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Transport of Sediments and Pesticides in Surface Water

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INTRODUCTION

Issues related to erosion and water quality are of increasing concern for Australian agriculture. In the past, erosion was seen as a threat to sustainable production on our most productive cropping lands (Freebairn and Boughton, 1981). Concerns about erosion related mostly to effects on agricultural production at the paddock scale—erosion removes fertile topsoil and causes problems with agricultural operations (Freebairn et al., 1993). With improved soil conservation practices, primarily construction of contour banks and increased retention of crop residues on the soil surface, erosion was reduced (Freebairn et al., 1986a). Damage to public utilities still occurs during floods but often sediment in these cases is sourced from stream banks or nearby areas, and damage is compounded by modifications to the natural flow of water (QDPI, 1980, 1981).

More recently, however, concern has shifted to the off-site impacts of agriculture on water quality. Community and regulatory authorities in Australia are increasingly concerned about quality of water, particularly levels of pesticides and nutrients in streams, wetlands and water storages. Their concerns are not unfounded. Pesticides are consistently detected in the riverine environment and the source of contamination is generally, but not exclusively, attributed to agricultural operations (e.g. Cooper, 1996).

Runoff is an important pathway for transport of pesticides off-site and into the riverine environment but methods of reducing pesticide transport in runoff are still not well developed. High pesticide concentrations in rivers and wetlands are often attributed to runoff, though drift and spillage are occasionally important (Raupach and Briggs, 1996). While our knowledge of how to control runoff and erosion at the paddock scale is relatively well developed (e.g. using contour banks or cropping systems

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which retain stubble) and behaviour of pesticides under controlled conditions is well known, little attention has been given to managing pesticide transport at the catchment or even farm level.

This chapter reviews issues related to transport of sediment and pesticides in runoff water from agricultural areas. The focus is predominantly on cropped catchments in central eastern Australia; impacts of agricultural activities on sediment and pesticide loads in runoff water are outlined, major processes relating to transport described and methods of managing or improving water quality summarised.

EXTENT OF THE PROBLEM IN AUSTRALIA

Why is Erosion a Problem?

Erosion has long been a problem in Australia, causing damage to public utilities and gradual reduction in productivity of croplands, and sedimentation of waterways and reservoirs. Since erosive events are highly episodic, erosion goes largely unnoticed most of the time. At the paddock scale, individual events are not likely to impact substantially on crop productivity. More likely is a gradual decline in soil productivity, possibly extending over decades. The National Soil Erosion-Productivity Research Planning Committee (1981) suggested that effects of erosion might not even be noticed until cropping viability has declined substantially. Flood damage to public utilities often captures attention, but sedimentation of waterways and reservoirs and increased turbidity of water bodies goes largely unnoticed (Ciesiolka, 1987). Despite, or possibly because of its somewhat insidious nature, erosion is still a problem in Australia.

At the paddock scale, loss of soil productivity is the most important long-term consequence of erosion. Erosion typically removes topsoil, which has the most favourable physical properties and is most fertile. Soil deeper in the profile with less desirable properties may be exposed. High rates of soil loss reduce the depth of the soil profile, reducing the amount of water the soil can hold and productivity of crops and pastures. Littleboy et al. (1992) estimated in a simulation study, that wheat yields would decline by 30–80% after 100 years of cropping where stubble was burnt and intense tillage used (Table 8.1). Rills, gullies and waterlogged areas also introduce workability problems. In the long term, these factors combine to reduce soil productivity and increase fertiliser and other management requirements.

Erosion from stream channels and banks as well as nearby floodplain areas is generally the main source of sedimentation and turbidity in streams, wetlands and larger dams (Ciesiolka, 1987; Preston, 1996). Most of the sediment eroded from farm paddocks does not move far down-

Table 8.1: Effects of fallow management in a wheat-summer fallow cropping system, 5% land slope, soil profile 1 m deep (Littleboy et al., 1992). Data were simulated using the PERFECT model for 100-year weather records.

Fallow management	*Decline in wheat yields (%) due to erosion over 100 years*		
	Emerald	*Dalby*	*Gunnedah*
Zero-till	10	5	5
Stubble mulched	12	6	6
Stubble incorporated	35	20	18
Stubble burnt	80	50	30

stream. Contour banks are particularly effective sediment traps, collecting 80–90% of the soil eroded within the contour bay (Freebairn and Wockner, 1986b). Coarse sediment transported off-paddock or eroded from waterways and minor creeks is deposited in the upper reaches of river catchments (Rutherford and Smith, 1992) or in farm dams (Neil and Galloway, 1989). So sediment transported downstream is likely to be comprised of smaller size particles primarily suspended in the flow. These particles probably do not contribute much to sediment load, but may be important carriers for soil-sorbed pesticides or contribute to turbidity of downstream water bodies.

Floodwaters can cause damage to farms, waterways and public structures and effects are compounded by modifications to natural flow paths. In a large flood event on 5–9 February 1981, 250 mm of rain caused widespread erosion and flooding on the Darling Downs (QDPI, 1981). About 2400 farms were affected and damage to soil conservation works, crops, fencing and land surfaces was estimated at $ M2.2. This figure does not include loss of crop yields as a result of topsoil erosion. Damage to roads, railways, power and electricity facilities was estimated at $ M3.6. Damage was worst where soil conservation structures failed or engineering structures (particularly at road and rail crossings) concentrated water instead of controling the flow.

Australia has high levels of erosion due to a combination of several factors, such as the nature of our soils, landscape, rainfall and agricultural systems originally based on European practices.

Many of our soils are highly erodible, particularly when cultivated to a fine tilth (Freebairn et al., 1996). Vertisols, for example, are highly erodible because they have low sediment density and their resistance to detachment by raindrops and flowing water is low because they shrink-swell and reform loose aggregates (Loch et al., 1998). Also, many of our soils have low aggregate stability under rainfall and hence tend to break down into small particles readily detached and transported in water. Cultivation of soils to a fine tilth further reduces resistance to detachment by water.

Our landscape, with steep slopes and long slope lengths, contributes to the erosion problem. Sloping land with long slope lengths is highly prone to erosion. Commonly, slope gradients on cropland range up to 7% and slopes may be many hundreds of metres long. Erosion increases sharply as slope increases because the erosive power of runoff water increases (Moore and Burch, 1986). As slope length increases the volume of runoff and chance of runoff accumulating in rills or gullies increases. The concentration of sediment carried in rills is 4–8 times greater than in shallow overland flow (Loch and Donnollan, 1982). Prior to the implementation of soil conservation works, particularly contour banks, erosion rills and gullies were common and where large amounts of topsoil were lost on shallow soils, these soils were rendered unsuitable for cropping (e.g. Galletly, 1985).

