# Establishment of experimental catchments to quantify water use by different vegetation types

## Estabelecimento de microbacias experimentais para quantificar uso de água por diferentes tipos de vegetação

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## Abstract

This paper describes the procedure developed to select representative experimental catchments to quantify water use and water use efficiency of different vegetation types. We combined freely available information such as LANDSAT satellite images, digital elevation model, Google Earth images, streamflow and rainfall historical data, and soils and vegetation data to select the experimental catchments. Once these catchments were indentified, sub-catchments with different vegetation were delineated, which were used to define the distribution and installation of the instrumentation. Forty eight catchments and respective sub-catchments of Tasmania in Australia were analysed and only two catchments were identified as ideal for the purposes of quantifying and comparing the historic and current water use by Eucalyptus plantation, native forest and pasture. We choose one catchment and created four experimental and instrumented sub-catchments with the following predominant land use: *Eucalyptus nitens*, native forest and pasture.

**Key words**: catchment; digital elevation model; LANDSAT images; Eucalyptus; water-use comparison and efficiency.

## Resumo

O presente artigo descreve o procedimento desenvolvido para selecionar microbacias representativas para quantificar o uso de água e a eficiência do

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uso de água de diferentes tipos de vegetação. Foram combinadas informações disponíveis sem custo tais como: imagens de satélite LANDSAT, modelo digital do terreno, imagens de Google Earth, escoamento superficial e dados históricos de precipitação pluviométrica, tipos de solos e cobertura vegetal para a seleção de microbacias experimentais. Uma vez identificadas as microbacias, sub-microbacias com diferente tipos de vegetação foram delineadas, as quais foram usadas para definir a distribuição e instalação de instrumentação. Foram analisadas quarenta e oito microbacias e respectivas sub-microbacias na Tasmânia na Austrália e somente duas microbacias foram identificadas como ideais para o propósito de quantificar e comparar o histórico e atual uso de água por plantações de eucalipto, florest nativa e pastagem. Ao final foi escolhida uma microbacia e quatro sub-microbacias experimentais intrumentadas com o uso de solo predominantemente de *Eucalyptus nitens*, floresta nativa e pastagem.

**Palavras-chave:** microbacia; modelo digital de terreno; imagens LANDSAT; Eucalyptus; comparação e eficiência do uso de água.

## Introduction

Catchment scale studies have been widely used to quantify the water use of different vegetation and the potential impact on water yield caused by changes on land use (BROWN et al., 2005). Bosch and Hewlett (1982) reviewed the results of catchments studies to quantify water use by vegetation. More recently forest and streamflow paired catchments studies have been reviewed and summarised by other authors in Hornbeck et al. (1993), Stednick (1996), Sahin and Hall (1996), Vertessy (2000) and Brown et al. (2005). The results of these studies show the importance of developing a well established process and criteria to select representative catchments in accordance with the aims of the water use study and proposed research questions. The most common theme of catchment studies is the analysis of the relationship between the water use of vegetation in a catchment, and the rainfall and streamflow data for the catchment, with particular focus on the water use of forest plantations (SAHIN; HALL, 1996; SCOTT; LESCH, 1997; ALMEIDA et al., 2007).

The total area of Australia's forest plantation estate is 2.02 million hectares. This area is comprised of about 0.99 million hectares (49 percent) of hardwood species, 1.02 million hectares (51 percent) of softwood species and a small area of other species. The total plantation area has increased by about 51 percent in the past ten years. A total of 49,658 hectares of new plantations were reported established in 2009. The new area comprised 43,231 hectares of hardwoods and 6,427 hectares of softwoods (GAVRAN; PARSONS, 2010). While it is now generally accepted that the conversion of pasture or crops to forest can result in reduced streamflow, there remain uncertainties as to the extent to which these changes are influencing water availability in particular catchments (POLGLASE; BENYON, 2009). In order to better understand the potential impact such plantations have on water resources, requires catchment experiments designed to not only quantify the water use, but also how the water is being converted into wood, carbon and other benefits of forests.

