VI
EFFECTS OF REFORESTATION OF A DEGRADED *IMPERATA* GRASSLAND ON DOMINANT FLOW PATHWAYS AND STREAMFLOW RESPONSES
Chapter 6

Effects of reforestation of a degraded *Imperata* grassland on dominant flow pathways and streamflow responses

**ABSTRACT:** Reforesting degraded land can increase soil permeability and the number of macropores, suggesting this may also change the dominant runoff generation mechanism. However, it is not clear to what extent these changes affect the hydrological response for different event sizes. Therefore, the responses of two small catchments with perennial flow near Tacloban (Leyte, the Philippines) were compared: one a degraded *Imperata* grassland micro-catchment (Basper, 3.2 ha), the other a catchment that had been reforested 23 years previously (Manobo, 8.75 ha). The two catchments had the same rock- and soil type. Precipitation, stream stage and electrical conductivity (EC) were measured continuously from June until November 2013 when the area was struck by typhoon Haiyan. Samples were taken from streamflow, precipitation, groundwater and soil water for geochemical and stable isotope analysis. The response of the degraded grassland was much more flashy and rapid than that of the reforest. Both streamflow and EC changed rapidly during almost every rainfall event in the grassland, but streamflow and EC responses of the reforest were much smaller and only occurred during larger events. Changes in stream chemistry and isotopic composition during stormflow conditions were also larger in the grassland. EC-based minimum pre-event water contributions to streamflow were much smaller for the grassland than for the reforest (medians of 26 and 81%, respectively) and suggested that overland flow occurred frequently and was much more widespread in the grassland. These differences in response were observed for all event sizes, including a major tropical storm event. The results indicate that the dominant flow pathways during rainfall have changed after reforestation from an overland flow dominated response in the grassland to a subsurface flow dominated response in the reforestation. The findings also demonstrate that successful reforestation can restore the hydrological functioning of degraded land, provided the soil is allowed to recover over a sufficiently long period.

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5 This chapter is based on van Meerveld HJ, Zhang J, Tipoli R, Bruijnzeel LA. 2018. Effects of reforestation of a degraded *Imperata* grassland on dominant flow pathways and streamflow responses in Leyte, the Philippines. Submitted to Water Resources Research.
6.1 INTRODUCTION

Swidden cultivation can be a sustainable agricultural practice (Brady, 1996), but when fallow periods become critically shortened due to increased population pressure, the repeated fire can lead to unproductive fire-climax grasslands dominated by *Imperata* and *Saccharum*. Garrity *et al.* (1997) estimated that the total area under *Imperata* grassland in South- and South-east Asia alone was about 35 million ha in the early 1990s, but also noted that this was likely an underestimation because their survey only included larger tracts of grassland. *Imperata* grasslands can have poor soil physical characteristics, such as low infiltration capacity, especially when grazed (Snelder, 2001a) and surface runoff on degraded grasslands often causes severe erosion, which together with increased landsliding leads to water quality problems (White, 1996; Trustrum *et al.*, 1999). Restoration and reforestation programmes therefore often target these degraded grasslands (Lamb, 2014). In the Philippines, *Imperata* grasslands are known as *cogon* and covered more than 6.5 million ha in 1990, of which two-thirds were considered to suffer moderate to severe erosion (Concepcion and Samar, 1995). Partly in response to such problems, the ‘National Greening Program’ of the Philippines aimed to plant 1.5 billion trees on 1.5 million ha of degraded land (much of it under *cogon* and shrub) as of 2011 in six years (Aquino and Daquio, 2014). However, the hydrological impacts of reforesting degraded land remain understudied in the tropics and are largely undocumented (Scott *et al.*, 2005). Understanding how runoff generation mechanisms and streamflow responses change after reforesting degraded land is important to understand the downstream impacts of large-scale reforestation projects (Trimble *et al.*, 1987; Zhou *et al.*, 2010; Liu *et al.*, 2014). In places like the Philippines, where tropical storms and typhoons are common, it is particularly important to study how reforestation affects runoff processes for very large events because nearly a third of all precipitation is derived from typhoons (Cinco *et al.*, 2016), and their intensity is expected to increase in the future (Balaguru *et al.*, 2016).

Changes in land-cover can have large impacts on water resources and numerous paired catchment studies across the globe have shown that forestation typically results in decreases in annual water yield and dry-season flows due to increased evaporative losses, whereas forest clearing typically results in increased flows. In global analyses of experimental results, Jackson *et al.* (2005) and Farley *et al.* (2005) showed that forestation of grass- and shrublands decreased streamflow (mostly baseflow) on average by 180 mm yr\(^{-1}\) or 38%. However, these data-sets included few tropical sites, and results from temperate forests are not necessarily transferable to the tropics, where soils are different and rainfall more intense (Bonell *et al.*, 2005).
2005; Wohl et al., 2012). Furthermore, degraded sites – where the dominant hydrological processes likely differ from those in controlled experiments (Bruijnzeel, 1989; Malmer et al., 2010) – were not included in these global analyses. When soils are not disturbed much, the relative effects of forest removal tend to decrease as event precipitation increases, and are often not detectable for the most extreme events (Hewlett, 1982; Hsia, 1987; Beschta et al., 2000; Levy et al., 2018) because the relative size of the soil water storage capacity becomes smaller as rainfall amounts increase (Scott et al., 2005). This is particularly the case for sites with shallow soils (Birkinshaw et al., 2011; Poca et al., 2018). However, land degradation typically results in decreased rainfall infiltration because declines in organic matter, exposure to raindrop impact, surface sealing, and compaction by cattle or machinery lead to fewer large pores and less ‘preferential’ flow (Lal, 1996; Deuchars et al., 1999; Shougrakpam et al., 2010). This causes a sharply reduced surface field-saturated hydraulic conductivity (Martinez and Zinck, 2004; Ziegler et al., 2006; Zimmermann et al., 2010; cf. Chapter 2) and concurrent increases in overland flow and storm runoff (Chandler and Walter, 1998; Zhou et al., 2002; Molina et al., 2007; Krishnaswamy et al., 2012; Ghimire et al., 2013; Toohey et al., 2018). Advanced surface degradation may cause such large changes in near-surface flow pathways and runoff response that the difference with non-degraded situations may persist across the runoff spectrum (Scott et al., 2005; Lana-Renault et al., 2014; cf. Mathys et al., 1996). In extreme cases, this may lead to reduced groundwater recharge and, ultimately, declined dry-season streamflow (Bruijnzeel, 2004; Recha et al., 2012; Krishnaswamy et al., 2012). On the other hand, natural regrowth or reforestation of degraded land may restore near-surface hydraulic conductivity and soil hydrological functioning possibly within one to two decades (Ziegler et al., 2004; Bonell et al., 2010; Zimmermann et al., 2010; Hassler et al., 2011; Zwartendijk et al., 2017), suggesting that surface runoff can be reduced and become less widespread again during forest maturation (Chandler and Walter, 1998; Zhou et al., 2002; Krishnaswamy et al., 2012). However, actual flow pathways and infiltration rates likely differ from those inferred from point-scale hydraulic conductivity measurements (Sherlock et al., 1996; Sherlock et al., 2000; Chappell and Sherlock, 2005; Vigiak et al., 2006) because of surface sealing (Rao et al., 1998), and macroporosity effects (Chappell et al., 1998; Sarkar et al., 2008; Chappell, 2010).