Erosion is broadly related to rainfall energy (Wischmeier and Smith, 1978), which increases from south to north in Australia. Figure 8.1 shows how sharply erosion increases as rainfall erosivity exceeds a threshold level of 100. Figure 8.2 illustrates the increase in erosion from the south of eastern Australia to the north, a result of increasing rainfall intensity. In Queensland and northern New South Wales, most runoff and erosion occurs in intense, often short duration rainfall events, which comprise a

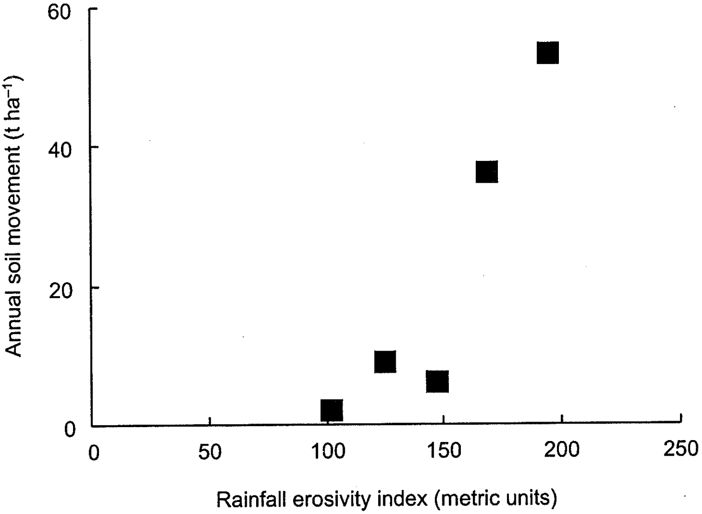

Fig. 8.1: Relationship between a measure of rainfall energy (erosivity index) and erosion.

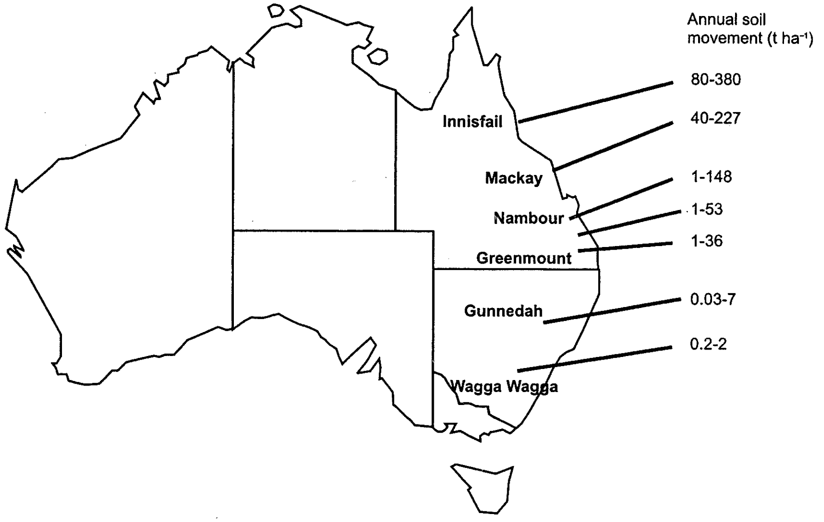

Fig. 8.2: Erosion increases from south to north because of increasing rainfall intensity (Freebairn, 1992).

relatively small proportion of annual rainfall (Freebairn and Boughton, 1985; Flanagan et al., 1988; Edwards and Owens, 1991). For example, Freebairn and Wockner (1986a) measured a rainfall event on the Darling Downs with a peak intensity over 15 minutes of 131 mm h^{-1}; 49% of the rainfall was lost as runoff and 99 t ha^{-1} soil was eroded within a contour bay in bare fallow. Rainfall intensities of this magnitude are likely to occur once every 10 years (Pilgrim, 1987), but even in events likely to occur at least every year more than 50% of rain frequently runs off (Freebairn and Wockner, 1986a; Freebairn et al., 1986b). So characteristics of individual rainfall events are a major driving force causing erosion.

Variable rainfall contributes to erosion problems, with dry periods causing variable crop growth, wet periods saturating the soil and intense storms occurring in either case. The coefficient of variation of annual rainfall varies from about 25% in southern Queensland up to 47% in the north (Willcocks and Young, 1991) and it is not uncommon to have either very wet or very dry periods (e.g. QDPI 1981; Webb et al., 1997). In dry spells, crops may fail, be used as supplemental feed for livestock or planting opportunities may be missed. As a result, the soil can be left uncovered for periods of up to 12 months, at risk from sudden, intense rainfalls. In wet periods, particularly on soils with shrink-swell clay types or with subsurface soil layers with low permeability, a large proportion of rain runs off (Freebairn and Wockner, 1986a). Adding to seasonal variability, large erosive rainfall events can occur in both wet and dry periods. As an indication of the importance of rainfall variability, management systems have been developed specifically to cater for variable conditions. For example, Carroll et al. (1997) found planting crops at the first opportunity, rather than using a fixed rotation, was the most appropriate cropping system for managing variable rainfall in central Queensland.

In the past, many cropping practices used in Australia were imported from Europe, including frequent and intense tillage, removal of surface cover and fixed rotations or continuous monoculture, which were not always suitable for local conditions. Burning or tillage was typically used to remove stubble soon after harvest, leaving soil bare and susceptible to erosion. Concerns relating to disease build-up on stubble encouraged burning and there was also a generally perceived need to cultivate to prepare a suitable seedbed as well as to control weeds (Freebairn et al., 1986a). As a result, machinery was largely developed to plant in bare soil cultivated to a fine tilth. Recently though, herbicide costs have fallen (Wylie, 1997b) and alternative methods of cropping, such as conservation tillage and improved crop rotations, have been widely researched (Conservation Farmers Inc., 1998; Freebairn et al., 1986a). But tillage and stubble removal is still common (ABARE, 1999), typically because existing machinery is unable to handle increased stubble levels, replacement machinery is expensive and disease outbreaks are exacerbated by the presence of stubble (Wylie, 1997b). Accordingly, it is recognised within the cropping industry that research and development are still needed to further adapt our cropping systems to local environments (e.g. GRDC, 1999).