Establishing catchment experiments to better inform forest management requires a good understanding of the interactions between the soils, climate, topography, and vegetation (CALDER, 1996). Managing a forest plantation estate in relation to water outcomes requires knowledge of small and large catchment-scale processes, and the ability to understand and model the consequences of management actions (LØRUP et al., 1998; NANDAKUMAR; MEIN., 1997). Forestry organisations worldwide have recognised this need for many years and expressed a desire to manage for catchment-scale outcomes. However, little practical progress has been made. One limitation has been a lack of quantitative links between wood production, streamflow and water quality. It also has been unusual to establish catchment monitoring systems that are able to comprehensively respond to forest management demands at both sub-catchment and catchment wide areas at the same time.

This study started in 2008 with the objective of quantifying the water use efficiency of forest plantations in Tasmania, south-eastern Australia, compared with native forest and pasture, (the later of which is normally represented by dairy farms), and analyse the impacts of land use changes that have occurred in the last two decades. The project is testing catchment scale and aggregated stand scale models of plantation water use using streamflow data from gauged catchments in which there has been large scale plantation establishment. It is also developing and field-testing a model of plantation growth and water use linked to a hill slope scale model of distributed flow. Data produced in this experiment are being used to develop and test a model to estimate water balance for different vegetation and regions, taking into account the movement of the water in the landscape from hill slopes to the valleys. This model also will quantify how water availability impacts the vegetation growth.

This paper focuses on the process undertaken to select representative catchments and sub-catchments to achieve the project objectives using available information in Tasmania.

## Methodology

### Study area

The study area from which the experimental catchments were to be selected is the state of Tasmania, which has an area of 68,102 square kilometres (ABS, 2008) distributed in 48 main catchments with areas varying from 6 to approximately 6,000km$^2$. These catchments, established by the Tasmanian Department of Primary Industries, Parks, Water and Environment (DPIPWE), include one or more watercourses and have been defined at a suitable scale for resource management based on a combination of water flow, land tenure and land management (DPIPWE, 2010). Each catchment contains more than one sub-catchment.

### Data requirements to identify and select experimental catchment

One of the first tasks of the study was identifying the best options of select representative experimental catchments and respective sub-catchments to quantify water use by forest plantation, native forest and pasture. We collated the required information

**Table 1.** Information and data used to select experimental catchments in Tasmania

| Data | Source | Scale |
|---|---|---|
| Digital elevation model | DPIPWE | 25m |
| Forest plantation area | BRS, TASVEG2, LANDSAT image, Google Earth image | State wide, variable |
| Native forest area | TASVEG2, LANDSAT image, Google Earth image | State wide, variable |
| Pasture area | TASVEG2, LANDSAT image, Google Earth image | State wide, variable |
| Catchment boundary | DPIPWE | Variable |
| Climate | Bureau of Meteorology<br>Silo / Bureau of Meteorology | Rainfall stations distribution<br>Spatial interpolation (0.5°) |
| Soil type | DPIPWE | 1:100,000 |
| Existing streamflow data | DPIPWE | Point data every hour |
| Existing stream gauge location | DPIPWE | Point data |
| Hydrograph | DPIPWE | 1:100,000 |
| Forest inventory | Forest companies | Plot |

of Tasmania and freely available sources as indicated in table 1.

### Digital elevation model (DEM)

We used the state digital elevation model at 25 meters resolution developed by the DPIPWE (2009) to define the boundaries and quantify the areas of the sub-catchment in the regions of interest. The DEM was also used to analyse classes of altitude and forest species distribution in these different classes.

### Forest plantation

A shape file containing the current forest plantations in Tasmania produced by the Bureau of Rural Science (BRS, 2007) was used to identify the forest plantation distribution at catchment scale. This information was then converted to percentage of plantation in each catchment. The percentage of forest planted area was used as the criteria of selection, prioritizing catchments with more than 25% of forest plantations and with a history of land use change during the last 10 years, in order to detect the potential effects of the change of the vegetation on water resources. We also used the vegetation classification map available for Tasmania (DPIW, 2009) to identify different types of native forest and agriculture.