Isotope-based hydrograph separation can be used to determine the contribution of event water (‘new’ water: overland flow and precipitation) and pre-event water (‘old’ water already present: groundwater and soil water) to the stream (Buttle, 1994; Klaus and McDonnell,
Isotope hydrograph separations are widely used to study runoff generation mechanisms in temperate forested catchments but have remained underutilized in the tropics (Buttle and McDonnell, 2005; Liu et al., 2009; Muñoz-Villers and McDonnell, 2013). Using stable isotopes in South-west China, Liu et al. (2009) showed that overland flow was much more widespread in a rubber plantation than in a nearby rainforest. Similarly, in a heavily grazed montane pasture catchment in Eastern Mexico, event-water contributions were much larger than for a nearby forested catchment during the largest monitored event (with a return period of 2 yr), indicating significantly more surface runoff in the grazed catchment (Muñoz-Villers and McDonnell, 2013). Alternatively, several recent studies have shown that, despite not being a fully conservative tracer, Electrical Conductivity (EC) can also be useful for hydrograph separation (Robinson et al., 2008; Inserillo et al., 2017), although there can be significant differences between EC- and isotope-based hydrograph separation results for specific events (Litt et al., 2015; Penna et al., 2015). Chemical tracer-based hydrograph separation and End Member Mixing Analysis (EMMA) can be used to determine contributions of different source waters to the stream channel as well (Hooper, 1990; Barthold and Woods, 2015) and have been used in multiple tropical studies (e.g., Bruijnzeel, 1983b; Elsenbeer et al., 1995; Elsenbeer and Lack, 1996; Kurtz et al., 2011; Hugenschmidt et al., 2014; Scholl et al., 2015). For instance, a hydrochemical study of two ephemeral streams in South-western Amazonia showed that throughfall (79%), groundwater (18%) and shallow soil water (3%) were the dominant streamflow components in an old-growth forest micro-catchment during times of rainfall, while that in a pasture consisted of surface runoff (66%), groundwater (35%) and some soil water (5%) (Chaves et al., 2008). Isotope and silica data from southern Brazil suggested that streamflow during rain in a forested catchment consisted mainly of rapid subsurface flow through macropores, while flows from an agricultural catchment were mostly due to surface runoff (Robinet et al., in press).

While these previous isotope and geochemical results suggest that surface runoff is more widespread in tropical agricultural or pasture settings than in forested catchments, they cannot be used directly to infer the hydrological effects of reforesting degraded fire-climax grasslands. Therefore, this study compares the runoff response of a semi-mature reforestation (Manobo site) with that of a degraded Imperata grassland micro-catchment (Basper site) on the island of Leyte (Philippines) to determine: (i) the effect of reforestation on the magnitude of runoff response, dominant flow pathways and amounts of pre-event water in stormflow, and (ii) how these are affected by event size.
6.2 STUDY SITES

To study the effects of reforestation of degraded *Imperata* grassland on dominant runoff pathways and streamflow response, two small headwater catchments near Tacloban, NE Leyte, the Philippines were instrumented (Figure 6.1) using a space-for-time substitution approach. The Basper catchment is a 3.20 ha degraded grassland catchment (11°15’ N and 124°57’ E). Vegetation consists of cogon grass (*Imperata cylindrica*), mixed with sedges (*Cyperus* sp.) in poorly-drained areas and mixed with shrubs (<1.5 m high; mostly *Melastoma malabathricum* and *Chromolaena odorata*) on mid-slope sites. Shrubs and small trees (2–3 m high; mostly *Neonauclea lanceolata* and *Leukosyke capitella* and a few remnant planted *Acacia mangium*) are common along the stream, covering ~14% of the catchment area. Landslide scars are also common and covered ~3.4% of the catchment area (Chapter 3).

In the 8.75 ha Manobo catchment (11°17’N, 124°56’E), reforestation of the degraded grassland started in 1990 when the Manobo tribe relocated to the area. First *Gmelina arborea* and mahogany (*Swietenia macrophylla*) trees as well as coconut palms (*Cocos nucifera*) were planted to shade out the *Imperata* grasses, after which other plants and trees, including almond, papaya, banana, and medicinally useful plants and rattans were planted (U. Padecio, personal communication). At the time of the measurements the forest consisted of a mixture of planted trees and naturally regenerating species. An 1850 m² plot in the catchment contained more than 50 different tree species. Average canopy height was 7.3 m and the basal area 15 m² ha⁻¹. The average Leaf Area Index (measured 12 times at 24 sampling locations before Typhoon Haiyan damaged the canopy in November 2013) on a mid-slope plot was 5.1 ± 0.65. Average interception loss prior to canopy damage was 18% (Chapter 4).

The space-for-time substitution approach used here assumed that the two catchments had a similar runoff response prior to reforestation of the Manobo grassland. The two catchments were located only 3.5 km from each other (Figure 6.1a), had a similar elevation range (50–135 m a.s.l for Basper and 33–200 m a.s.l for Manobo) and the same soil type and geology, and were exposed to the same climatic conditions, suggesting that hydrological processes in the two catchments were originally very similar.

