

A Review of Water Flow Pathways through the Riparian Zone

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ABSTRACT

The current level of understanding of riparian zone hydrology is reviewed and gaps in our knowledge identified. Since riparian zone hydrological research has largely been focused in temperate, humid areas with near stream areas prone to saturation, the knowledge base may not be relevant to many Australian environments. To date most studies have identified subsurface flow and saturation overland flow as the major hydrological processes occurring in riparian zones. Flow pathways and processes in environments where pollutants are predominantly transported to the riparian zone as overland flow, including in semi-arid and degraded environments, are a major knowledge gap.

1. INTRODUCTION

The term "riparian" has its origins in the Latin term for bank or shore, and refers to land adjacent to a body of water. Although definitions of the riparian zone may vary according to the perspectives of different interest groups, the term is generally used to denote vegetated areas of land which bound stream channels. Riparian zones do not have fixed boundaries but vary in width, shape and character. Problems of declining stream water quality in Australia, have generated considerable interest in the potential of riparian zones to buffer streams from terrestrially-derived sediments and nutrients. Increases in stream turbidity and nutrient loads are often attributed to poor land management practices and the use of fertilisers and pesticides to increase productivity on pasture and crop lands. From a water resources management perspective, the riparian zone is being viewed as a key area for reducing non-point source pollutants to the stream. Underlying this is the recognition that the near stream area is the immediate source of all streamflow outputs from a catchment, including all water-borne pollutants (Lowrance *et al.*, 1985).

Although this paper does not address all the functions of riparian zones in detail, their multi-functionality should be recognised. Not

only do riparian zones moderate fluxes of water, sediment and nutrients to streams, they also serve ecological functions: wildlife corridors; sources of organic carbon, detritus and large woody debris; provision of shade and greater habitat structure (Vought *et al.*, 1995; Sweeney, 1992). In addition, riparian vegetation can contribute to stream bank and channel stability (Karl & Schlosser, 1978), and in some locations it creates aesthetic river side areas for recreational purposes. It is the purpose of this paper to review our current knowledge of riparian zone hydrology, as it is generally agreed that not enough is known about the processes driving sediment and nutrient delivery to streams (streambank sources of sediments and nutrients are not considered in this review), including what controls water flow paths and flow rates within, and to, riparian systems (Gilliam, 1994; Bosch *et al.*, 1994; Eshleman *et al.*, 1993; Cooper, 1990; Warwick & Hill, 1988; Rhodes *et al.*, 1985; Hynes, 1983). Characterisation of the various components of the hydrologic cycle, and the sources and sinks of water and pollutants in a catchment is essential to prudent water resources management (Shirmohammadi *et al.*, 1984; 1986). Before reviewing the current level of understanding of near stream hydrology, a brief comment on why riparian zone hydrology warrants special attention is needed.

2. LITERATURE REVIEW

2.1 A Hydrologically-Distinct Unit

Riparian zone hydrology is concerned specifically with the passage of water in the near-stream zone. The same hydrologic processes operating in the catchment generally operate in the riparian zone, but the zone is distinguished here, from the catchment as a whole, for the following reasons:

- The topographic position and the soil and vegetation characteristics are sufficiently distinct from those of the rest of the catchment to constitute a hydrologically distinct system. It is generally agreed that although only a small part of the catchment, the near-stream zone is hydrologically dynamic

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and exerts a major control on catchment hydrology (Smith, 1992; Pionke *et al.*, 1988; Dunne and Black, 1970a, b; Hewlett and Hibbert, 1967). Altering riparian land use can have complex, disproportionately large effects on catchment hydrology (Smith, 1992).

- It is the zone which directly links source areas of runoff, sediments and nutrients with the channel network.
- The occurrence of reverse flow, i.e. flow from the stream channel into the banks, can complicate local hydrology.
- Management strategies aimed at influencing hydrological flow paths in the riparian zone are often quite separate from those for agricultural land in the catchment generally.

Although a distinction is drawn here between hillslope and riparian hydrology, their connectivity is paramount. The riparian zone is important because it is well connected to both terrestrial and aquatic systems. This link is especially close in headwater streams (Karr & Schlosser, 1978; Vought *et al.*, 1994) which, despite draining relatively small catchments, contribute as much as 85% of water in large rivers (Vought *et al.*, 1994; Welsch, 1991). Baseflow in headwater streams is maintained by groundwater flow which may be influenced by passage through the riparian zone. Consequently, low order stream catchments are preferred management target areas as their riparian areas represent the maximum interface between terrestrial and aquatic environments. Most sediment enters the stream network from headwater catchments and the most extensive channelisation has occurred in these areas (Karr & Schlosser, 1978).

