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Understanding the effectiveness of vegetated streamside management zones for protecting water quality

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SUMMARY

We set out to improve understanding of the effectiveness of streamside management zones (SMZs) for protecting water quality in landscapes dominated by agriculture. We conducted a paired-catchment experiment that included water quality monitoring before and after the establishment of a forest plantation as an SMZ on cleared farmland that was used for extensive grazing. In a second study, we monitored water quality during the harvesting of a 20-year-old plantation in an SMZ. We found concentrations of bacteria, sediment and phosphate were lower in the buffered paired catchment, but that lower nitrogen concentrations could not be attributed to the intervention. Harvesting caused no appreciable increase in sediment delivery to the stream and we found it to be a minor source compared to other disturbances (road drainage and cattle disturbance).

Simulation of hillslope processes and stream flow illustrated that uptake by SMZ vegetation was a more important nitrate-mitigating process than denitrification. Because this model thoroughly integrates climate and within-soil processes, its usefulness should also be tested for other nutrients and chemicals. For example, the observed decrease in phosphate concentrations in stream water due to the SMZ treatment was probably predictable. However, additional modelling approaches are needed to simulate SMZ effects on sediment and bacteria.

Key factors contributing to the success of the studies were the cooperation of land owners who understood the research aims and were willing to collaborate with on-ground actions essential to the study, convergence of the interests and resources of multiple partners, the proximity of research staff and laboratory to the field site, early peer review of aims and methods, and experimental designs that controlled many potentially confounding factors (e.g. farm management, roads, catchment geomorphology). Some of our results and interpretations were compromised by limited pre-treatment data during a period of high inter-annual variability in rainfall and flow. Longer-term datasets would have improved assignment of measured water quality changes to the watershed management interventions. Apart from climate variability, these changes were also driven by high variability in other natural characteristics (e.g. size, soils and topography of each catchment), multiple interacting drivers of change, long time-lags between intervention and response, and non-linear processes driving undefined thresholds of change. Our key results and limitations are presented as a guide to planning future research.

BACKGROUND

Water quality in many agricultural landscapes worldwide is poorer than desired, presenting a risk to stream biota, people and livestock. Water quality comparisons across broad land use categories show Tasmania is no exception. For example, Chapter 2 (this volume) and Broad and Corkrey (2011), summarising nitrogen and phosphorus contamination in a wide range of Tasmanian catchments, found that streams with highest nutrient concentrations and loads also have the highest proportion of intensive agriculture. In contrast, streams draining mainly native or plantation forestry have relatively low concentrations of inorganic nutrients. Chapter 3 (this volume) and Magierowski *et al.* (2010) found a similar trend with aquatic habitat quality related to land use, stream water quality and riparian shading. Livestock access to streams is a primary concern for land managers, because it provides a point source of contamination by nutrients, sediment and bacteria. Water temperature increases are also a concern where trees have been removed from streamsides since they affect physical, chemical and biological processes of stream biota (Neary 2002).

Such concerns have motivated some natural resource managers, including farmers, to consider SMZs for buffering water quality from the potentially adverse affects of up-slope agricultural activities. The term 'SMZ' is preferred here to synonymous terms such as 'riparian buffers', because it is not limited to a particular landscape position, hydrological function or management system (see Neary *et al.* 2010 for a discussion of terminology). The water quality benefits of SMZs at plot and hillslope scales have been amply demonstrated (Collier *et al.* 2001; Mayer *et al.* 2007; Zhang *et al.* 2010), along with improved aesthetics, property values, native habitat, stock safety, wood production and carbon sequestration. However, water quality benefits at a catchment scale have not been clearly established because of temporal changes in up-slope land use, insufficient proportion of streams with SMZs, a preference for buffering low-risk high-order large rivers rather than higher-risk small headwater streams, and the associated disturbances related to roads and drains (Cotching, *pers. comm.*; Sutton *et al.* 2010).

Overall, the adoption of SMZs in Tasmania has been very low for a variety of reasons. For example, among 146 landholders who responded to a survey of riparian management in six Tasmanian catchments, only 75 500 trees or shrubs had been planted (Curtis *et al.* 2009; Chapter 6, this volume). Assuming 2000 trees or shrubs were planted per ha, it implies 38 ha had been planted in total. This planted area was probably less than 0.01% of the total cleared area in these catchments, compared to 5–10% coverage expected if all streams had been buffered. A common deterrent to farmer adoption is that the SMZ area is perceived to be lost from agricultural production. This deterrent led Robins (2002) to describe several potential income-generating activities for this zone, one of which was commercial wood production. Commercial forestry in this zone is accepted and used widely in the US and Europe, but not in Australia (Smethurst 2008). A possible deterrent to SMZ plantation use in some parts of Australia are state-based codes of forest practice that discourage commercial forestry next to streams. While these codes can be revised periodically to account for new information and changes to forestry practices (Smethurst 2008), the investment risk is generally borne by the landholder and involves dependence on changing policies or regulations.

While the effect of removing streamside vegetation has been documented in several studies internationally (e.g. Coweeta Hydrologic Laboratory; Swift and Messer 1971), we found only one study where the effect of tree establishment had been quantified in an agricultural catchment (Newbold *et al.* 2010). We found no studies that reported the use of fast-growing *Eucalyptus* or *Pinus* plantations for SMZs in Australia. This highlighted a need for water quality research at a small catchment scale that documented the effects of commercial plantation forestry in SMZs. Our interest was shared by a number of collaborators – a forest practices regulator (Forest Practices Board, Tasmania), the forest industry (Cooperative Research Centre for Forestry and its partners), a state government body charged with encouraging forestry on private land (Private Forests Tasmania), natural resource management organisations (partners in Landscape Logic) and CSIRO's Water for a Health Country Flagship and its Sustainable Agriculture Flagship.