The climate is tropical ever-wet (Köppen-type Af). Monthly average temperatures vary between 25.7 °C in January and 28.1 °C in May (measured at Tacloban Airport between 1977 and 2011; PAGASA Office, Tacloban). Annual precipitation at Tacloban Airport varied between 1435 and 4790 mm for the 1977-2011 period and averaged 2660 mm. Average
monthly precipitation is highest in December and January (average monthly precipitation of 378 and 323 mm, respectively) and lowest in April and May (127 and 147 mm, respectively). This study focuses on the period between 12 June and 7 November 2013, rather than a full year because typhoon Haiyan caused widespread destruction of vegetation in both catchments and severe landsliding at Basper on 8 November 2013 (Chapters 3–5). Total precipitation during the study period was 1028 mm in Basper and 1004 mm in Manobo; average precipitation at Tacloban airport for the June-October period is 950 mm. The median five-min rainfall intensity for the June–November 2013 period was 3.0 mm hr\(^{-1}\) for both catchments (90\(^{th}\) percentiles: 18 and 24 mm hr\(^{-1}\) for Manobo and Basper, respectively).

Soils in both catchments are Eutric Cambisols with a clay loam texture that grades into sandy clay loam below 0.9 m depth (Chapter 2). Both catchments are underlain by mafic bedrock (gabbro). Field measurements using a constant-head permeameter suggested large differences in saturated soil hydraulic conductivity \(K_{\text{sat}}\) between land covers. The median \(K_{\text{sat}}\) at 20 cm was 2.9 mm hr\(^{-1}\) for the Basper grassland (\(n = 17\)) and 59 mm hr\(^{-1}\) for the Manobo reforest (\(n = 18\)) with inter-quartile ranges of 0.8–6.6 mm hr\(^{-1}\) at Basper and 32–114 mm hr\(^{-1}\) at Manobo. In addition, median surface \(K_{\text{sat}}\) at Basper (measured by double-ring infiltrometer) was equally low at 2.1 mm h\(^{-1}\) (\(n = 13\)), whereas the median surface \(K_{\text{sat}}\) (measured on small cores in the laboratory) for the reforest was much higher (368 mm h\(^{-1}\); \(n = 27\)). These differences suggest that overland flow (both infiltration-excess and saturated overland flow) is much more likely to occur at Basper than at Manobo (Chapter 2). Further details on soil characteristics are given in Chapter 2.
Figure 6.1 Maps of (a) the Basper grassland micro-catchment and (b) the Manobo reforest catchment showing drainage lines, contour lines (10 m interval) and locations of soil profiles, Amoozemeter measurements, and basic hydrological instrumentation.

6.3 METHODS

6.3.1 Field measurements

Precipitation was measured at two locations in each catchment using recording tipping bucket rain gauges (Onset Computer Corporation, USA connected to HOBO Pendant event data-loggers; 0.25 mm resolution). One gauge was located in an open area near the outlet of each catchment and the other near the ridge (Figures 6.1b-c). Daily precipitation measurements with a 100 cm$^2$ manual rain gauge placed next to the lower recording gauges were used as a check of the latter. All rain gauges were placed ~ 1 m above the soil surface. For the analyses we used the average precipitation of the two recording gauges for each site. We did not correct precipitation amounts for wind-related catch errors because wind speeds were generally low (median value of 1.2 m s$^{-1}$ at the Basper ridge site). Sequential rainfall samplers (Kennedy et al., 1979) installed near the lower rain gauges were used to obtain samples of the rain in 8 mm increments.
Water levels were measured behind sharp-crested compound weirs at 5-min intervals using HOBO U20 loggers (Onset Computer Corporation, USA). The atmospheric pressure was measured in a nearby hut in each catchment using HOBO U20 loggers as well. Volumetric (bucket and stopwatch) and current-meter measurements (Price Type AA current meter) were used to check the validity of the stage-discharge equations for the two weirs. For water levels above the V-notch, the Bergmann compound weir equation (as given in USBR, 1997) was used. The water level was higher than the V-notch for 0.12% of the total time (representing 21% of the total flow) at Basper versus 0.13% (18% of the total flow) at Manobo.

The Electrical Conductivity (EC) of the stream water was measured using a HOBO U24 logger installed behind each weir. The data from the loggers were regularly checked against manual EC measurements using a CyberScan PC300 pH/Conductivity/TDS Meter (ENVCO, Australia). Stream samples were collected using U59 single stage samplers (*i.e.* bottles with a siphon-shaped air exhaust; Colby, 1961; Schick, 1967) installed at different heights behind the weirs. Bottles were replaced after events. During some events, manual samples were taken using clean 500 ml polyethylene sampling bottles.

Ceramic-cup suction lysimeters were installed at 20 and 55 cm below the soil surface at foot-, mid- and upper slope locations in the Basper catchment (sites G1, S2 and S1) and at lower and mid-slope locations at Manobo (sites G3 and S3). A suction of 600 hPa was applied. Soil water samples were taken regularly and the sample closest to an event was used to represent the soil water composition during the event. Groundwater samples were taken from piezometers installed at the same locations as the suction lysimeters in both catchments (Figure 6.1). However, for most events, groundwater samples were available only for the foot-slope piezometers.

All water samples were filtered at Visayas State University using Millipore 0.45 µm filters. The samples were analysed for the stable water isotopes ($^{18}$O and $^2$H) using laser spectroscopy at the Global Institute for Water Security at the University of Saskatchewan, Canada and using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) for base chemistry at the Water Laboratory of the VU University Amsterdam, The Netherlands.
6.3.2 Data analysis

6.3.2.1 Streamflow characteristics during the study period

To compare streamflow characteristics for the two catchments without introducing a bias due to different periods of missing data, only days for which complete streamflow data were available for both catchments were included (i.e. 127 days out of the 149 day period between 12 June and 7 November 2013, or 85%). Total precipitation during these days was 842 mm for Manobo and 915 mm for Basper, representing 84 and 89% of the respective rainfall totals of 1004 mm and 1028 mm for the entire study period. For the matching time periods, several streamflow characteristics were calculated describing the magnitude of the streamflow, such as the total amount of streamflow, the mean, median and maximum streamflow, as well as the variability in streamflow, such as flood pulse counts (i.e. the number of times that streamflow increased and was higher than three times the median flow or higher than the 75th percentile of flow), the slope of the flow duration curve between the 33rd and 66th percentile of flow (Olden and Poff, 2003), and the Richard-Baker Flashiness index (Baker et al., 2004). A master recession curve was constructed for each catchment using the matching strip technique (Toebes and Strang, 1964) and an exponential curve was fitted through the lowest points to determine the master recession constant (Nathan and McMahon, 2010). All streamflow characteristics were based on 5-min data, except for the high flood pulse counts, the number of significant streamflow increases, the fraction of time that streamflow increased significantly, the Richard-Baker flashiness index, the percentage of time on the rising limb and the master recession constants, which were based on hourly averaged data to minimize the effect of noise in the 5-min data.