Impacts of Agricultural Pesticide Use on Water Quality

Pesticides used in grain- and cotton-growing areas are regularly found in reservoirs, rivers and groundwater at concentrations causing concern to community groups and regulators. Regular sampling of rivers and reservoirs by the Condamine Balonne Water Committee from 1993 to 1998 (Condamine Balonne Water Committee Inc., 1998) found atrazine in as many as 90% samples and endosulfan and metolachlor in a relatively large proportion of samples. Routine sampling in the Macquarie, Namoi, Gwydir and Border rivers in central and north-western New South Wales consistently finds a range of pesticides in particular endosulfan and atrazine (Cooper, 1996). Mawhinney (1998) during an intensive sampling programme in the Liverpool Plains, New South Wales, found atrazine in 100% samples taken from streams and rivers and 40% groundwater samples. Not only are pesticides detected regularly, but concentrations commonly exceed published guidelines for water quality. Mawhinney (1998) found 71% samples of surface water on the Liverpool Plains exceeded NHMRC/ARMCANZ (1996) concentration guidelines, requiring action to identify the source and avoid further contamination. Pesticide concentrations were highest immediately downstream of agricultural areas. Regardless of the concentration of pesticides detected, there is general concern that the frequency of observations of agricultural chemicals in the riverine environment is too high.

No doubt a strong contributor to the occurrence of pesticides in the riverine environment is increased usage, particularly during fallow periods when the likelihood of runoff is high. Pesticides, including herbicides used during fallows, are used more frequently, especially in conservation cropping systems in which chemical control of weeds replaces tillage and because pesticide costs have fallen (Wylie, 1997b). This accounts for the sharp increase in pesticide sales in recent years (Fig. 8.3). More recent data is available. The herbicides atrazine and glyphosate are used extensively for weed control. Mawhinney (1998), for example, found 558 t of glyphosate and 470 t of atrazine were applied in the Liverpool Plains in 1996/97. About 500,000 ha of land was cropped in the Liverpool Plains during that period. Runoff is likely during summer fallows because the soil becomes wet from February to April, and cover levels decline. Even with high cover levels, runoff still occurs during intense rainfall events or when the soil is wet (Freebairn and Wockner, 1986a).

Another important factor determining pesticide transport off-farm is farm layout, particularly in dryland cropping areas. In dryland areas, crops are commonly grown up to the edge of watercourses. As a result, there is little buffer between the farm paddock and watercourses so runoff

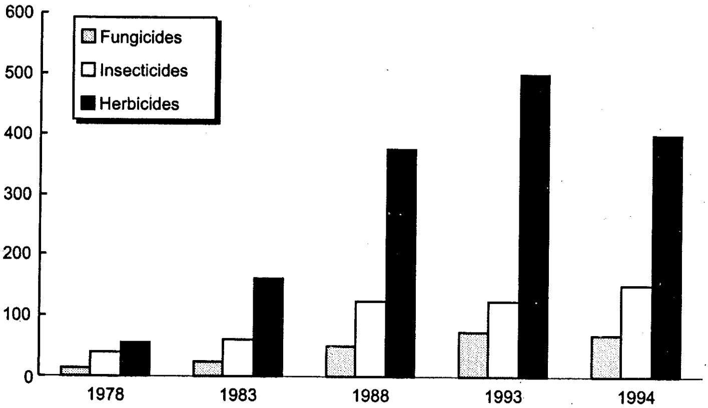

Fig. 8.3: Trends in sales of pesticides in Australia. *Source:* Kookana et al. (1998) after Avcare (1995). Data not corrected for inflation.

water containing pesticides can quickly enter the riverine environment. Even soil conservation works, particularly contour banks and waterways, transport runoff water efficiently off-farm and into downstream watercourses. Contour banks trap larger sediment particles but do little to remove pesticides attached to fine sediment or organic matter particles or dissolved in runoff water. In irrigated environments, excess irrigation or runoff water is captured in drains and storages but only to a certain extent. Most irrigation layouts are not designed to capture more than the first 25 mm of runoff (Barrett et al., 1991), but intense runoff events are frequently bigger than this (Freebairn and Wockner, 1986a; Connolly et al., 1999). With such an easy path from the farm paddock to watercourses and high usage rate, it is not surprising that pesticides are consistently transported off-farm.

However, there is little local, integrated research into how pesticides are reaching the riverine environment and the dynamics of pesticide transport is complex. Monitoring programmes in the past have tended to concentrate on the large catchment scale (e.g. Condamine Balonne Water Committee Inc., 1998) or small catchment or plot scale (e.g. Finlayson and Silburn, 1996) with little consideration of the mechanisms of transport between the two. Pesticide transport is more complicated than sediment transport because pesticides dissipate in the environment even when in transit from the farm paddock downstream. Pesticides are also transported partially as adsorbates on sediment or organic matter; this partitioning varies between pesticides. So conservation tillage methods that reduce erosion do not necessarily eliminate or even reduce pesticide transport. Recognising these gaps, funding bodies are encouraging an improved understanding of the movement of pesticides in the runoff pathway (e.g. Schofield et al., 1998).

PROCESSES RELATED TO SEDIMENT AND PESTICIDE TRANSPORT

Broadly speaking, the amount of pesticide transported in runoff water is related to the amount available for transport, portioning of the pesticide between water, soil and organic matter, erosion and sediment load, and any dissipation or loss in transit.

Amount of Pesticide Available for Transport

When a pesticide is applied for agricultural purposes, not all of it reaches the target (i.e., the soil or plants) (Fig. 8.4). Some may move off the paddock at the time of application as a result of volatilisation or drift. Drift, in particular, may cause off-site damage to other crops or the sensitive areas or the pesticide may settle on nearby areas and be entrained later in runoff water. Pesticides moved into the air by volatilisation can settle in