PAIRED-CATCHMENT EXPERIMENT

DESCRIPTION

We established a paired-catchment study in a single paddock in a mixed grazing and native forest landscape in southern Tasmania (Figs 5.1, 5.2). Fertilisers were not used on pastures or native forest for several years prior to and during the study. Water quality measurements for one year prior to SMZ establishment in 2008 provided pre-treatment data. Changes as a result of the SMZ were determined by comparison with these pre-SMZ measurements and with the adjacent reference catchment that was not fenced and did not have trees planted. We monitored stream flow, temperature, salinity and turbidity every 15 minutes, and several other water quality parameters (e.g. oxygen, bacteria, nitrogen and phosphorus) about three-weekly or less frequently using grab samples. Several storms were automatically sampled every few hours for several days for measurements of various water quality parameters. Further details of methods are provided in Smethurst *et al.* (2011).

RESULTS

Our data showed that cattle exclusion using the fenced SMZ reduced the delivery of bacteria, phosphate and sediment to the headwater stream (Figs 5.3, 5.4, 5.5). The buffering effect on turbidity (cloudiness) became quite noticeable within a year of SMZ establishment, and was most apparent during storms that coincided with a grazing event during a relatively wet winter–spring period. Nitrogen may have been attenuated by tree establishment, but pre-SMZ variability in nitrate concentration indicated that some of this effect might not have been SMZ-related.

Figure 5.1: The paired-catchment experiment showing catchments with (1) and without (2) streamside management zones of eucalypts and acacias planted in 2008. Additional SMZs shown adjacent (left) and below these catchments are one year older. Photo: P. Smethurst.

Figure 5.2: A streamside management zone showing a plantation of *Acacia melanoxylon* (blackwood), *Eucalyptus globulus* (blue gum) and *Eucalyptus nitens* (shining gum) in the paired-catchment experiment. Seedlings were planted on spot-cultivated mounds next to pits that intercepted overland flow. Photo: P. Smethurst.

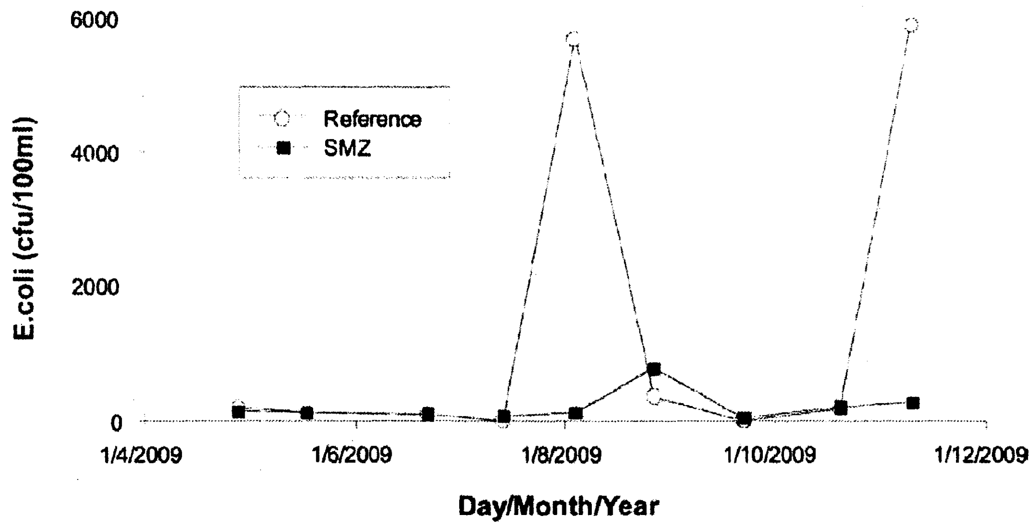

Figure 5.3: Bacterial counts (*E. coli*) in paired catchments with (SMZ) and without (Reference) streamside management zones showing higher values in the reference catchment on two occasions coinciding with severe cattle disturbance of the reference riparian zone during a very wet high flow period.

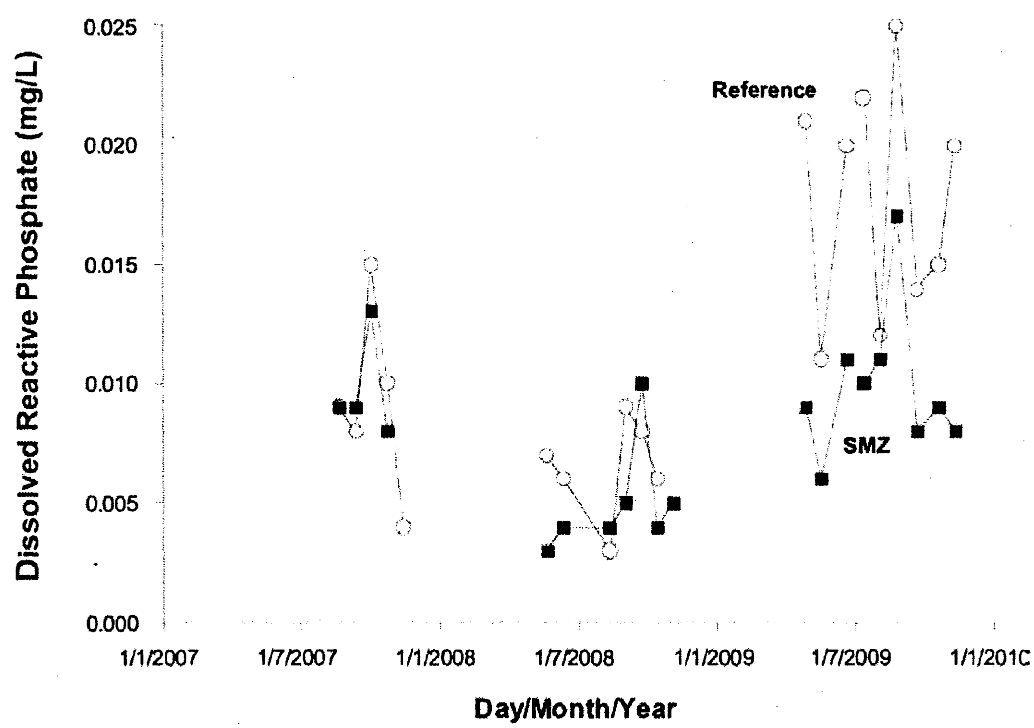

Figure 5.4: Phosphate concentrations in paired catchments with (SMZ) and without (Reference) streamside management zones showing similar concentrations for two years prior to and during SMZ establishment in mid-2008, but higher in the reference catchment during the wet winter of 2009.