6.3.2.2 Event characteristics

All events larger than 5 mm that were preceded by at least 6 h without precipitation and that resulted in a clear storm hydrograph were included in the analyses. To determine the amount of stormflow for each event, the straight-line separation method was used (Hewlett and Hibbert, 1967). The start of the event was defined as the first time step that streamflow increased after the start of precipitation, while the end of the event was defined as the time that stormflow ended or the start of the next event. If an event was followed by another event within 6 h, the next event was only counted as a separate event if stormflow was less than 5% of the total measured flow at the start of the next event. Otherwise, the two events were
analysed together. These event selection criteria resulted in 35 events for the Manobo reforest and 40 events for the Basper grassland.

For each event, several characteristics were determined using the 5-min precipitation and streamflow data, such as the total amount of stormflow, the storm runoff ratio, the lag time between peak precipitation intensity and peak streamflow (peak lag time), and the lag time between the centroids of precipitation and stormflow (centroid lag time). The storm runoff ratio was determined by dividing total event stormflow amount by event precipitation. Note that this straight-line based determination of stormflow amounts and the resulting runoff ratios differ from the isotope-based event-water contributions to streamflow described below.

The Mann-Whitney U-test and a significance level of 0.05 were applied to determine whether median event characteristics differed significantly between the two catchments.

6.3.3 Hydrograph separation and mixing plots

To determine whether differences in streamflow amount and timing were caused by differences in flow pathways and runoff generation mechanisms, isotope-based hydrograph separation was used for two events for which good isotope data were available for both catchments. The fraction of pre-event water for each time step was determined, according to:

$$f_p = \frac{C_s - C_e}{C_p - C_e}$$  \hspace{1cm} (Eq. 6-1)

where $f_p$ is the fraction of pre-event water in streamflow, $C_s$ is the concentration (here $\delta^2$H or EC) of streamflow, $C_e$ is the concentration of the event water and $C_p$ is the concentration of the sample taken before the event, which was assumed to represent the pre-event water composition. In doing so, the incremental weighted mean of the precipitation was used (McDonnell et al., 1990) to characterize event-water composition. Next, the pre-event water fractions were interpolated linearly for the different sampling times and multiplied times streamflow amount to obtain the pre-event water contributions during the event. The average pre-event water contribution to streamflow was calculated as the ratio of the sum of pre-event water and the sum of total streamflow. The minimum pre-event water contribution for the event (coinciding with the timing of maximum contribution of event-water) was also determined.

The two matching events for which good isotope data allowed isotope-based hydrograph separations were the event of 27 July 2013 (bringing ~50 mm of precipitation to both catchments) and tropical storm Rumbia (locally known as tropical storm Gorio, delivering
150–175 mm of precipitation on 28–29 June 2013). The latter event was the largest during the study period. Between 1977 and 2011, there were 21 events with more than 150 mm of precipitation in one day at Tacloban airport (daily precipitation was larger than 160 mm for only 10 days). Detailed chemical data were available for these two events and for the 43–47 mm event occurring on 21 June 2013 (for which good precipitation isotope data were not available) and mixing diagrams were used to visually determine the relative contributions of groundwater, soil water and precipitation to streamflow during these events. End Member Mixing Analysis (EMMA; Hooper, 1990) was used to explore the relative contributions of soil water, groundwater and precipitation (or throughfall) for these events. Unfortunately, for all three events, calculated fractions of groundwater contributions at the time of the lowest stream water concentrations at Basper were negative, which is physically impossible. This was also the case for two samples taken during the peak of tropical storm Rumbia for the Manobo catchment.

In addition, changes in stream water EC as observed during all storm events were analyzed and used to obtain an estimate of the minimum pre-event water contribution to streamflow for almost all events (no EC data were available for one event in Manobo and two events in Basper). Because rainfall EC data were not available for each individual event, an average EC of 8 µS cm⁻¹ was used in the computations for all events (range: 3–20 µS cm⁻¹; EC < 10 µS cm⁻¹ for all 18 but two samples).

6.4 RESULTS

6.4.1 Streamflow response

Even though total precipitation during the study period was 8% higher for the Basper catchment compared to the Manobo catchment (Table 6.1), there were no statistically significant differences in median event size or event average rainfall intensity for the two catchments (Table 6.2).
Table 6.1 Streamflow characteristics for the Manobo and Basper catchments for the 127 days between 12 June and 7 November 2013 for which streamflow data were available for both catchments (127 days out of the 149-day period).