### Catchment boundaries

We used the available catchment boundaries spatial data produced by DPIPWE as starting point, and calculated the first level of sub-catchments using the DEM. These sub-catchments defined smaller, self contained areas that could have less interference for multiple activities.

### Current vegetation cover

As the study intends to compare the water use by plantation, native forest and agriculture, we identified and selected catchments and sub catchments each containing significant areas of these three types of vegetation.

### Land use change

Using historical LANDSAT images (available from USGS Global Visualisation viewer) (USGS, 2010) we classified the land use change from 1980 to 2009 to detect catchments with increasing plantation area (at least during the last ten years).

### Streamflow data

Tasmania has currently 40 active gauged catchments with historical streamflow data. The available daily streamflow data was analysed in all the potential experimental catchments to ensure the quality of the data was sufficient for modelling, and to avoid catchments with long periods of missing data.

### Climate data

Historical daily precipitation is available from the Bureau of Meteorology (2010) for most of the catchments in Tasmania. The Bureau of Meteorology and the Government of Queensland also provides surfaces of daily climate called SILO (http://www.bom.gov.au/silo/) which includes precipitation, minimum and maximum temperature, vapour pressure deficit, solar radiation and evapotranspiration. More details about the interpolation techniques are described in Jeffrey et al. (2001).

### Procedure to select experimental catchments

The following sequence of activities and data collate were adopted to select the most adequate catchment for the objectives of the project:

1- Obtain and calculate a catchment map boundary;

2- Use a forest plantation map to classify the total plantation area (giving priority to catchment with plantation area higher than 20% of the catchment);

3- Soil classification map; quantify the area and distribution of the most representative soils;

4- Historical land use change maps; identify the catchments that have undergone land use change (and, hopefully, a corresponding water use change) over the duration of the streamflow gauge data.

5- Identify the catchments with existing streamflow gauges and at least 20 years of historical daily streamflow data;

6- Delineate existing well defined areas of plantation, native forest and pasture;

7- Identify sub-catchments with a high predominance of plantation, native forest or pasture.

Figure 1 shows the soil type classification map, the distribution of forest plantation and the main catchment boundaries and the location of the active stream gauge operated by DPIPWE. The figure also shows a map with sub catchments in the areas with stream gauges, and the digital elevation map of Tasmania.

## Sub catchment delineation

After analysing the available catchments for ones that matched the modelling requirements, we developed a more detailed analysis establishing sub-catchment boundaries and land use in the potential candidates. A primary condition was that each sub-catchment should have at