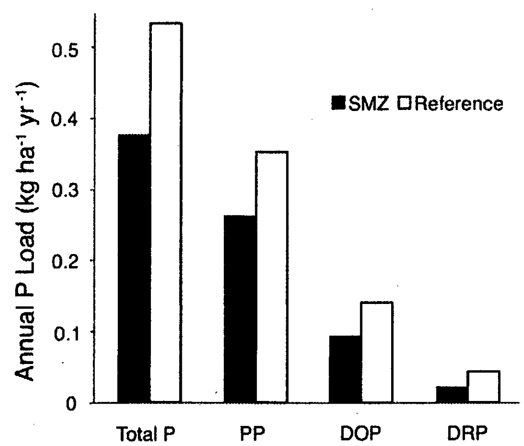

Figure 5.5: Annual loads (export in stream water per ha of catchment) of various forms of phosphorus in the paired-catchment experiment showing lower values in the treated (with SMZ) catchment during the wet winter of 2009. PP = particulate P, DOP = dissolved organic P, DRP = dissolved reactive phosphate.

The benefit of the SMZ for reducing turbidity was most evident on one high flow occasion when grazing was associated with off-scale turbidity readings in the reference catchment (>300 nephelometric turbidity units, NTU). During the same storm, values in the SMZ catchment were 50–140 NTU. During the dry-weather period preceding the winter storms, turbidity was approximately 16 NTU without and 5 NTU with an SMZ. The only clear negative effect of SMZ establishment on water quality parameters was a small transient increase in turbidity during one storm soon after cultivation, attributed to sediment originating from cultivated mounds used for tree planting. Turbidity at that time peaked around 29 NTU and turbidity without the SMZ was 11 NTU. Cultivation pits (Fig. 5.2) might have exacerbated tunnel erosion in the SMZ catchment, but this was not assessed.

Reduced phosphate concentrations in SMZ stream water were probably due to diversion of overland flow through the soil via the cultivation pits and other surface roughness features. A portion of phosphates in water percolating through soil would have been sorbed to the soil particles.

Sediment trapping by pits created during cultivation for trees likely contributed to reduced delivery of these contaminants to the stream, along with the presence of tall ungrazed remnant pasture. In addition, below-ground processes were likely important for attenuating the delivery of dissolved nitrogen and phosphorus (Smethurst *et al.* 2011). Observations and simulation modelling predicted that nitrate removal via denitrification occurred throughout the catchment where a water table existed, which was up to about halfway up the hillslope. However, nitrogen uptake by pasture and trees is likely to become a far more important nitrogen removal process than denitrification in this catchment. Since trees tend to reduce soil moisture and groundwater levels, denitrification is not expected to increase with SMZ establishment (Smethurst *et al.* 2011). Because this model thoroughly integrates climate and within-soil processes, its usefulness for simulating other nutrients and chemicals should be tested. For example, the observed decrease in phosphate concentrations in stream water due to the SMZ treatment was probably predictable using the model. However, additional overland flow modelling approaches are needed to simulate SMZ effects on sediment and bacteria.

HARVESTING AN SMZ PLANTATION

By good fortune, our team's work coincided with the harvesting of an SMZ plantation. Details of the opportunity and the water quality impacts we measured are outlined below.

DESCRIPTION

We identified the opportunity in 2009 to conduct water monitoring as part of a commercial plantation harvest in an SMZ on farmland in north-western Tasmania (Fig. 5.6). The plantation was located on a tributary of the Pet River, near Burnie, Tasmania. The predominantly north-flowing tributary included an upstream SMZ plantation that was not to be harvested and could therefore serve as a reference. Pre-harvest monitoring using grab samples started in December 2008. The larger eastern side of the SMZ was harvested in March–April 2009, after which the grab sampling program was augmented by continuous monitoring above and below the harvested reach every 15 minutes. Rainfall at Burnie for 2009 was 11% below average, but included several large storms that caused many trees in the remaining western side of the SMZ to be blown over. Salvage harvesting of this area was conducted November 2009 to January 2010. Harvesting was conducted as a routine commercial operation in accordance with the Tasmanian Forest Practices Code using tracked tree-felling and log-forwarding machinery. Machinery was required to stay out of a 5 m machinery exclusion zone next to the tributary stream. The plantation was well-stocked and had grown vigorously, with some trees in excess of 60 cm diameter over bark at 1.3 m height.

RESULTS

Our data showed total harvesting of a 20-year-old pulpwood plantation of *Eucalyptus nitens* in an SMZ was conducted without adversely affecting turbidity during the operation or subsequently during a wet winter period that included several storms (Figs 5.7, 5.8, 5.9; Neary *et al.* 2010). Turbidity is a measure of the cloudiness of water due to suspended sediment. Overall, the erosion risk at this site was considered low because the soil is a red-brown, well-structured, basalt-derived Ferrosol soil on low-gradient slopes. Upstream of the harvested area, which

Figure 5.6: A view upstream of the SMZ harvesting experiment showing (1) harvesting adjacent to the tributary, (2) the dam sampled below the harvested reach (dam 13 in Fig. 5.7) and (3) the upstream unharvested SMZ plantation. Photo: P. Smethurst.