<table>
<thead>
<tr>
<th></th>
<th>Manobo</th>
<th>Basper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total precipitation (mm)</td>
<td>842</td>
<td>915</td>
</tr>
<tr>
<td>Total streamflow (mm)</td>
<td>244</td>
<td>391</td>
</tr>
<tr>
<td>Runoff coefficient (%)</td>
<td>29</td>
<td>43</td>
</tr>
<tr>
<td>Mean flow (mm h(^{-1}))</td>
<td>0.08</td>
<td>0.13</td>
</tr>
<tr>
<td>Median flow (mm h(^{-1}))</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>Maximum flow (mm h(^{-1}))</td>
<td>14</td>
<td>26</td>
</tr>
<tr>
<td>Ratio of mean and median flow ((-))</td>
<td>7.2</td>
<td>2.8</td>
</tr>
<tr>
<td>Coefficient of variation ((-))</td>
<td>6</td>
<td>5.6</td>
</tr>
<tr>
<td>Ratio of the difference between the 75(^{\text{th}}) and 25(^{\text{th}}) percentile of flow and the median flow ((-))</td>
<td>2.99</td>
<td>1.86</td>
</tr>
<tr>
<td>Slope of the flow duration curve between the 66(^{\text{th}}) and 33(^{\text{rd}}) percentile ((-))</td>
<td>0.05</td>
<td>0.18</td>
</tr>
<tr>
<td>Flood pulse count (&gt;75(^{\text{th}}) percentile) ((-))</td>
<td>17</td>
<td>36</td>
</tr>
<tr>
<td>Flood pulse count (&gt;3x median flow) ((-))</td>
<td>21</td>
<td>37</td>
</tr>
<tr>
<td>Number of streamflow increases &gt;10% and 0.1 mm h(^{-1}) (with more than 2 hours of no increase prior to the increase) ((-))</td>
<td>10</td>
<td>32</td>
</tr>
<tr>
<td>Percentage of time on fast rising limb (fraction of time where flow is higher than in the previous hour by at least 10% and 0.1 mm h(^{-1})) (%)</td>
<td>0.6</td>
<td>1.6</td>
</tr>
<tr>
<td>R-B flashiness index</td>
<td>0.16</td>
<td>0.47</td>
</tr>
<tr>
<td>Recession constant (h(^{-1}))</td>
<td>0.012</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Streamflow responses for the Manobo and Basper catchments were very different (Figure 6.2). Streamflow at Basper was much more variable and increased in response to almost every precipitation event, whereas streamflow at Manobo only responded significantly to the largest events (Figure 6.2). This is reflected in the higher flood pulse counts, larger number of flow increases, higher flashiness index and longer time on the rising limb obtained for the Basper grassland compared to the reforested catchment (Table 6.1). Peak flows as well as mean and median flows were also much higher for the grassland than for the reforestation (Table 6.1). The double-mass curves were also very different for the two catchments (Figure 6.2). At Basper, cumulative streamflow increased almost linearly with cumulative precipitation, while the curve for Manobo was much more step-like, reflecting the more delayed response (e.g. the large increase in cumulative streamflow after the major increase in precipitation during tropical storm Rumbia in late June) and the many rainfall events that did
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not produce significant streamflow response (e.g. the flat part of the curve for the month of July, for which the runoff ratio was 16% compared to 47% for the Basper catchment).

Table 6.2 The median (and mean), range (min-max) and relative frequency distribution of the event characteristics for the Manobo (lower box plots in green) and Basper (upper box plots in orange) catchments, as well as the Mann-Whitney ranked sum test p-values. The box represents the 25th and 75th percentiles, the solid line the median, the dashed line the mean, the whiskers the 10th and 90th percentiles, and the dots are outliers.

<table>
<thead>
<tr>
<th>Event Characteristic</th>
<th>Manobo</th>
<th>Basper</th>
<th>p-value</th>
<th>Relative frequency distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of events</td>
<td>35</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Event size (mm)</td>
<td>11.3 (18.5)</td>
<td>11.6 (18.6)</td>
<td>0.996</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.3-174</td>
<td>4.1-154</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum rainfall intensity (mm 5-min⁻¹)</td>
<td>2.7 (3.3)</td>
<td>3.6 (3.9)</td>
<td>0.222</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5-6.3</td>
<td>0.5-8.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total stormflow (mm)</td>
<td>0.09 (3.5)</td>
<td>1.7 (5.0)</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.002-80</td>
<td>0.01-76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Runoff ratio (%)</td>
<td>0.5 (6.8)</td>
<td>12.5 (15.0)</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.04-46</td>
<td>0.17-50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak streamflow (mm 5-min⁻¹)</td>
<td>0.01 (0.06)</td>
<td>0.20 (0.53)</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0007-1.18</td>
<td>0.0009-2.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lag time between peak rainfall intensity and peak streamflow (min)</td>
<td>20 (39)</td>
<td>10 (11)</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0-270</td>
<td>0-60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lag time between centroid of rainfall and centroid of stormflow (min)</td>
<td>50 (130)</td>
<td>25 (34)</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10-485</td>
<td>5-90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Change in EC during the event (µS cm⁻¹)</td>
<td>51 (77)</td>
<td>187 (162)</td>
<td>&lt;0.001</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11-199</td>
<td>20-282</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.2 Time series of hourly and cumulative rainfall (a-b) and 5-min streamflow and EC of stream water (c-d) for the Manobo (a, c; left) and Basper catchments (b, d; right) for the period between 10 June and 10 August 2013.

Figure 6.3 Double-mass curve of precipitation versus streamflow for the days with data for the Manobo and Basper catchments. Thy symbols indicate the values on the first of July, August, September, October, and November 2013.
Event stormflow amount increased with event precipitation for both catchments (Figure 6.4). There appears to be a threshold at ~10 mm of precipitation for both catchments but due to a lack of data for small events and the big influence of tropical storm Rumbia, it was difficult to define the threshold exactly. The slope of the relation between event stormflow and precipitation for events below the threshold was much larger for the Basper catchment than the Manobo catchment (0.054 versus 0.006), but the correlation between the two variables below the threshold was very low (R2 < 0.1) and not significant. The corresponding slopes after the threshold also differed between the two catchments (0.41 and 0.20 for Basper and Manobo, respectively, when excluding the Rumbia event; but 0.51 and 0.48 when including the tropical storm). Similar to the overall storm runoff ratios for the study period (Table 6.1), the median event-based runoff ratios were much larger for the grassland catchment than for the reforested catchment (Table 6.2).

![Figure 6.4](image)

**Figure 6.4** Event total stormflow (a) and storm runoff ratio (b) as a function of event total precipitation for the Manobo (green circles) and Basper (orange triangles) catchments. The stormflow amount and storm runoff ratio were based on the straight-line hydrograph separation method. Note the break in the x-axis between 60 and 160 mm of precipitation and the total amount of stormflow between 25 and 60 mm in order to be able to show all events in the same graph.

Streamflow responses were not only larger for the Basper catchment, they were also significantly faster. The median lag time between peak rainfall intensity and peak streamflow was only ~10 min at Basper, significantly shorter than the 20 min for the Manobo catchment (but note the large uncertainty because the data were recorded at 5-min intervals). The
difference in median lag times between the centroids of precipitation and stormflow was also a factor of two, although the differences in average centroid lag times were much larger (23 min for Basper versus 130 min for Manobo; Table 6.2). On the other hand, the master recession constant was larger for the Manobo catchment (Table 6.1), suggesting that low flows in the reforested catchment decreased faster than in the grassland catchment.

