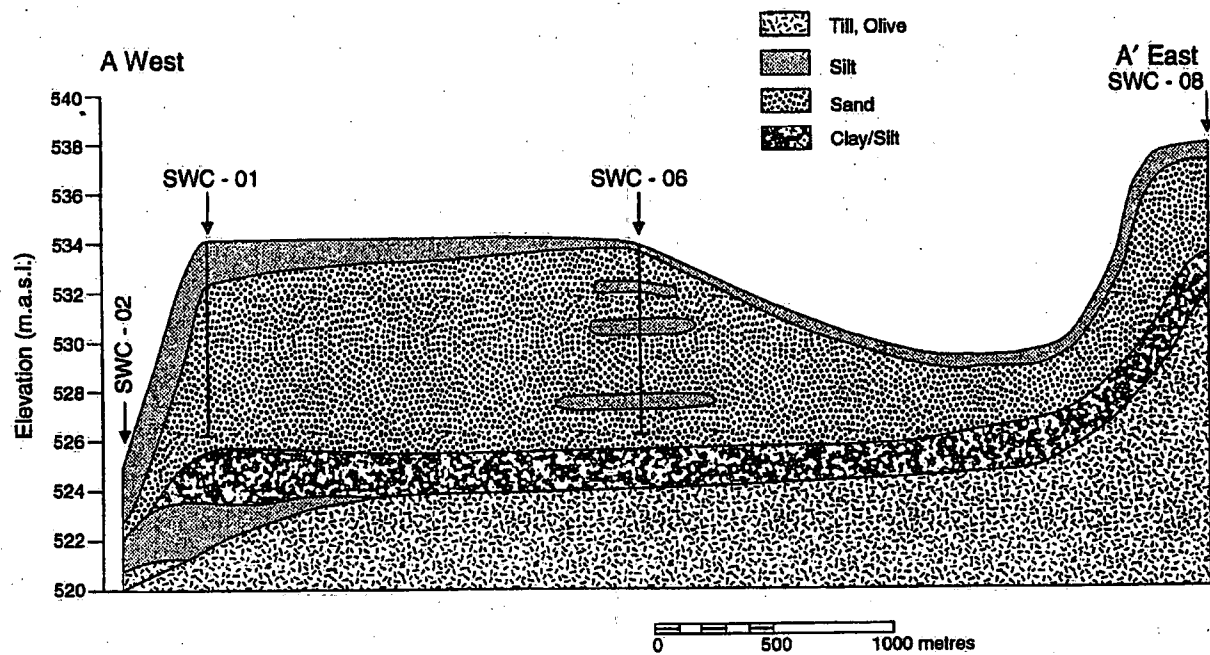


Figure 7. Stratigraphic cross-section through the Konst site.

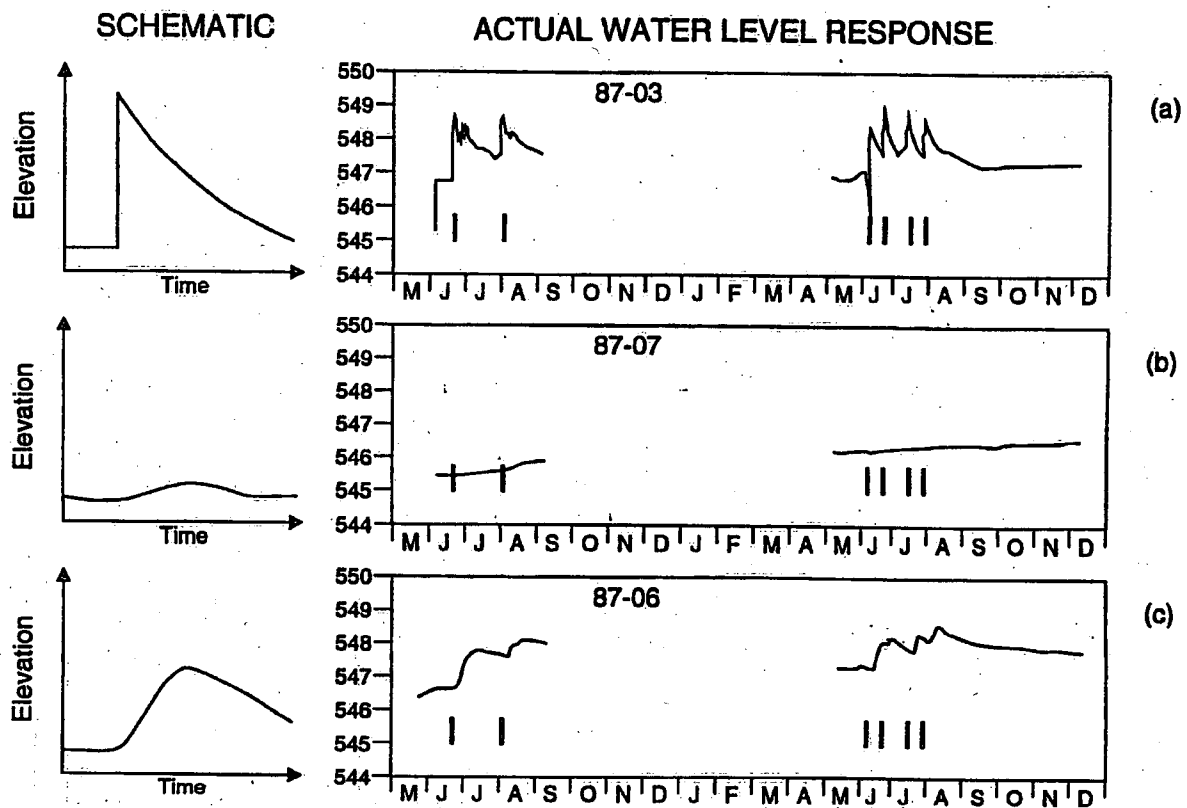


Figure 8. Hydraulic head responses in piezometers at the Pederson site due to (a) flow through vertical fractures, (b) intergranular flow, and (c) both fracture and intergranular flow, due to irrigation events.

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