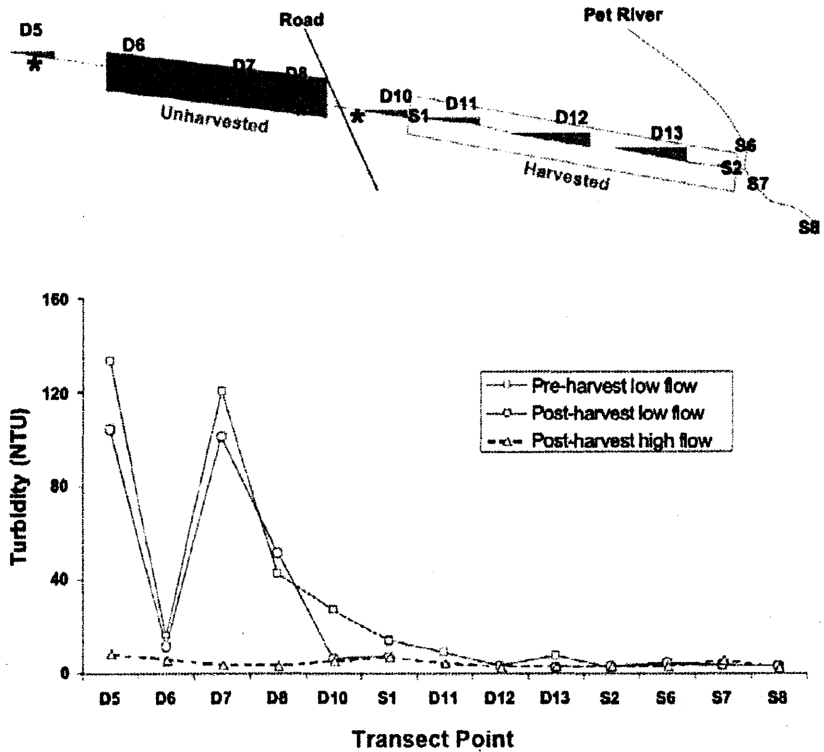

Figure 5.7: Schematic of the harvested catchment (top) showing the relative layout of dams, roads, streams, plantations and regular cattle access points (*). During the flow season, water flowed from dam 5 (D5) to stream sampling point 8 (S8) and beyond. Plantation SMZs are shown unharvested (shaded) and harvested (unshaded). Turbidity measurements along the catchment are shown for three occasions (bottom).

included an SMZ that was not harvested, turbidity was seriously affected by cattle access and road runoff. Most of the sediment generated by cattle disturbance and the road was captured in a dam above the reach of the harvested SMZ. Hence, in-stream dams throughout the catchment acted as filter traps.

Continuous monitoring in the dam just above the harvested SMZ (D10, Fig. 5.7) started soon after harvesting during low flows. Stream water there usually had turbidity values an order of magnitude higher than those observed below the harvested SMZ (D13, Figs 5.7, 5.8). Turbidity at the upper dam was more responsive to storms than the dam at the bottom of the SMZ. However, on occasions during high flows, connectivity increased between the dams and similar values were recorded for several days when turbidity in the lower dam reached a maximum of 33 NTU. Turbidity in the dam just above the harvested SMZ (D10, Figs 5.7, 5.8) was probably a combination of newly delivered sediment and resuspended sediment that had previously accumulated, but the relative contributions were not determined.

SUCCESS FACTORS

Several technical, organisational, collaborative and coincidental factors contributed to the success of our team's research.

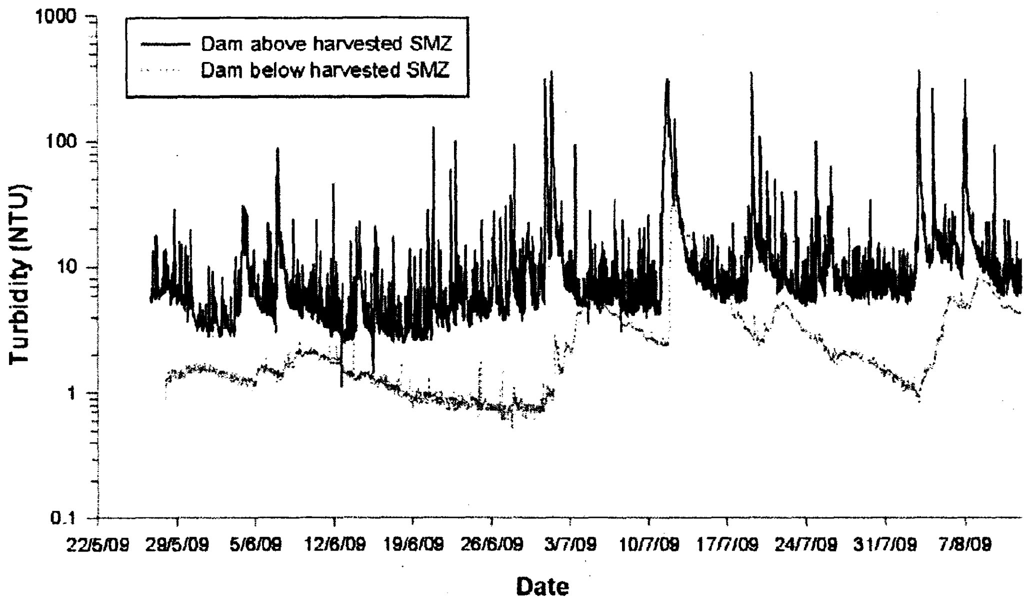

Figure 5.8: Turbidity trends before and during the winter of 2009. High values in the dam above the harvested reach were associated with sediment generated upstream by the road or cattle disturbance. For short periods, similar turbidity values were measured in the dam below the harvested reach, which coincided with storms and dam overflows that probably resulted in flow- and water-quality connectivity between the two dams.