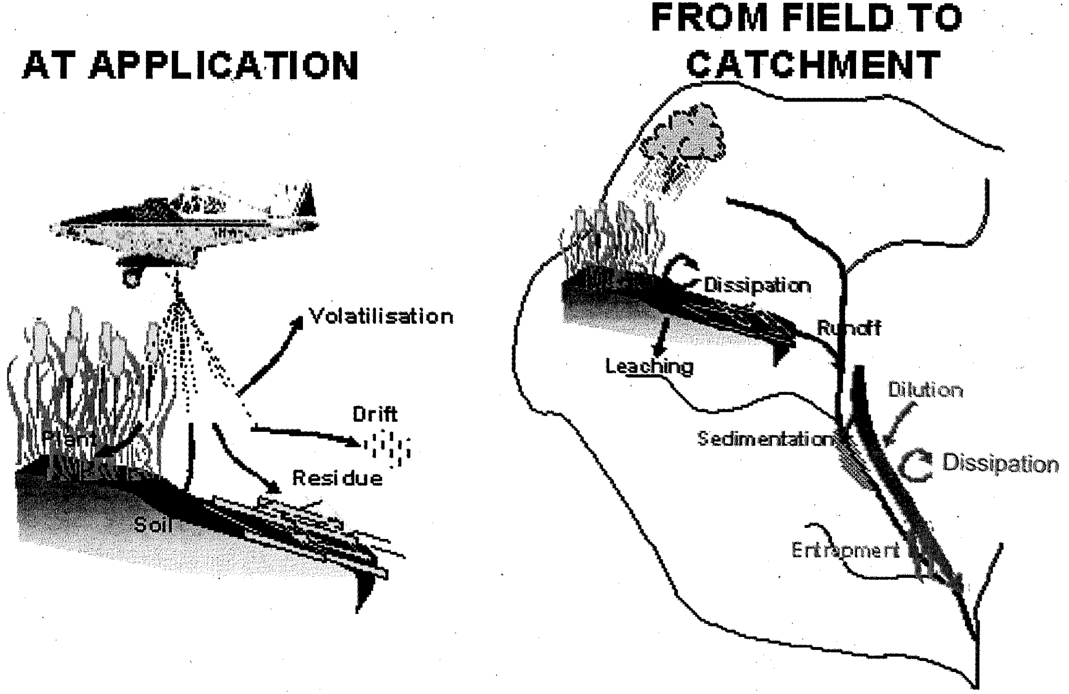

Fig. 8.4: Schematic representation of the fate of pesticide in agricultural systems. At the time of application, the pesticide can contact living plants, plant residue or the soil and be lost to drift and volatilisation. After application, the pesticide can dissipate, leach or be transported in runoff. As the pesticide moves downstream, concentrations tend to dilute, the pesticide is deposited with sediment, dissipated further or entrapped in vegetation.

downstream water bodies and the low, consistent levels of pesticides found in routine sampling are sometimes attributed to this phenomenon (Raupach et al., 1996). The remainder of the pesticide applied comes into contact with plants or residue (if present) and the soil. In some cases the target may receive only a small proportion of the pesticide, with the remainder contacting non-target soil or plant matter. For example, endosulfan is often sprayed on young cotton when the plants cover only 10% of the soil surface; the remainder of the pesticide falls on the soil where it is available for detachment and transport in runoff.

Once on the field, most pesticides dissipate or degrade *in situ* but characteristics of the individual pesticide greatly affect its persistence. Figure 8.5 illustrates differences in dissipation rates. Rates of dissipation may also depend on soil type, pH, clay and organic matter levels, temperature and moisture. Quoted half-lives for atrazine on soil in farm fields, for example, vary from 6–150 days (Hamilton and Haydon, 1996). By-products of some pesticides can themselves be toxic and have different properties from the parent product. For example, endosulfan is composed of two isomers, alpha and beta. Typical half-lives for alpha and beta on soil are 5 and 17 days (Connolly et al., 2001). Endosulfan sulphate, a toxic breakdown product, has a half-life on soil of about 60 days.

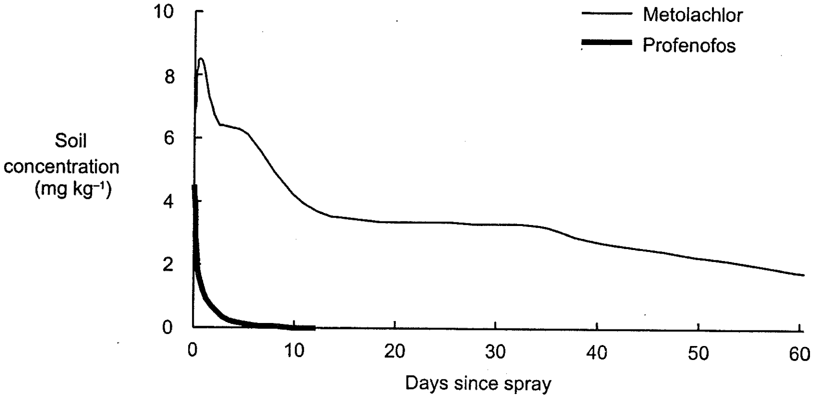

Fig. 8.5: Different pesticides have different rates of dissipation. Data are for bare soil at Jondaryan, west of Toowoomba, exposed to natural rainfall (after Silburn and Connolly, 1998).

Pesticide persistence greatly affects the potential for transport as concentration in runoff is related to the concentration of pesticide on soil or plants at the time of a runoff event. Leonard et al. (1979) found a consistent relationship between concentrations of atrazine, cyanazine, diphenamid and propazine in surface 0.01 m soil and in runoff (Fig. 8.6). It follows that pesticides with slow rates of dissipation are a greater risk to the riverine

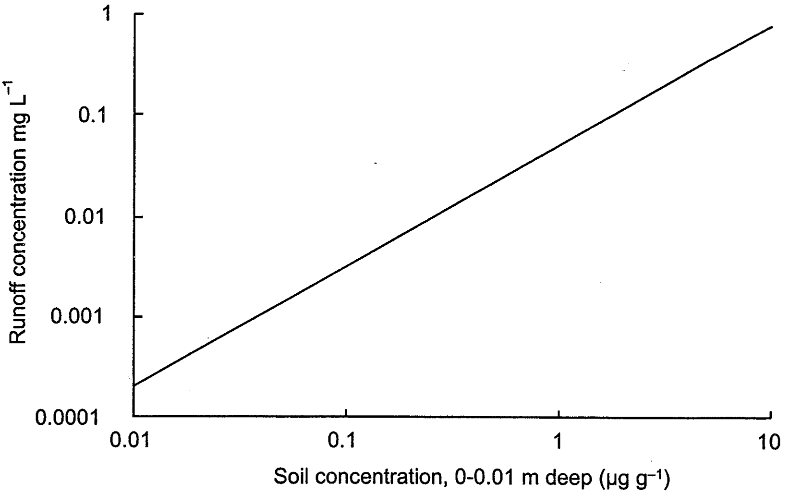

Fig. 8.6: Concentration of pesticide in runoff is strongly related to concentration in soil (Leonard et al., 1979). Pesticides represented in this graph are atrazine, cyanazine, diphenamid and propazine.

environment than pesticides that rapidly break down into harmless by-products. Cooper and Riley (1996), for example, found residues of atrazine in storm runoff from the Liverpool Plains up to 12 months after application. Glyphosate, on the other hand, is rarely transported in runoff because it is rapidly degraded by microbial action.