2.2 Flow Pathways

The question of whether storm flow is composed primarily of surface or subsurface flow contributions is important because of the different sediment and nutrient transport capabilities of the two pathways. The former pathway allows for very little contact between water and soil, while the latter permits considerable interaction with subsurface materials (Eshleman *et al.*, 1993; Hynes, 1983). Maintaining a riparian zone may mean the difference between a near stream hydrologic regime dominated by subsurface flow and one dominated by overland flow. Their value as hydrologic buffers arises because of their potential to store and retard the flow of water from precipitation and upslope sources. Located

in the topographically low area of a watershed, they frequently possess thick alluvial soils, relative to the adjacent hillslopes (Lowrance *et al.*, 1985). The volume of valley floor sediment varies as a function of valley geometry, position within the stream network, and the flood characteristics of the system. The storage capacity of this sediment varies, in turn, as a function of soil texture, porosity, transmissivity and structure. In headwater areas, streams drain small watersheds and often have narrow valley floors. Accordingly, the available volume of soil adjacent to the stream is relatively small per unit length of stream and the potential to store water is limited by this volume and the water-holding characteristics of the soil. However, the total length of these low order streams far exceeds that of the larger streams. As stream order and the catchment area increase, valleys tend to be wider and occupied by low flat floodplains, often terraced. The volume of sediment stored in these floodplains per unit length of stream is many orders of magnitude greater than in headwater catchments and the water storage potential is vast. Consequently, floodplains tend to have an attenuating effect on both lateral contributions from adjacent hillslopes and on routing of high flows in the channel (Beven *et al.*, 1988). Catchment response to rainfall events will tend to reflect the available water storage volume of the near stream area, with headwater streams exhibiting flashier responses than higher order streams.

Although, little research has been directed at riparian zone hydrology *per se*, there is a considerable body of literature that deals with hydrological processes in the near stream zone. In particular, near stream areas have been identified as important source areas of overland flow because of their propensity to be saturated or at near saturation for significant portions of the year (Dunne and Black, 1970a, b; Hewlett and Hibbert, 1967; Betson, 1964). As a result, available storage is small and the area responds more rapidly than other parts of the watershed to rainfall events. In some situations this rapid response can be explained by a capillary fringe effect and water table mounding (Abdul and Gillham, 1989; Sklash and Folvolden, 1979). Soils characterised by a capillary fringe, the zone above a water table that remains near-saturated under negative pressure, have little or no storage capacity. Where this zone extends to the ground surface, the application of only a small quantity of

water can cause a rapid and large water table rise and almost immediate generation of saturation excess runoff. Where this process operates, instead of retarding or preventing the passage of contaminants to the stream, the riparian area becomes an efficient conveyor of sediments and nutrients to the stream, and the possibility for biological nutrient uptake and removal is diminished.

Subsurface flow is also an important source of nutrients to streams and delivery can be very rapid, such as in steep forested environments (Bonell and Gilmour, 1978; Mosley, 1979; McCaig, 1983; Sklash *et al.*, 1986; McDonnell, 1990), but sediment is far less likely to reach streams by this pathway. Because many nutrients are sediment-attached, a near stream hydrologic regime that promotes the deposition of sediment will reduce the nutrient flux to the stream also. This is particularly pertinent to phosphorus which is mostly transported in particulate or sediment-bound forms (Karr and Schlosser, 1978; Cooke, 1988; Lee *et al.*, 1989). Nutrients moving in solution, however, do reach the stream by subsurface flow pathways and rapid transit times will

diminish the opportunity for nutrient uptake by plants and limit the denitrification potential. Like surface runoff, subsurface flow contributions to storm flow are also associated with saturated areas, although saturation is not a prerequisite if an extensive piping network exists (McCaig, 1983).