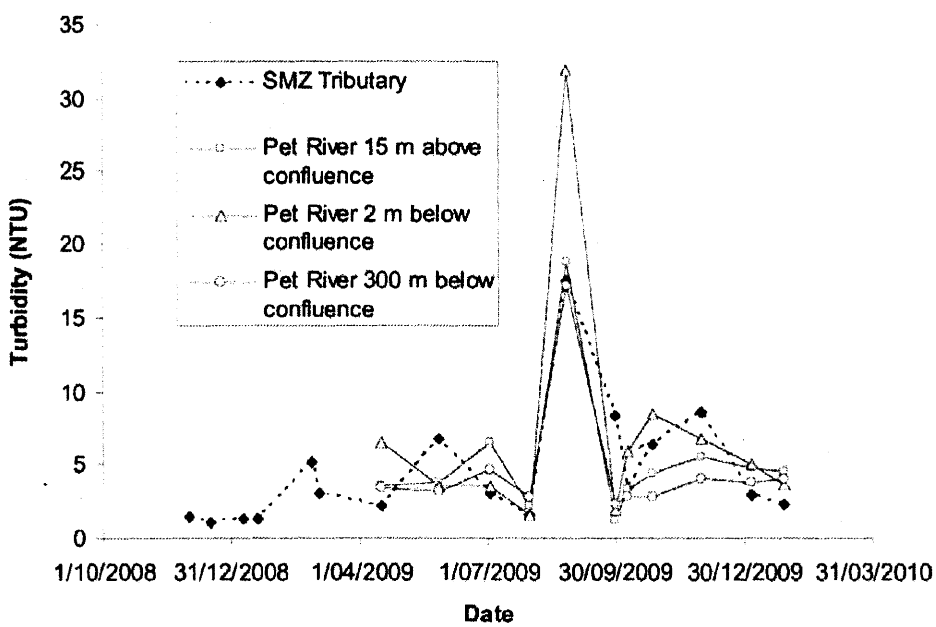

Figure 5.9: Patterns of turbidity around the confluence of the Pet River (which had little upstream SMZ harvesting) with the tributary containing the SMZ. Harvesting periods were March–May 2009 and November 2009–January 2010. Changes in turbidity in the tributary appear unrelated to harvesting, and values were generally similar to those above and below the confluence in the Pet River. Observed variations in turbidity are probably due to an interaction of rainfall patterns, landscape management unrelated to the SMZ and stream turbulence.

TECHNICAL FACTORS

There were six factors to which we attribute the technical success of our team's research. These are experimental design, peer review of the experimental objectives and methods, catchment options and selection, measurement systems, staff and other resources, and proximity to research sites. These factors are discussed below.

Experimental design

Paired catchments are a strong experimental design for catchment-scale studies, especially if the catchments are identical or similar in size and shape and an adequate pre-treatment measurement period is included when catchment replication is low (Brown *et al.* 2005). The paired-catchment method is schematically explained for flow in Figure 5.10. Two approximately identical catchments are identified. Flow is monitored across a range of rainfall conditions for several years to build a relationship between the two catchments for flow, i.e. a

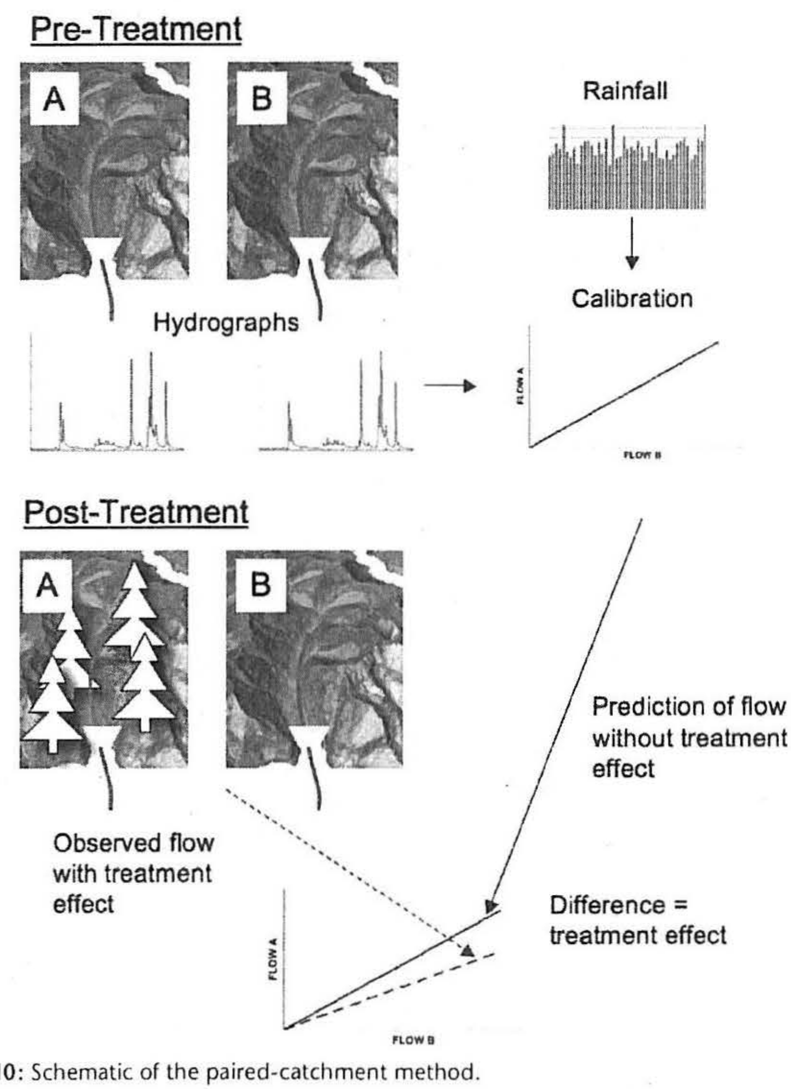

Figure 5.10: Schematic of the paired-catchment method.

pre-treatment calibration of flows. One catchment is then treated with a vegetation change, e.g. plantation establishment, fire or another management treatment, and flow monitoring continues for a few more years. Observed flow in the treated catchment is plotted against flow in the untreated reference catchment, along with that expected from the original calibrations; the difference is due to a treatment effect. These analyses are usually done with annual data, but monthly, seasonal, high flow or low flow examples are also available. Water quality comparisons are also possible.

In the current study, we attributed pre- and post-treatment changes in the flow ratio between treated and reference catchments to a treatment effect, e.g. vegetation change. If data are available, more sophisticated empirical regression techniques could be used to relate the difference in flows to season and rainfall. For example, Bren and Hopmans (2007) presented outputs for the conversion of eucalypt native forest or pasture to *Pinus radiata* plantation. An overview of empirical relationships for vegetation changes in South African studies is provided by Scott *et al.* (2000).

Our establishment experiment included replication of reference catchments for some measurements and one year of pre-treatment measurements for the paired treated and reference catchments. For our harvesting study, a paired-catchment approach was not possible, but a nested longitudinal design enabled some degree of temporal and spatial controls for water quality.

Peer review of experimental objectives and methods

We sought peer review at an early stage by coordinating an on-site inspection and discussion with an expert panel of several catchment hydrologists familiar with forestry and agriculture. We employed standard methods of measurement, which facilitated the set-up and maintenance phases.