### 6.4.2 Isotope-based hydrograph separations and mixing diagrams

The streamflow responses to the precipitation event of 27 July 2013 (~50 mm of precipitation) were very different for the two catchments (Figure 6.5). Streamflow in the Basper grassland increased from 0.004 mm 5-min\(^{-1}\) to 2 mm 5-min\(^{-1}\) within 75 min. The peak lag time was only 15 min and the centroid lag time was 10 min. Streamflow in the Manobo reforestation changed from a low 0.0003 mm 5-min\(^{-1}\) to 0.039 mm hr\(^{-1}\); peak and centroid lag times were 10 min and 3 h 35 min, respectively. Storm runoff ratios for this event were 36% at Basper and 3% at Manobo. The isotope-based hydrograph separation result for this event suggested average pre-event water contributions to streamflow of 19% for Basper and 65% for Manobo. Corresponding minimum pre-event water contributions were 3 and 20% for Basper and Manobo, respectively, implying maximum ‘new’ water contributions of 97 and 80%, respectively. However, the results are somewhat uncertain, particularly for the Basper case, because of a lack of samples during peak flow conditions and the rapidly changing isotopic composition of precipitation and streamflow. Furthermore, one rising limb sample was more depleted isotopically than any of the precipitation samples until that time and was excluded from the calculations. EC-based hydrograph separations suggested average pre-event water fractions of 19 and 73% for Basper and Manobo, respectively, while the corresponding minimum pre-event water fractions were 5 and 36%. Using the higher average EC of throughfall (52 µS cm\(^{-1}\); \(n=6\)) instead of that for precipitation (8 µS cm\(^{-1}\)) gave average and minimum EC-based pre-event water contributions at Manobo of 69 and 25%, respectively.

During tropical storm Rumbia, streamflow increased significantly at both locations (Figure 6.6). Peak flow rates were higher than the V-notch weir and are thus somewhat uncertain (because of the lack of discharge data at high flow rates) but were significantly different between catchments (2.1 mm 5-min\(^{-1}\) for Basper versus 1.2 mm 5-min\(^{-1}\) for Manobo). This time, streamflow peaked within 5 min of the peak rainfall intensity for both catchments. The centroid lag time was longer for the reforested catchment than for the grassland catchment (2
h 40 min *versus* 1 h 25 min). However, the storm runoff ratios were comparable at ~49 and ~46% for the Basper and Manobo catchment, respectively, also in view of the somewhat uncertain high flows and possible under-catch of rainfall during this tropical storm. The averaged pre-event water contributions to streamflow were also very different: 53% at Basper *versus* 77% at Manobo while corresponding minimum pre-event water contributions were 24% for Basper and 55% for Manobo. The EC-based average and minimum pre-event water contributions were 24 and 4% for Basper, and 50 and 31% for Manobo, respectively (and 41 and 18%, respectively, when using throughfall EC instead of precipitation EC).

Changes in the concentrations of silica, calcium, magnesium and most other ions during these two events were similar to those in EC (Figures 6.5c-d and Figures 6.6c-d). Soil water concentrations were highly variable, but the mixing plots clearly indicated that stream water was largely a combination of groundwater and precipitation and some soil water. The relative contribution of precipitation was reflected more in the chemistry of the stormflow at Basper than at Manobo (Figure 6.7). The mixing diagram results for the event of 21 June 2013 were similar to those for the other events (Figures 6.7a-b), and again indicated that streamflow was a mixture of precipitation and groundwater at both sites. End Member Mixing Analysis calculations were not possible for all samples collected during the events, but they did suggest that groundwater contributions to streamflow declined (and precipitation contributions increased) during the events. Soil water contributions remained relatively stable during the events (10–26% for Basper and 12–30% for Manobo). End Member Mixing Analyses were not possible for any of the peak flow samples taken at the Basper grassland (producing negative groundwater contributions and precipitation contributions >100%), but for the reforested Manobo catchment, inferred maximum precipitation contributions to streamflow were 74% (21 June event) and 80% (27 July event). Calculations for the peak flow samples collected at Manobo during tropical storm Rumbia also produced negative groundwater contributions and physically impossible precipitation contributions.
Figure 6.5 Hourly and cumulative precipitation and the isotopic composition of precipitation (deuterium) (a-b), 5-min streamflow and EC data, and silica and calcium concentrations (c-d), isotopic composition (deuterium) of stream water and the deuterium-based pre-event water contribution to streamflow (e-f) during the 27 July 2013 event for the Manobo (left; a, c, e) and Basper catchments (right; b, d, f). The streamflow when the weir overflowed is indicated by the light blue line. Figures c-d show streamflow on a linear scale, while figures e-f show streamflow on a log scale in order to better show the streamflow response at Manobo.
Figure 6.6 Hourly and cumulative precipitation and the isotopic composition of precipitation (deuterium) (a-b), 5-min streamflow and EC data, and silica and calcium concentrations (c-d), and isotopic composition (deuterium) of stream water and the deuterium-based pre-event water contribution to streamflow (e-f) during the 28–29 June 2013 event (tropical storm Rumbia) for the Manobo (left; a, c, e) and Basper catchments (right; b, d, f). The streamflow when the weir overflowed is indicated by the light blue line. Figures c-d show streamflow on a linear scale, while figures e-f show streamflow on a log scale.
Figure 6.7 Mixing diagrams for the events of 21 and 27–28 June 2013 (upper row; a-b) and 27 July 2013 (lower row; c-d) for the Manobo catchment (left column; a, c) and the Basper catchment (right column; b, d). The individual rainfall, throughfall (Manobo only), groundwater and soil water samples are indicated by open symbols. The filled symbol indicates the average; the error bars indicate the standard deviation of all precipitation, throughfall, soil water and groundwater samples when more than one sample was available. The streamflow samples are indicated by the blue circles.
6.4.3 **EC-based hydrograph separations**

The EC of stream water decreased much more and during many more events at Basper than at Manobo (Figure 6.2). There was also a significant difference in the median change in stream water EC during an event at the two locations (median change of 187 µS cm\(^{-1}\) for 38 events in the Basper grassland *versus* 51 µS cm\(^{-1}\) for 34 events in the Manobo reforestation; Table 6.2). This large difference resulted in major differences in the inferred EC-based minimum pre-event water fractions of streamflow for the two catchments: 26% for Basper, compared to 81% for Manobo (Figure 6.8).