Because riparian zone research has tended to be concentrated in areas subject to waterlogging, shallow subsurface and saturation overland flow pathways appear to dominate near stream storm responses. Generally, infiltration-excess (or Hortonian) runoff is not recognised as a significant component of storm flow from riparian areas. Table 1 contains an overview of various riparian zone studies that have been undertaken. Much of the research has been focussed in the Coastal Plain area of the southeastern United States where streams flow over broad alluvial flats with intact riparian forests. These forest belts have survived clearing because annual rainfall in excess of evapotranspiration, impeded drainage and seepage faces along the valley flanks have resulted in significant areas of agriculturally non-productive wetlands (Gilliam, 1994). Of

Author	Climate	Land use	Topography	Hydrology
Eshleman <i>et al.</i> (1993, 1994)	Not stated MidAtlantic Coastal Plain, so similar to below	75% forest; 25% agric.	Low relief	Dominated by subsurface discharge; SOF during high intensity storms
Shirmohammadi <i>et al.</i> (1984, 1986)	1200 mm/yr summer - convect. early spring - cyclonic. storms - short, high intensity	Agricultural	Relatively flat	Some HOF (summer convective); mostly sub-surface, but SOF in higher order streams
Bosch <i>et al.</i> (in prep.)	As for Shirmohammadi (1984, 1986)	Tilled field	Relatively flat	Winter - subsurf. fluxes towards stream Summer - flux reversal driven by ET demands of riparian forest
Yates and Sheridan (1983)	As for Shirmohammadi (1984, 1986)	K: 37% crop, 56% woods Z: crop	Gently sloping uplands	Swampy riparian area. SOF and subsurface drainage
Pionke <i>et al.</i> (1988)	1100 mm/yr temperate humid	Crop/forest RZ - grass strip (15m wide)	350 m relief	SOF and subsurface drainage
Hill (1990)	Not stated located near Toronto, Canada	60% forest 40% grass	Gentle to steep sloping hummock moraine cut by dry valleys	Shallow subsurface flow from hillslope, saturated RZ
Chappell <i>et al.</i> (1990)	2629 mm/yr	Forest	150 m relief; steep slopes	Lateral subsurface flow from hillslope; perched water table
Abdul & Gillham (1989)		Grassed	Low relief	Water table mounding and subsurface flow. SOF

Table 1. An overview of riparian zone hydrological studies (SOF - saturation overland flow, HOF - Hortonian overland flow).

these studies, only one identifies Hortonian overland flow as a source of runoff in the near stream zone (Shirmohammadi *et al.*, 1984; 1986). Rather than conclude that Hortonian overland flow is a relatively insignificant phenomenon in riparian areas, I suggest that this mechanism of runoff generation has been neglected because the location of riparian forests, and our interest in the denitrification potential of wetlands, has dictated experimental site selection. If, as the U.S. examples indicate, riparian forests have largely survived where the underlying soil is waterlogged and agriculturally non-viable, results will show the dominant runoff process to be saturation overland flow. The other factor which biases the outcomes of riparian zone research is the predominance of field sites in temperate, humid areas with land uses dominated by crop production and forestry.

I would suggest that in semi-arid areas, and in areas where pastoral production is the dominant land use, Hortonian overland flow could be an important process. Soil compaction, associated with intensive grazing for example, leads to a reduction in the infiltration capacity of the surface soil and a hydrological shift towards infiltration-excess generated runoff. The efficiency of livestock tracks in conveying water, nutrients and sediments to and across the riparian zone has not been determined, yet the damage done to stream banks by stock trampling and the linking, by livestock tracks, of streams with upslope sources of contaminants suggest that tracks may be significant and rapid conveyors of materials to streams. Further research is needed to ascertain the importance of this form of surface runoff as riparian zone management strategies may differ depending on the nature of the runoff generating process.

2.3 Spatial distribution

As noted above, most studies in the literature deal with near stream areas that are consistently wet. However, soil saturation is not normally uniform along the entire length of a stream. Wetter and drier areas do exist. Downslope water flow tends to be via preferred pathways, therefore, near stream areas will not supply water to a stream uniformly along its length (Anderson and Kneale, 1980; Anderson and Burt, 1978). Cooper (1990) observed markedly non-uniform lateral inputs along a small New Zealand headwater stream during low flow conditions. Several reaches of 50 m or more showed no increase in flow

whereas other reaches of 10-20 m showed substantial increases. During conditions of higher flow, lateral inputs of flow tended to be more uniformly distributed, with most reaches exhibiting some longitudinal flow increase. Whether a particular area is a source of or a sink for storm runoff, and the relative proportioning of the flow pathways depends upon topography, soil properties, and individual storm characteristics (Dunne and Black, 1970a, b; Engman, 1974; Yates & Sheridan, 1983; Pionke *et al.*, 1988). Although controls have been identified, very little research has been directed at quantifying their relative importance to processes in the riparian zone. An exception, perhaps, is the buffer effectiveness modelling of Phillips (1989) which indicates that the gradient of the riparian zone is a more important control on riparian zone effectiveness than saturated hydraulic conductivity or soil moisture storage capacity. Heede (1990) also suggests that riparian buffer effectiveness will reflect slope gradient.