Catchment options and selection

Initially, we selected only one tree establishment catchment for study in a pre-treatment versus post-treatment comparison. Expert input encouraged division of this larger catchment into several smaller subcatchments and selection of two for a paired-catchment design. This change of design enabled us to avoid potentially confounding hydrological effects of roads and farm tracks and to work with smaller catchments, which in turn provided logistical, technical and budgetary efficiencies.

We spent considerable time searching Australia (by telephone and email) for a suitable harvesting catchment, since we needed an SMZ plantation that had reached a harvesting age and was scheduled for harvesting within a year. This constraint required an SMZ plantation that had been established 15–20 years earlier, when the concept of streamside tree establishment was not typically considered. Fortunately, the best of three potential sites located in three different states was in Tasmania, which was close enough to the CSIRO research base in Hobart to facilitate its use.

Measurement systems

The experimental design was matched by adequate measurements provided by automatic and manual instruments and technical support, that in turn enabled data acquisition.

Staff and other resources

Our team consisted of scientists with complementary skills in hydrology (K. Petrone), agriculture, forestry and soil science (P. Smethurst), and soil science and hydrology (D. Neary). We were well supported by several technicians with complementary skills. Apart from their agricultural experience, the farmers already had an interest in plantation forestry, and Private Forests Tasmania provided advice and funding to establish the SMZ plantation. The research budget primarily came from federal sources (CRC and CERF programs) and was boosted by industry funds via the CRC for Forestry. Modern telecommunications and air travel facilitated key staff contributing from distant locations, networking generally, and awareness and access to relevant literature.

Proximity

The establishment research site was reasonably close (40 minutes drive) to the CSIRO research base in Hobart, which allowed frequent visits for set-up, servicing, maintenance and measurements. By comparison, the harvesting research site was four hours drive away and this limited the effort that could be put into this site. Fortunately, one of the team (B. Cotching) was based within 15 minutes of the site, which greatly assisted site measurements and visits.

COLLABORATIVE FACTORS

There was a very strong convergence of organisational interests that included setting up a demonstration site of an SMZ plantation for farmers, the general public and other stakeholders, improving the level of confidence of natural resource managers (including regulators and farm foresters) in SMZ plantations as a potential land use, and publishing scientific papers and other communication materials that document knowledge advances in this field. Of primary importance for selection of research sites was the involvement of Private Forests Tasmania staff and the farmers who were contacted for possible collaboration.

The success of our team was greatly assisted by the fact that everyone involved shared the research vision and worked very constructively towards its implementation. The productive working relationships between the farmers and researchers were also of major importance.

COINCIDENCE

It was fortunate that the above-mentioned factors coincided in space and time to ensure a successful outcome. An example is that the harvesting site was probably the only highly suitable site in Australia, and it was a coincidence that it became available when a satisfactory monitoring site was being sought.

LIMITING FACTORS

All projects operate within a number of constraints which significantly affect the nature of their work. The constraints that our team was aware of were imperfections implicit in paired-catchment designs, time, distance and budget.

IMPERFECTIONS OF PAIRED-CATCHMENT DESIGNS

Knowledge of process gained from catchment-scale studies can provide considerable insight that is not gleaned from modelling studies alone. Used carefully, the paired-catchment design is the best option available for detecting treatment effects at a catchment scale and it performs best when its limitations are acknowledged. Considerations we made when employing this research design were:

- paired catchments can lead to substantial errors when applied to other catchment conditions because derived relationships are empirical (Bren and Hopmans 2007);
- climate variability that coincides with a potential treatment effect can reduce the usefulness of the pre-treatment calibration. This factor increases the necessity for modelling approaches (Moore and Scott 2006);
- similar problems arise when rainfall patterns do not match for the treatment–reference comparisons (Liu *et al.* 2004);
- extrapolation of small-scale paired-catchment results to much larger catchments can be problematic if vegetation changes and rainfall patterns across the larger catchment are not well defined (Best *et al.* 2003; Brown *et al.* 2005);
- very few paired catchments are identical in geology, soils and topography.

These differences invariably affect comparisons to some degree.

Long pre-treatment calibration periods and replication through space and time help address many of these limitations of the paired-catchment approach. Although the paired catchments we used in the establishment study were adjacent and selected by an expert panel, they were not identical. They did not have the same proportions of rock types (syenite and mudstone; discovered after catchment selection) or vegetation (native forest and pasture) and did not have identical size, slope or shape. These factors could variously affect the interpretation of results for several water parameters and need to be considered when interpreting results. For example, the SMZ catchment consistently had much higher electrical conductivity (EC, salinity) values than the non-SMZ catchment. This observation could indicate that syenite rock (formed under highly saline conditions) weathers to yield highly saline water.

The SMZ catchment was also larger than the non-SMZ catchment, yet the catchments had similar stream length. It could therefore be expected that the catchments differ to some degree in wetness and biogeochemical behaviour. For example, the SMZ catchment most likely has a higher incidence of tunnel erosion. A dramatic example of a difference in catchment behaviour was observed when tunnel erosion was first detected in the SMZ catchment during an early winter storm when a sudden drop in EC coincided with an increase in turbidity (Fig. 5.11). Several days later, after most storm rainfall, a similar rapid increase in turbidity was observed in the reference catchment while there was only a minor decrease in EC. This is a demonstration that turbidity and EC patterns in response to rainfall were substantially different between the two catchments, and this could not be attributed to an SMZ effect. Thus, the differences in these non-linear responses and undefined threshold relationships between catchments had implications for the interpretation of results.

TIME

For most flow and water quality parameters, our study was restricted to 1.5 years pre-treatment and 1.5 years post-treatment monitoring. The net effect was that the limitations and associated risks of the paired-catchment design were substantial since the full range of rainfall, soil water and management conditions were not provided pre- and post-treatment. Time limitations also put pressure on skill development, because some team members were unfamiliar with hydrological methods. Some aspects of the study (e.g. the detailed nitrogen component, Smethurst *et al.* 2011) had their time-frames significantly reduced because of delays in finalising grant contracts. Fortunately, other aspects of the research had commenced two years earlier.