Pesticide Partitioning

Pesticide is transported in runoff adsorbed in water and attached to sediment or organic matter. A measure of pesticide partitioning between soil/organic matter and water is the adsorption coefficient, $K = C_s/C_w$, where C_s is the equilibrium concentration attached to soil/organic matter and C_w the concentration in water. Pesticide with a high K indicates a preference for transport attached to sediment/organic matter; low-K pesticide is more likely to move in the water phase (Fig. 8.7).

Because properties of individual pesticides vary greatly, success of management strategies directed towards minimising transport likewise varies. Soil conservation works and conservation cropping techniques reduce transport of coarse sediment off-paddock, but do not necessarily reduce the volume of water from large, intensive rainfalls nor concentrations of pesticide dissolved in runoff water or attached to fine sediment particles and organic matter (Fawcett et al., 1994). Accordingly, one would

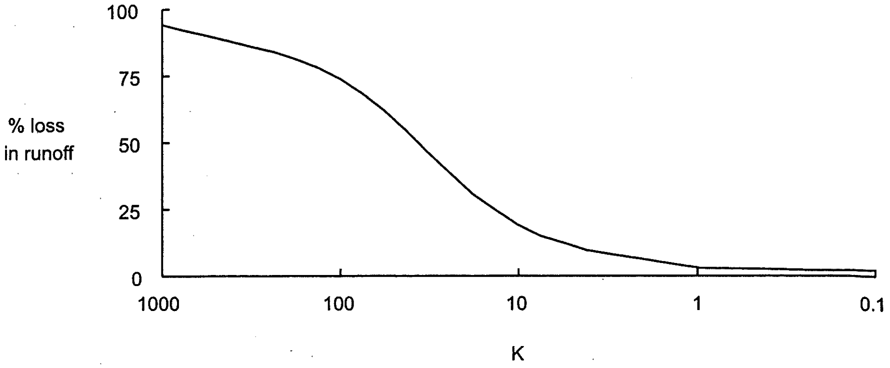

Fig. 8.7: Relationship between adsorption coefficient K and losses of chemicals in runoff water (Baker and Johnson, 1983).

expect that pesticides with low K values would be harder to control at the field scale. That soil-sorbed pesticides (e.g. endosulfan with a K of around 200) are consistently found some distance downstream of agricultural areas (Cooper, 1996) indicates that control of moderately soil-sorbed pesticides is also not straightforward.

Erosion and Sediment Load

At the paddock scale, soil is detached by the impact of raindrops and the erosive capacity of flowing water (Meyer et al., 1976). The erosive capacity of water and its ability to transport detached sediment depend on the velocity and quantity of water flow (Loch and Donnollan, 1982). Quantity of water flow is determined by rainfall intensity, infiltration capacity of the soil and catchment area (Freebairn and Wockner, 1996a). Velocity of flow is determined by the cross-sectional area of the flow channel, flow depth, friction and land slope, and is heavily influenced by the presence of crop residue or roughness elements on the soil surface. Plant residue and other materials providing surface cover protect the soil from raindrop impact and increase flow tortuosity, thus reducing detachment and transport capacity of the water. Roughness elements and depressions on the surface, usually resulting from tillage, can also increase flow tortuosity and may retain runoff water. Benefits of roughness are likely to be more transient though than cover, since roughness elements tend to break down or erode over time.

As discussed above, most sediment eroded at the paddock scale does not move far downstream but a proportion of primarily smaller, suspended particles can be transported some distance. Coarser sediment in the water is encouraged to settle out when flow transport capacity decreases to the point that larger sediment particles can no longer be transported. This occurs in the first instance at changes in land slope. Contour banks, with a slope of about 0.1%, intercept 80–90% of sediment transported from the hill slope (Freebairn and Wockner, 1986b). Still, sediment concentrations in runoff water leaving the contour bay outlet can be as high as 20 g L^{-1} (Freebairn and Wockner, 1986b) and contain some relatively large sediment particles. Much of the larger sediment probably settles out in waterways, dams and low lying areas not far down stream of the contour bank outlet. Grass filters and well designed and maintained grass waterways can slow runoff velocity and allow depo-sition, but waterways that are too narrow, steep or with poor grass cover erode and gully, contributing to the sediment load (QDPI, 1980, 1981). Little is known about the sources of suspended sediment found lower in the catchment, but that soil-sorbed pesticides used on farms are found downstream in rivers indicates that some sediments, probably small particles and organic matter, make their way down through the catchment.

Loss in Transit

Sediment and pesticide moving in runoff water are subject to a number of processes that act to reduce the latter's concentration (see Fig. 8.4). The major processes are deposition of sediment, dissipation or degradation in transit, dilution with 'clean' water, or entrapment/filtering in vegetation. These combine to reduce pesticide load with increasing distance downstream (Fig. 8.8).

Loss to deposition is likely to occur relatively close to the sediment source and is probably among the first processes to reduce pesticide concentrations in runoff water. As mentioned earlier, most coarse sediment eroded from farm paddocks is deposited in nearby channels or waterways. While it is possible for pesticide persisting in these deposits to be re-entrained in later runoff events, this is most likely when the deposit lies in a major watercourse and the pesticide is persistent. Presumably, these deposits will mostly occur in dryland cropping areas where crops are grown close to major watercourses. While processes of sediment transport are understood in theory, practical aspects of transport and deposition at the catchment scale are not well specified, despite its obvious importance.

Pesticides degrade or dissipate with time as they move off-field and through downstream waterways. This is particularly important in large catchments because of the time scales involved; water may take several days to several months to reach the catchment outlet. Rates of dissipation depend on pesticide properties, oxygen levels, moisture content, temperature, and chemical and biological characteristics of the environment (such

Fig. 8.8: The amount of pesticide in runoff water can tend to decrease with distance downstream through a catchment. Results are for endosulfan and methoxychlor in a 2000 ha catchment (after Willis et al., 1987).

as pH). Pesticide properties are an important determinant of pesticide fate. Foster et al. (1996), for example, found some pesticides were completely dissipated after travelling 1.9 km in a low sloping drain while others were unaffected.