The minimum pre-event water fraction during an event decreased rapidly with increasing event size for both catchments, but the change for events between 6–12 mm was much larger for the Basper catchment than for the Manobo catchment (Figure 6.9a). Similarly, the minimum pre-event water fraction decreased rapidly with rainfall intensity at Basper for maximum rainfall intensities larger than 2.0 mm 5-min\(^{-1}\) whereas at Manobo it did not change significantly until a rainfall intensity of 3.5 mm 5-min\(^{-1}\) was reached (Figure 6.9b). There was a significant decrease in minimum pre-event water contribution to streamflow for increasing antecedent streamflow in the Basper catchment \(R^2 = 0.39\) for the power law relation), but there was no such correlation for the Manobo catchment.

![Figure 6.8](image-url) **Figure 6.8** Boxplots of the minimum pre-event water contribution to streamflow based on the EC data for the analysed events at the Manobo catchment \((n=34)\) and the Basper catchment \((n=38)\). The box represents the inter-quartile range, the solid line the median, the dashed line the mean, the whiskers the 10\(^{th}\) and 90\(^{th}\) percentiles, and the symbols the outliers. The difference for the Manobo and Basper catchments is statistically significant \((p < 0.001)\)
Chapter 6. Reforestation and runoff pathways

6.5 DISCUSSION

6.5.1 Runoff generation mechanisms in the Imperata grassland and reforestation catchments

The runoff responses were very different for the two catchments, indicating significant differences in the underlying runoff generation mechanisms. The storm runoff ratios for events smaller than ~10 mm were about 5% for Basper and 0.6% for the Manobo catchment. This suggests minimum contributing areas (Dickinson and Whiteley, 1970) that included the stream channel, near-stream zones and landslide slip surfaces for the Basper catchment, but only the channel network (and perhaps a small fraction of the riparian zone) for the Manobo catchment. Average runoff ratios for events larger than 8–12 mm were 41 and 20% for the Basper and Manobo catchment (~25% for Manobo when using net rainfall instead of gross rainfall), suggesting contributions from much larger fractions of the catchment for the grassland compared to the reforestation for all events, except tropical storm Rumbia.

The extremely rapid responses, the much larger changes in stream chemistry, and the lower pre-event water contributions derived for the Basper catchment compared to Manobo all suggest that surface runoff dominated streamflow in the grassland for most rainfall events (cf.

Figure 6.9 Minimum pre-event water contribution during an event derived from the EC data as a function of event total precipitation (a) and the maximum 5-min precipitation intensity (b) for the Manobo (green circles) and Basper (orange triangles) catchments. Note the break in the x-axis between 50 and 150 mm of precipitation for figure a.
the inferences made in Chapter 2 based on the comparison of rainfall intensities and surface $K_{sat}$). The mixing diagrams showed that streamflow mainly consisted of a mixture of groundwater and rainfall (or throughfall in the case of Manobo), while contributions by soil water were smaller and rather stable at ~10–30% (Figure 6.7). The very low surface- and near-surface soil hydraulic conductivities measured at Basper (Chapter 2), along with shallow-groundwater observations (Chapter 3) suggest widespread infiltration-excess overland flow to be the dominant runoff mechanism, along with saturation overland flow on some parts of the hillslope. The rapid changes in stream stage and EC observed for almost all events (Figure 6.2) further suggest that surface runoff was generated during almost all rainfall events in the grassland. Conversely, in the reforested catchment, only large events led to a significant response and changes in stream water EC (Figure 6.2). Streamflow at Manobo barely responded to the 50 mm event of 27 July. The very low storm runoff ratio (3%) and relatively low average pre-event water fraction (65%) suggest a significant portion of the runoff during this event was generated from rain falling on the channel and riparian zone. At Basper, on the other hand, surface runoff must have been widespread, given the runoff ratio of 30% and the average pre-event water fraction of 19% (Figure 6.5). Runoff ratios for the largest event (tropical storm Rumbia) were almost equal between catchments (given the uncertainties in rainfall and streamflow measurements for this extreme event), but the differences in the timing of the centroid of the response, the magnitude of peak streamflow and pre-event water contributions all suggest that runoff processes were still very different, with surface runoff dominating at Basper and lateral subsurface flow at Manobo. Foot-slope groundwater levels during the event rose to 30 cm below the surface in the reforestation (cf. Supporting Figure 5.3), thereby activating any lateral macropores present (cf. Noguchi et al., 1997; Schellekens et al., 2004; Cheng et al., 2017). No macropore flow samples were collected, but a sample of concentrated seepage in the streambank during the 27 July event had the same chemical signature as streamflow (i.e., a mixture of groundwater and throughfall).

### 6.5.2 Effect of reforestation on runoff generation mechanisms

The comparative results of the space-for-time substitution strongly suggest that reforestation of the Manobo catchment has significantly improved soil hydraulic properties (Chapter 2), thereby significantly reducing amounts of surface runoff, so that streamflow increases at Manobo during rain are now much smaller, more delayed and only occur during large events (Figure 6.2). Streamflow at Manobo is still a mixture of groundwater and
precipitation (throughfall) but the fraction of precipitation is now much smaller (Figure 6.7). The results, therefore, suggest that reforestation can significantly change streamflow dynamics and dominant flow pathways for the better, provided the forest and soil are allowed to develop uninterrupted over a sufficiently long period (cf. Ghimire et al., 2014). García-Ruiz et al. (2008) reported a similar difference in runoff response for catchments in the Pyrenees, where a highly degraded catchment responded to all rainfall events, and a forested catchment only to large rainfall events in the wet period. Zhou et al. (2002) and Krishnaswamy et al. (2012) showed major reductions in storm runoff response after reforesting bare land in South China and overgrazed degraded forest land in India, respectively. The results are also in agreement with previous hydrochemical studies (Chaves et al., 2008; Robinet et al., in press) and runoff plot studies (Chandler and Walter, 1998; Ghimire et al., 2013) that showed surface runoff to be much larger in grazed pastures or pasture fallows than in reforested sites.