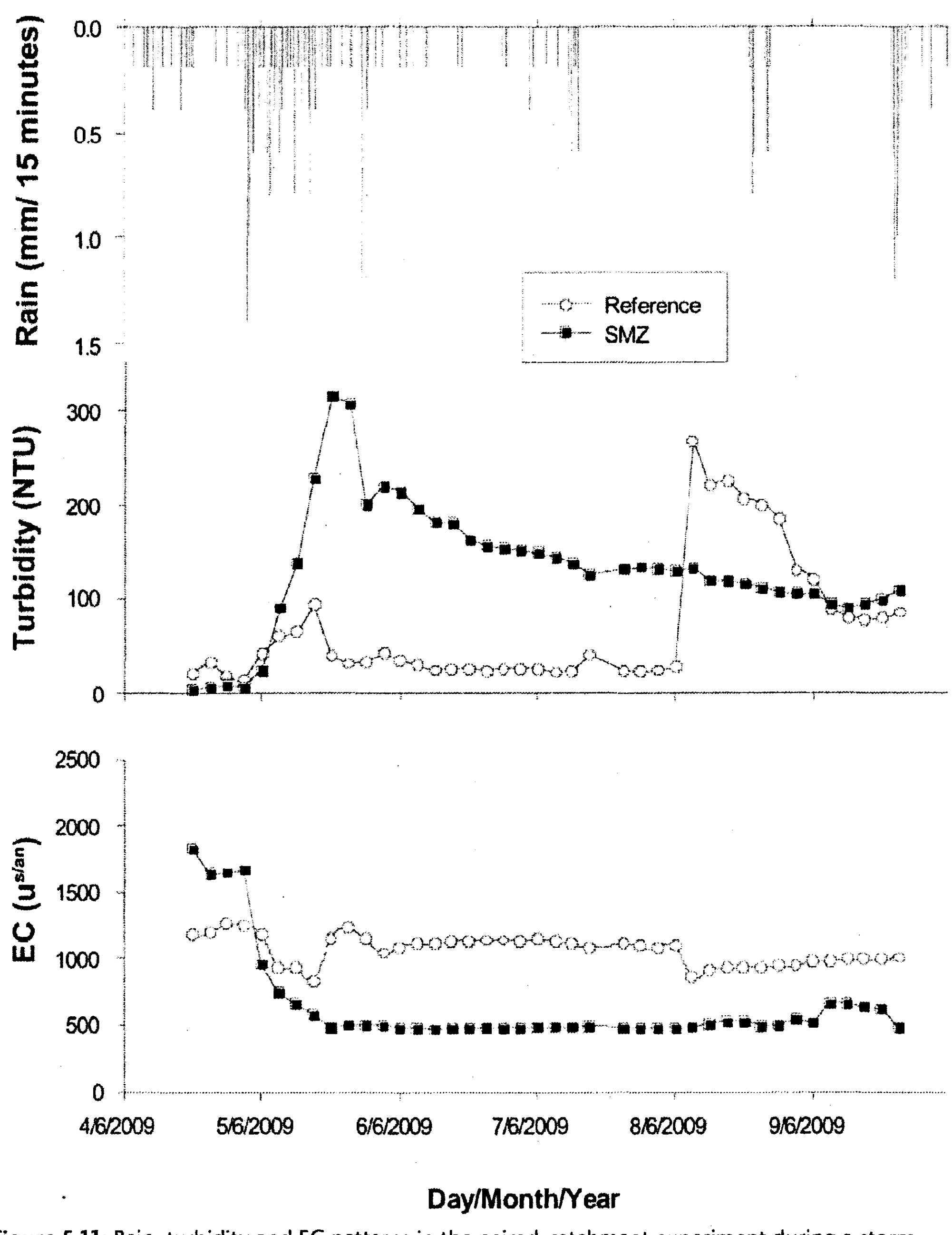

Figure 5.11: Rain, turbidity and EC patterns in the paired-catchment experiment during a storm early in the flow season during 2009 when tunnel erosion was identified as influencing flow and water quality patterns differentially in each catchment.

DISTANCE

The main hydrologists involved in the study were located elsewhere in Australia or overseas, which limited interactions and in-person participation. While within-team communication was very good and locally based staff were very adaptable and quick-learning, co-location of all staff in Hobart would have reduced communication overheads and may have improved outcomes.

BUDGET

As with most research, budget limitations contributed to the other issues listed above, e.g. low replication, short pre- and post-treatment periods and limitations on staff time, instrumentation and sampling. This necessitated frequent appraisal of the effectiveness of expenditure in terms of the value of data likely to be gained.

IMPLICATIONS OF THE RESEARCH

Here we distinguish between two key audiences for our research: land managers and other researchers.

IMPLICATIONS FOR LAND MANAGERS

Exclusion of livestock from streams can substantially improve water quality. Marked water quality benefits can be expected only where SMZs are established over a large proportion of headwater stream length, and even narrow buffers can deliver substantial benefits. In this study, SMZ width ranged from 10 m to 30 m and the area was fenced to exclude livestock access. Even with SMZs, major sources of poor water quality will remain where livestock continue to have access to the stream and drainage from roads and tracks is not diverted across pasture or other vegetation before it reaches the stream (Grayson *et al.*1993; Croke and Mockler 2001; Lane and Sheridan 2002). These are factors that contribute to the commonly observed overall negative effect of agriculture on water quality (Chs 2 and 3, this volume).

Logistical and financial considerations are important for establishing SMZs. Establishment of an SMZ requires a definition of situation-specific objectives such as aesthetics, property values, stock safety, commercial options, water quality, habitat enhancement and the use of native or introduced plant species. Second, potential financial and non-financial costs and benefits need to be weighed for different options. Third, detailed plans are needed for establishment and long-term maintenance of the SMZ. Fencing and off-stream watering points for livestock and stream crossings can be expensive and therefore a major consideration.

Commercial tree-farming for wood production or carbon credits is an option compatible with many commercial and environmental objectives. Dry-weather crash-grazing might be an option for utilising grass within the SMZ once trees have reached a suitable size, but the effects on water quality have not been evaluated. Potential practitioners of these management techniques are encouraged to seek advice from agroforestry regulators and advisors.

Our results show that, at least at some sites, forest plantations in an SMZ can be harvested to the water's edge without adversely affecting turbidity. While these results should encourage broader adoption of SMZs on farmland, care with harvesting and use of best management practices will be needed to ensure that it does not lead to unacceptable sedimentation. Harvesting methods may need to be adapted to suit different conditions of erosion risk (e.g. soil type and slope).