Sediment and pesticide concentration are reduced by dilution with 'clean' runoff water from areas with no pesticide or less erosion/sediment transport. Dilution tends to increase as catchment area increases because of spatial variability in land-use, but localised affects may be important at any scale. At a sampling point in a large catchment, for example, runoff water from a nearby paddock containing high sediment or pesticide loads may reach the sampling point much more quickly than 'clean' water, if its catchment lies farther away. It is reasonable to expect that for effective dilution to occur, clean water must mix with the contaminated water close to its source. Also, the volume of clean water must match to some degree the volume of contaminated water. Land-use in a catchment will greatly influence the volume of 'clean' runoff water. Cropland in fallow, for example, is likely to contribute more runoff than pasture (Lawrence and Cowrie, 1992), so pasture is less useful as a source of clean water.

Entrapment of pesticides and sediment in vegetation, filter strips, riparian areas, marshes or wetlands is potentially important in reducing concentrations in water. Wetlands can efficiently remove pollutants from water and are often constructed specifically for that purpose as well as for aesthetic and recreational value (e.g Raisin and Mitchell, 1996; Wong, 1997). Natural riparian areas, marshes or areas of pasture or weeds are also favourable. Even narrow filter areas can slow water flow and cause coarse sediment to deposit. Queensland guidelines for filter strips prepared by Karssies and Prosser (1999) specify only a 2–5 m wide strip of high cover pasture to reduce sediment transport from cotton farms.

MANAGING PESTICIDE AND SEDIMENT MOVEMENT

The primary objective of pesticide management is to keep the product in the place it was applied, maximise the rate of breakdown into harmless by-products and concomitantly control target pests or weeds. The primary objective of techniques to control erosion, such as soil conservation practices, is to reduce erosion and rilling on the paddock itself and capture eroded sediment in contour bays where the soil is at least not lost from the paddock and can be relocated at a later date if necessary. This implies that management to minimise sediment and pesticide transport off-farm should concentrate on techniques to keep soil and pesticide within the paddock. Indeed, much research in the past has focused on this aspect.

But, management at the catchment and regional scale is also needed since pesticides are mobile and it is generally considered important to maintain high water quality in reservoirs and downstream water bodies. While soil conservation techniques are effective in reducing erosion at the paddock scale, it is not practically possible to retain all pesticide on-paddock, particularly during large runoff events. Pesticides carried in water or on fine sediments or organic matter are readily transported off-farm. In fact, many existing soil conservation systems and farm layouts move water (and any suspended sediment and pesticide) efficiently off the farm. Transport off-paddock may also occur via volatilisation, drift or leaching. So not only do mechanisms for transport off-paddock require consideration, techniques for managing the pollutants once they have moved off the paddock and the farm are needed for environmental protection at the catchment and regional scale.

Field Scale

Pesticide losses from the field are reduced by reducing concentration in the carrier (water and sediment), reducing the mass of the carrier, or both.

The most effective way of reducing the risk of pesticide loss is to reduce the amount of pesticide on the paddock. This can be achieved by reducing the amount and frequency of applications and/or improving application methods. Immediate reductions in amount can be achieved by applying the pesticide more accurately or specifically to the target rather than broadcasting it. A pesticide can be applied to a narrow band over the top of the target crop or vision-sensing sprays can be used that only spray specific plants or areas. Guillard et al. (1999), for example, found that broadcasting atrazine over the entire paddock led to 3–4 times more leaching than applying the product in 15 cm bands over crop rows. In a simulation study, Connolly et al. (2001) found that halving the number of endosulfan sprays halved transport in runoff from irrigated cotton farms (Fig. 8.9). Other techniques commonly used in the cotton industry to reduce reliance on pesticides include using trap crops to attract insects, then spraying only the small trap crop area, and using genetically modified, pest-resistant plants (de B. Lyon, 1994). Increasing frequency of application and reducing application rates may reduce transport risk by reducing concentration on the field at any one time, though this may mean pesticide is present for a longer period, albeit at a lower concentration.

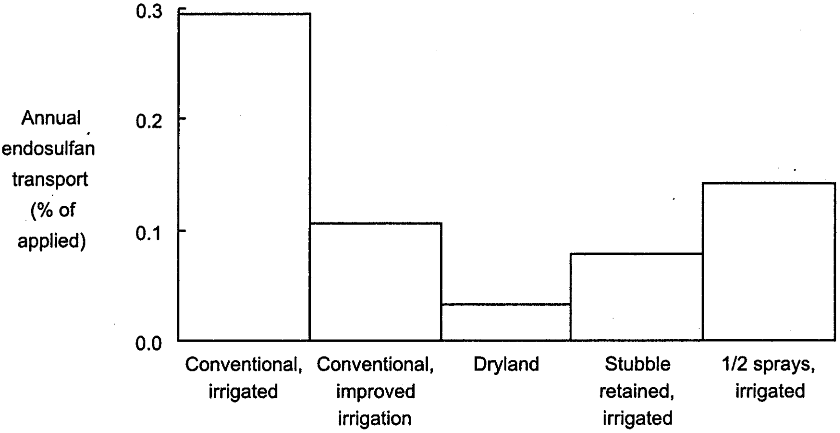

Fig. 8.9: Effect of in-field management on average annual transport of endosulfan off-field. Results were simulated with the GLEAMS model for a farm at Warren, NSW (after Connolly et al., 2001).

Surface cover is highly effective in reducing the mass of the carrier, i.e., sediment and water. Cover reduces the impact of raindrops, increases flow tortuosity and resistance, and reduces runoff velocity, thus reducing detachment and transport capacity of runoff water. Furthermore, cover increases infiltration and reduces runoff by reducing crusting and encouraging formation of macroporosity. Figure 8.10 illustrates that as little as 20–30% cover can reduce erosion to nearly one-third that seen in bare-fallow systems.