2.4 Temporal Distribution

Not only is there uncertainty about spatial behaviour of riparian systems, but the hydrology of riparian systems has a temporal dynamism which adds to the overall complexity of their processes and management. Stable isotopes are being used increasingly to investigate the proportions of event water and stored water comprising storm runoff (Pearce *et al.*, 1986; Sklash *et al.*, 1986; McDonnell, 1990; Stewart and McDonnell, 1991). McDonnell (1990) observed differences in the sources of storm flow to be dependent on peak runoff rates. In smaller events, matrix-dominated near-stream water was able to account for storm period streamflow. In larger events ($>2\text{mm hr}^{-1}$ peak runoff), however, perched water tables developed and storm flow was attributable to rapid hillslope hollow drainage via a well-connected pipe network. From a study of chemical-hydrologic interactions in the near stream zone, Pionke *et al.* (1988) described the changes in the relative contributions of surface and subsurface flow pathways during the passage of a single storm. Hydrologic sources of streamflow were observed to progress from (1) baseflow dominated to (2) rainfall-diluted baseflow, to (3) surface-runoff dominated flow, to (4) a progressively subsurface-discharge dominated flow, before draining back to (5) normal baseflow, corresponding to the expansion and contraction of seep zones. In temperate, humid areas, such as the area

investigated by Pionke *et al.* (1988) and the other experimental catchments on the south-eastern U.S. Coastal Plain, the initiation of surface runoff during a storm depends on the antecedent moisture conditions of the near stream area. However, antecedent moisture is not the only control, nor necessarily the dominant control in all environments. A preliminary investigation of the controls on water fluxes through riparian zones (Herron and Hairsine, *in prep.*) demonstrates that topographic convergence and the infiltration capacity of the soil are also extremely influential. Soils characterised by surface crusting, surface compaction and/or hydrophobicity can be significant source areas of overland flow because their infiltration rates are limiting.

Temporal variations also reflect seasonal climate changes. Using the riparian forest buffer specifications of Welsch (1991) as a starting point (a three-zone structure of minimum 30 m width), Bosch *et al.* (1994), working in the southeastern United States Coastal Plain, investigated the seasonal and spatial patterns in water flow pathways through riparian areas. The influence of season was found to be pronounced. During the wetter winters, soils are close to saturation and shallow subsurface flow is driven by the gravitational component of the hydraulic head in the direction of the stream. In summer, riparian plant water demands are large enough to cause a drop in the local water table elevation and a reversal in the gradient of saturated flow back toward the grass/forest interface. The authors attribute this high water usage to the riparian forests. However, transpiration demands of the grass buffer may also be significant, since grasses will transpire at rates similar to trees where surface soil water is non-limiting (Hodnett *et al.*, 1995). Such a seasonal flow reversal is believed to significantly retard the movement of contaminants travelling via subsurface flow from the hillslopes, at a time when solutes are most likely to be transported from the field to the riparian buffer (Bosch *et al.*, *in prep.*). Seasonal reversals in hydraulic gradients within the riparian zone may depend on the nature of the forest zone. A forest comprising species with a high leaf area index will transpire more than those characterised by less foliated species, and rainfall interception will be higher. For evergreen species, such as eucalypts or conifers, water table fluctuations may not be as pronounced as those observed

under deciduous trees, but higher transpiration rates and interception during winter should reduce the extent of saturated conditions. Once again, it is in humid, temperate areas that seasonal influences on soil water status will be most important. Where infiltration capacity limits soil water uptake, hydrological flow paths will only reflect seasonal differences in areas where seasons are characterised by different average rainfall intensities, such as monsoonal climatic regimes.

3. KNOWLEDGE GAPS

To summarise, our current understanding of riparian zone hydrology is based on research that has largely been undertaken in humid, temperate areas, characterised by waterlogged soils adjacent to stream channels. Accordingly, the bulk of available information emphasises the role of shallow subsurface flow and saturation overland flow as principal pathways of water to streams. It is suggested that the range of environmental conditions in which riparian zone studies are undertaken needs to be broadened and that the role of Hortonian overland flow be evaluated in semi-arid and degraded areas. The significance of livestock tracks as conveyors of water and contaminants to streams also needs to be determined.

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