Prior to the initiation of the research described here, farm forestry advisors of Private Forests Tasmania had worked with the farmers at our research sites to plan or establish the

SMZ plantations. This partnership ensured excellent transfer of lessons about practices and outcomes, which are now being shared with other farmers in similar situations.

IMPLICATIONS FOR RESEARCHERS

While SMZ plantation practices are common in some countries, very few examples exist in Australia where the water quality impact of harvesting techniques can be evaluated. We believe additional Australian examples would improve the confidence in adopting these SMZ practices. We recommend that future research in this field draw on our experience to strengthen research planning and maximise the return on investment.

While many researchers, land managers and regulators are now aware of the research described here, there is no indication yet that the research has had an impact on policy. However, regulators were involved with the research from its inception and results are expected to help improve codes of forest practice during the next decade as they are reviewed in each Australian state and territory.

REFERENCES

Best A, Zhang L, McMahon T, Western A and Vertessy R (2003) 'A critical review of paired catchment studies with reference to seasonal flows and climatic variability'. CSIRO Land and Water Technical Report 25/03. CRC for Catchment Hydrology Technical Report 03/4. Murray-Darling Basin Commission, Canberra, Publication 11/03. <http://www.clw.csiro.au/publications/technical2003/tr25-03.pdf>.

Bren L and Hopmans P (2007) Paired catchment observations on the water yield of mature eucalypt and immature radiata pine plantations in Victoria, Australia. *Journal of Hydrology* **336**, 416–429.

Broad ST and Corkrey R (2011) Estimating annual generation rates of total P and total N for different land uses in Tasmania, Australia. *Journal of Environmental Management* **92**, 1609–1617.

Brown AE, Zhang L, McMahon TA, Western AW and Vertessy RA (2005) A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology* **310**, 28–61.

Collier KJ, Rutherford JC, Quinn JM and Davies-Colley RJ (2001) Forecasting rehabilitation outcomes for degraded New Zealand pastoral streams. *Water Science and Technology* **43**, 175–184.

Croke J and Mockler S (2001) Gully initiation and road-to-stream linkage in a forested catchment, southeastern Australia. *Earth Surface Processes and Landforms* **26**(2), 205–217.

Curtis A, Race D and Sample R (2009) 'Management of riparian zones in Tasmanian agricultural catchments'. Technical Report no. 11. Landscape Logic, Hobart. <http://www.landscapelogic.org.au/publications/Technical_Reports/No_11_Tas_riparian.pdf>.

Grayson RB, Haydon SR, Jayasuriya MDA and Finlayson BL (1993) Water-quality in mountain ash forests: separating the impacts of roads from those of logging operations. *Journal of Hydrology* **150**(2–4), 459–480.

Lane PN and Sheridan GJ (2002) Impact of an unsealed forest road stream crossing: water quality and sediment sources. *Hydrological Processes* **16**, 2599–2612.

Liu S, Leslie LM, Speer M, Bunker R and Mo X (2004) The effects of bushfires on hydrological processes using a paired-catchment analysis. *Meteorology and Atmospheric Physics* **86**, 31–44.

Magierowski RH, Davies PE and Read SM (2010) 'The Tasmanian River Condition Bayesian Network'. Technical Report no. 26. Landscape Logic, Hobart.

Mayer PM, Reynolds SK, McCutchen MD and Canfield TJ (2007) Meta-analysis of nitrogen removal in riparian buffers. *Journal of Environmental Quality* **36**, 1172–1180.

Moore RD and Scott DF (2006) Response to comments by PF Doyle on 'Camp Creek revisited: streamflow changes following savage harvesting in a medium-sized, snowmelt-dominated catchment'. *Canadian Water Resources Journal* **31**, 135–138.

Neary DG (2002) Environmental sustainability of forest energy production. In *Bioenergy from Sustainable Forestry: Guiding Principles and Practices.* (Eds J Richardson, T Smith and P Hakkila) pp. 37–67. Elsevier, Amsterdam.

Neary DG, Smethurst PJ, Baillie BR, Petrone KC, Cotching WE and Baillie CC (2010) Does tree harvesting in streamside management zones adversely affect stream turbidity? Preliminary observations from an Australian case study. *Journal of Soils and Sediments* **10**, 652–670.

Newbold JD, Herbert S, Sweeney BW, Kiry P and Alberts SJ (2010) Water quality functions of a 15-year-old riparian forest buffer system. *Journal of the American Water Resources Association* **46**, 299–310.

Robins L (2002) *Managing Riparian Land for Multiple Uses.* RIRDC Publications, Canberra.

Scott DF, Prinsloo FW, Moses G, Mehlomakulu M and Simmers ADA (2000) 'A re-analysis of the South African catchment afforestation experimental data'. Report 810/1/00, CSIR Report ENV-S-C 99088. Water Resources Commission, South Africa.

Smethurst P (2008) 'Summary of Australian codes of forest practice as they pertain to managing commercial plantations in stream-side buffers on cleared agricultural land'. CRC Forestry Technical Report no. 178. <http://www.crcforestry.com.au/publications/downloads/TR178-Smethurst-FORPRINT.pdf>.

Smethurst PJ, Petrone KC, Baillie CC, Worledge D and Langergraber G (2011) 'Streamside management zones for buffering streams on farms: observations and nitrate modelling'. Technical Report no. 28. Landscape Logic, Hobart. <http://www.landscapelogicproducts.org.au/site/products/57-technical-report-no-28-streamside-management-zones-for-buffering-streams-on-farms-observations-and-nitrate-modelling>.

Sutton AJ, Fisher TR and Gustafson AB (2010) Effects of restored stream buffers on water quality in non-tidal streams in the Choptank River Basin. *Water Air Soil Pollution* **208**, 101–118.

Swift LW and Messer JB (1971) Forest cuttings raise stream temperatures of small streams in the southern Appalachians. *Journal of Soil Water Conservation* **26**, 111–116.

Zhang X, Liu X, Zhang M, Dahlgren RA and Eitzel M (2010) A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. *Journal of Environmental Quality* **39**, 76–84.