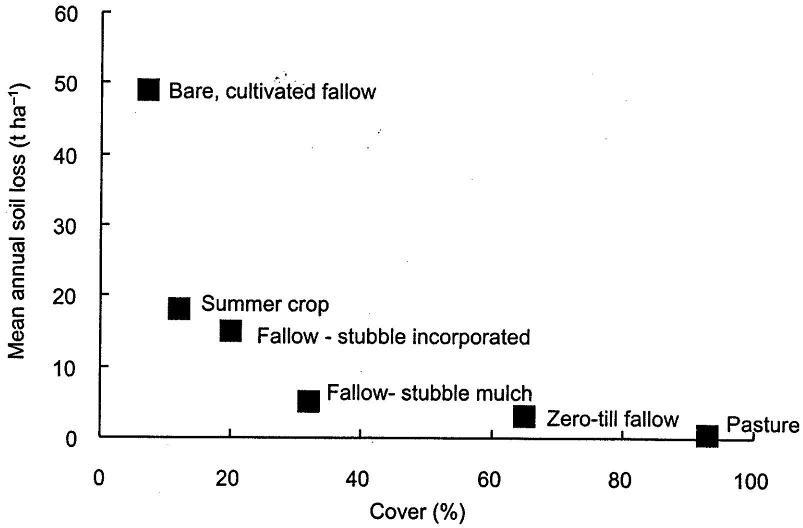

Fig. 8.10: Soil loss versus cover for contour catchments on the eastern Darling Downs (after Freebairn et al., 1996).

Crop management practices that maintain surface cover and encourage favourable soil physical properties, often called conservation tillage systems, have been developed but not yet widely adopted. Zero-till cropping systems use herbicides to control weeds (Freebairn et al., 1986a; Wylie, 1997a). This maximises surface cover but also increases herbicide use. Stubble mulch or minimum tillage systems (Freebairn and Wockner, 1986a) use strategic tillage for weed control, to break up hardset soil and to prepare seedbeds while maintaining soil cover. Controlled traffic or tram tracking (Tullberg, 1998) confines traffic to set paths, reducing wheel track compaction and improving operational efficiencies—spray application accuracy, control over runoff flow paths and field access in-crop. In general, conservation tillage systems reduce sediment and pesticide transport (Fawcett et al., 1994; Freebairn and Wockner, 1986a). Unfortunately, uptake of tillage systems that retain stubble has been limited because of problems with disease build-up on stubble and because planting machinery needs to be modified or upgraded to operate in high stubble levels (Wylie, 1997b; ABARE, 1999).

While pesticide transport can be managed at the field scale, it is unlikely that movement off-field can be eliminated entirely; instead reduction in current export rates should be targeted. Regardless of surface management, high concentration of pesticide on the soil increases the risk of pesticide loss in runoff. Freebairn and Wockner (1986a), for example, found that cover did not reduce runoff on Vertisols when they were very wet and particularly during very large storms. The capacity of farm drainage networks is also limited. Most soil conservation works are only designed to contain runoff from a once-in-10-year large-size event (QDPI, 1966). Poorly maintained channels can overtop in smaller events. So it is not likely that pesticide movement from farm fields can be eliminated entirely; more attainable is the widespread adoption of sound management practices that seek to minimise risk of transport. The Australian cotton industry's implementation of best management practices is one example of an industry-wide approach to improved pesticide management (Australian Cotton Industry, 1997).

Farm Scale

Management options at the farm scale involve capturing contaminated water in storages and improving vegetation management and farm layout. Farm storages, if operated as a flood mitigation device, can effectively capture contaminated water, allowing safe disposal or reuse for irrigation (Fig. 8.11). Farm storages, drainage networks and low-lying areas capable of temporarily collecting water are common in cropping areas. Storages are even more effective when used with field management that reduces the volume of contaminated runoff.

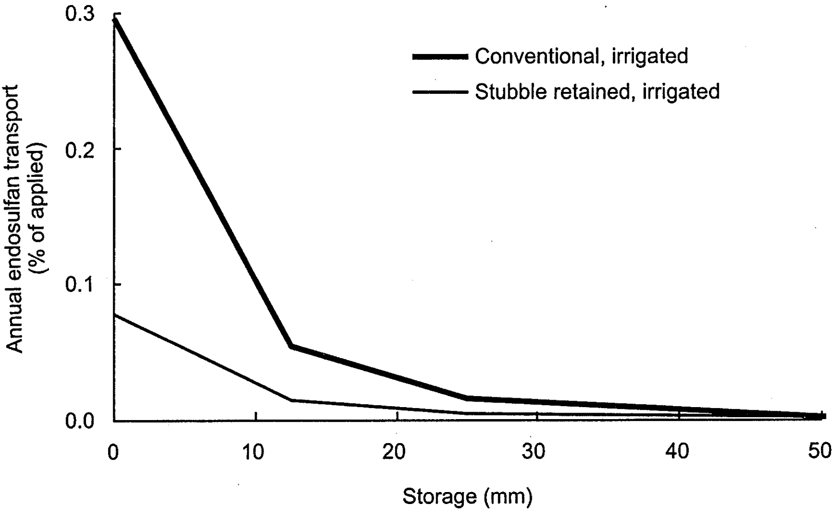

Fig. 8.11: Effect of size of farm water storage combined with in-field management on average annual transport of endosulfan off-farm. Results were simulated with the GLEAMS model for a farm at Warren, NSW (after Connolly et al., 2001).

Filter strips, grassed waterways, marshes and wetlands are important buffers between the farm and the downstream riverine environment but are generally not well developed. Techniques are available for developing windbreaks and filter areas (e.g. Karssies and Prosser, 1999; RIRDC, 1999; Queensland Department of Natural Resources property management planning). Implementation of improved vegetation and layout principles on-farm is slow though, a reflection of the costs involved and farmer focus on the production side. The problem is compounded in areas where farms are small and intensively cropped and where existing farm drainage networks are designed to efficiently transport water off-farm.

Catchment Scale

In some areas runoff water can be managed better at a catchment scale than within individual farms. Not all farms and farm fields have layouts conducive to storing or filtering runoff, either because they are too small, are located in areas that flood, lie immediately adjacent to streams or have soil conservation works that quickly transfer runoff water off-farm. Strip-cropping on the Darling Downs is an example of across-farm management in cropland prone to flooding (DNR, 1999). Alternating strips of crop and fallow land spread, slow and filter floodwater. In areas where farm sizes are small and runoff water discharges directly into drains, such as in high-density irrigation areas, downstream farmers capable of constructing farm storages can capture and recycle the water from upstream farms (e.g. the Emerald Irrigation Area, central Queensland).

Wetlands, riparian zones or even areas of pasture can be useful for filtering sediment and pesticides from runoff water. Currently, neither wetlands nor riparian areas are developed in cropping areas for the purpose of improving water quality. Riparian zones have been degraded by grazing, stream bank degradation and other pressures (McCosker, 1996), so their effectiveness in filtering runoff water is greatly reduced.