The difference in size between the two catchments is probably not responsible for the very large differences in observed runoff responses. Neither catchment had a significant riparian zone and hillslopes were steep. Both catchments are also much bigger than runoff plots for which the scale effect on surface runoff is often large, while research in drylands has shown that the effect of plot size on surface runoff is smallest for the most degraded sites (Moreno-de las Heras et al., 2010; cf. Molina et al., 2007). The Basper catchment has more gullies and the mapped drainage density is higher (Figure 6.1), reflecting both the prevailing higher erosion rates (Chapter 3) and a greater visibility on aerial photographs in the absence of trees. The literature on the effect of catchment size on pre-event water contributions is unclear (Klaus and McDonnell, 2013). Litt et al. (2015) explained the higher pre-event water fractions inferred for a pasture catchment compared to forest in Panama by the smaller size of the pasture catchment (differences in hydrometric responses were much larger than those based on geochemical and isotope tracers). If this would be the case for the study catchments as well, this would mean that the difference in pre-event water fractions for the Basper and Manobo catchments would be even larger if they had the same size.

The differences in the centroid lag time, pre-event water contributions, and peak flow rates for the two catchments during tropical storm Rumbia suggest that differences in runoff generation processes and responses persist, even for the largest events. This is different to the results for most paired catchment studies where soils were not degraded (e.g., Hewlett, 1982; Hsia, 1987; Levy et al., 2018) but is in line with results obtained in the Pyrenees (Lana-
Renault et al., 2014) and South-east France (Mathys et al., 1996) for badland and reforested catchment responses during large events. The difference in runoff generation mechanisms between the Basper and Manobo catchments is reflected in their sediment production (much higher at Basper; Chapters 3 and 5). The streamflow response at Manobo during typhoon Haiyan (228 mm of rain within several hours on 8 November 2013) was not very different from that during tropical storm Rumbia, but streamflow at Basper was very much larger and the weir became completely buried by landslide sediment (Chapter 3). Such observations corroborate the contention that the runoff generation mechanisms at the two sites also differ for even larger events than those reported here.

6.5.3 Effect of event size and rainfall intensity on pre-event water contributions

Even though EC is not a fully conservative tracer, the good correspondence between the isotope- and EC-based hydrograph separations for the two events for which good isotope data were available (Figures 6.5 and 6.6), suggests that the influence of the non-conservative behaviour of EC was small compared to the large differences in EC-based minimum pre-event water contributions for the two catchments. A decrease in minimum pre-event water contribution to streamflow with increasing event size has been shown previously for other catchments (James and Roulet, 2009; Segura et al., 2012; Penna et al., 2015; Fischer et al., 2017). However, some of these studies did not observe the power law relations between rainfall and pre-event water contributions obtained here (Figure 6.9a). For example, for very wet catchments with low-permeability clay soils in Switzerland, the relations between minimum pre-event water contribution and event precipitation were linear up to 84 mm of event precipitation (Fischer et al., 2017). Using EC- and isotope data in a more seasonally wet montane catchment in northern Italy, Penna et al. (2005) showed that the average and minimum pre-event water contributions decreased with event size according to a similar power law relation, but constant pre-event contributions were only reached for events > 25–50 mm, much larger than the 6–12 mm threshold derived for the Basper catchment. Above all, the minimum and median minimum pre-event water contributions at Basper (4 and 26%, respectively) were much lower than corresponding values for these other study sites (Penna et al., 2015; Fischer et al., 2017).

The minimum pre-event water contributions also decreased with rainfall intensity at both sites, but much more quickly and for lower intensities for the grassland than the reforestation (Figure 6.9b). This is likely due to the occurrence of overland flow at Basper, which is more
widespread during high-intensity events. In the very wet and responsive Babinda catchments in North-east Australia, pre-event water contributions were smaller for an event with high rainfall intensity than for an event with low rainfall intensity, because hillside saturated overland flow was much more widespread during the high intensity event (Elsenbeer et al., 1995). Fischer et al. (2017) showed for the wet and responsive Alptal catchments in Switzerland (where water tables are close to the surface) that minimum pre-event water contributions decreased linearly with rainfall intensity (but their maximum hourly rainfall intensity of 18 mm hr\(^{-1}\) was much lower than in this study).

Minimum pre-event water contributions also decreased with increasing antecedent wetness conditions for the Basper catchment, suggesting more widespread overland flow when soil storage capacity is lower. However, this effect was much smaller than the effect of event size, suggesting that the available storage is small and quickly filled by rainfall (cf. Chapter 3). Others have also shown pre-event water contributions to decrease as the catchment wets up (McGlynn and McDonnell, 2003; Litt et al., 2015). Conversely, antecedent conditions did not affect the minimum pre-event water contributions for the Manobo catchment. Fischer et al. (2017) found no correlation between pre-event water contributions and antecedent wetness conditions for the very wet Alptal catchments. However, several other studies have reported that event-water contributions to streamflow are high for dry antecedent conditions, while these contributions decrease as the catchment wets up (Jordan, 1994; James and Roulet, 2009; Muñoz-Villers and McDonnell, 2013). This is generally attributed to the relatively large contribution of channel precipitation and surface runoff from near-stream areas during dry conditions and a lack of contributions from the hillslopes, where rainfall water replenishes soil moisture storage. The larger pre-event water contributions with increasing wetness conditions are then assumed to reflect the gradual increase in connectivity of the hillslopes and streams (Sidle et al., 2000; Muñoz-Villers and McDonnell, 2013). No events were studied during the driest part of the year in Leyte (April–May) and therefore it is possible that antecedent conditions do affect pre-event water contributions to streamflow for the Manobo catchment during the dry part of the year.

6.6 CONCLUSIONS

Runoff responses of a degraded Imperata grassland catchment and a semi-mature multi-species reforested catchment on Leyte (the Philippines) were compared. In the grassland catchment, streamflow increased, and streamwater EC decreased in response to almost all
rainfall events. In the reforested catchment, streamflow and EC only changed in response to large events. In both catchments, streamflow was a mixture of groundwater and precipitation, but the fraction of precipitation was much smaller for the reforested catchment than for the degraded catchment. Minimum pre-event water contributions were much lower and decreased more rapidly with event size for the degraded grassland than for the reforested catchment. The results suggest that surface runoff is much more widespread in the degraded grassland than in the reforested catchment, and that reforestation can thus significantly improve infiltration, reduce surface runoff and improve streamflow regulation, provided the forest and soil are allowed to develop over a sufficiently long period without disturbance. The differences in the peak flow, centroid lag time and pre-event water contributions to streamflow were also observed during a very large tropical storm, suggesting that these large differences in runoff generation mechanisms between the two catchments also persist for the largest events.