Agronomic coordination across farming areas has been developed to some extent in Australia, with benefits for runoff management. Integrated use of pesticides (e.g. integrated pest management) in conjunction with genetically modified and pest-resistant plant species is commonly used in cotton-growing areas to reduce the development of resistant pest populations and to maintain the effectiveness of pesticides (de B. Lyon, 1994). Ultimately, integrated pest management aims to reduce the amount and frequency of pesticide application. This reduces the risk of transport in runoff water by reducing the concentration of pesticides on-field.

Regional Scale

Education and involvement of the community is important if pesticides are to continue as a sustainable management option for farmers. A number of community groups are actively involved in promoting improved management of agricultural lands and waterways in Australia (e.g. Water Watch, Landcare). With education comes increasingly informed debate about techniques for management of agricultural pesticides in our environment.

Land managers are under increasing pressure to reduce exports of pesticides but better alternatives are not always immediately obvious. Guidelines for water quality are often contradictory or incomplete (e.g. Cooper, 1996) and community expectations hold there should be no detectable levels of pesticides in water bodies. Increased regulation of pesticide use, or even withdrawal of pesticides from use is a constant threat. But removing one pesticide from use is not necessarily an improvement if alternatives are more expensive, less effective, applied in greater quantities or behaviour in the environment is not well quantified. Compounding the pressure on land managers are problems dealing with persistent and hard-to-control weeds and insect resistance (de B. Lyon, 1994).

Accordingly, much research and development are still needed if management of agricultural pesticides is to be imporved. We need pesticides with more favourable properties, such as increased efficacy. As little as 20% atrazine, for example, when applied to high clay content soils, is effective in controlling target weeds (Walker et al., 1997). The remaining 80% is persistent and still considered toxic. Ways of using pesticides that require smaller application amounts, improved application mechanisms, improved community awareness and more fully trained operators are imperative. Problems with poorly applied pesticides still needlessly occur (e.g. instances of drift damaging crops downwind are regularly reported to QDPI) reminding us of the need for further improvement.

CONCLUSIONS

While erosion is an important issue for the sustainable management of croplands, export of pesticides off-farm in runoff is of greater concern to the Australian community as a whole. It is generally accepted that levels of pesticides found in our riverine systems are too high, with pesticides consistently detected in concentrations exceeding guideline values. Transport in runoff is often the cause of high pesticide concentrations in water bodies.

Even though much research has been done on erosion and transport of sediment and pesticides at the paddock scale, and pesticide and general water quality is actively monitored in rivers, little is known about the processes involved with transport of pesticide from the farm to the river. It is fairly well accepted that coarse sediment eroded from farm paddocks does not move far downstream in upland catchments, or moves very slowly, and that the source of much of the sediment in rivers is from nearby stream banks or eroded from channels or previously deposited silt fans. Yet soil-bound pesticides are regularly transported off-farm and into downstream rivers, most likely on smaller, suspended sediment particles that comprise a small proportion of the mass of sediment carried by the river at any point in time. We have yet to ascertain the relative importance of the various mechanisms for entrainment of sediment and pesticide and interactions between elements of the landscape as water moves downstream.

One can conclude that while runoff is recognised as a problem pathway, because our understanding of the processes involved is limited, success in managing the problem will likewise be limited. This is borne out by persistent detections of pesticides in riverine environments and slow or patchy uptake of catchment and regional strategies directed towards better management of pesticides (the Australian cotton industry is a notable exception). While several management techniques are available at the field, farm, catchment and regional scale that can be used to address problems of water quality, with few exceptions these techniques have yet to be widely adopted.

Yet there are pressing reasons to address our relatively poor water quality, including growing concern in the wider community and the threat of increased regulation. It appears obvious that more effort is needed to reduce export rates of sediment and pesticides from agricultural areas, to reduce in-stream transport and to improve downstream water quality.

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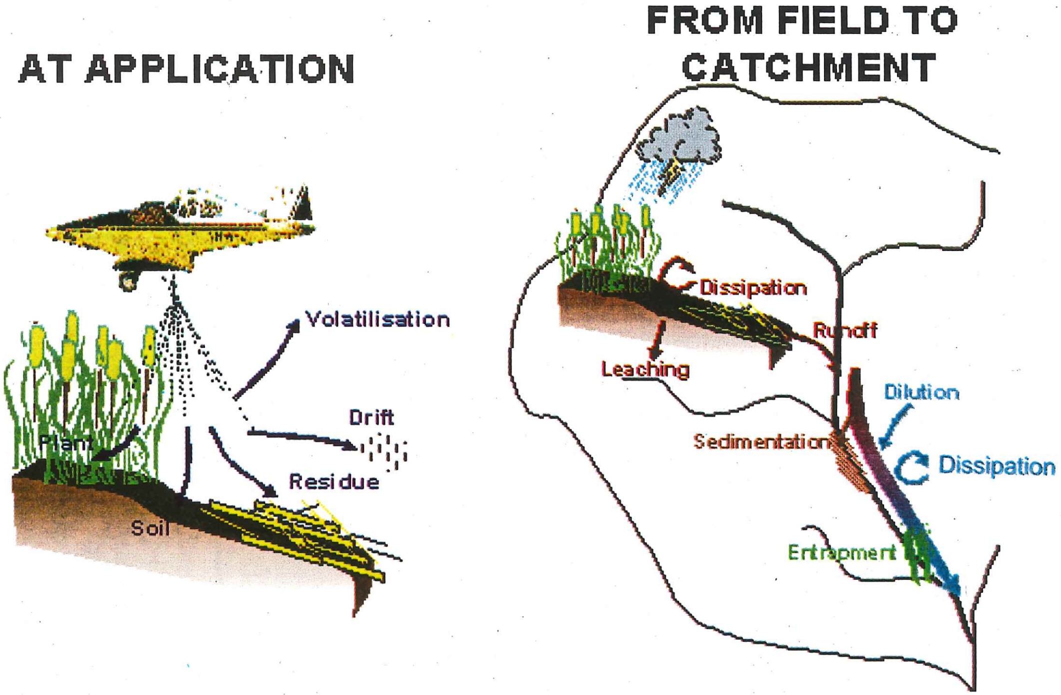

Fig. 8.4: Schematic representation of the fate of pesticide in agricultural systems. At the time of application, the pesticide can contact living plants, plant residue or the soil and be lost to drift and volatilisation. After application, the pesticide can dissipate, leach or be transported in runoff. As the pesticide moves downstream, concentrations tend to dilute, the pesticide is deposited with sediment, dissipated further or entrapped in vegetation.