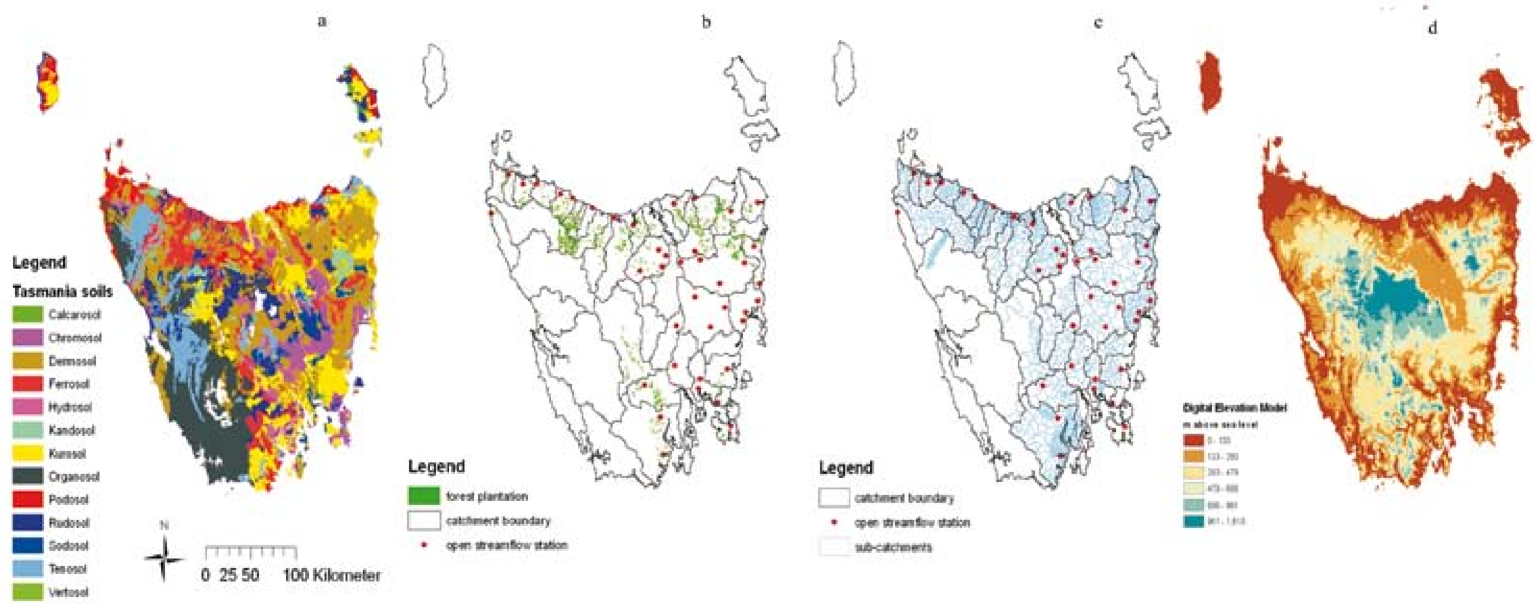


**Figure 1.** Examples of spatial available information used to select experimental catchments in Tasmania. (a) soils map; (b) main catchments in Tasmania, forest planted distribution and current streamflow gauged stations; (c) catchments and sub-catchments boundaries and respective streamflow gauged stations; (d) digital elevation model with classes of altitude.

least 85% of one specific land use of interest (forest plantation, pasture and native forest).

The ArcHydro tools (ESRI, 2009) were chose for sub catchment delimitation. ArcHydro is a set tools developed for the ArcGIS environment that can be downloaded from the ESRI website. The tools incorporate a comprehensive suite of hydrological algorithms, and can take the user through each process involved in the modelling, from pre-processing raw digital elevation models (DEMs) to make them suitable for hydrological modelling, to the subsequent mapping of stream networks and catchment (and sub-catchment) areas.

The DEM of the selected experimental catchment was filled to remove sinks (points on the DEM that are significantly lower than surrounding regions - typically due to artefacts introduced when constructing the DEM), then processed to produce slope, flow direction and flow accumulation layers. Batch points were identified on the DEM at the locations specified for the established streamflow gauges in the field, and then the contributing (upstream) area was calculated for each point. The regions produced by this process represent the number of DEM cells (or the total area) that contributes to the flow of water through that batch point (streamflow gauge).

### Use of images to define instrumentation location

The high resolution images available from Google Earth, along with stream gauge data locations, vegetation maps, and altitude maps, enabled the selection of initial instrumentation (soil moisture measurement tubes) positions, as well as refining these locations after visits to the field.

### Modelling

The selection of a representative catchment is a key element to calibrate and validate models to apply in other regions. We are developing a process-based model framework to estimate the water-use and water use efficiency of the three vegetation types using a hill slope approach, and quantifying the water movement and availability across the landscape. The results of the modelling are not shown in this paper. Development of models to predict the impacts of afforestation on water yield for larger catchments are often based on experimental results from smaller, steeper and more homogeneous catchments (VAN DIJK; KEENAN, 2007).

### Results and Discussion

Following the sequence of activities described in the methods section we classified the catchments according to the percentage of plantation as indicated in figure 2a. Only four catchments had more than 20% of plantation and had been measured the streamflow for more than 20 years. A more detailed analysis of land use change and the current land use followed by a field inspection showed that two catchments would cover the requirements of being well representative in terms of soil, climate and containing established sub-catchment with different land use. The selected catchments are called Flowerdale and Brid (Figure 2b). The precipitation distribution of the two catchments is very different. Flowerdale's average annual precipitation is 1500mm and Brid is 750mm, providing what would be an ideal comparison of the water-use efficiency in the two catchments. However due to

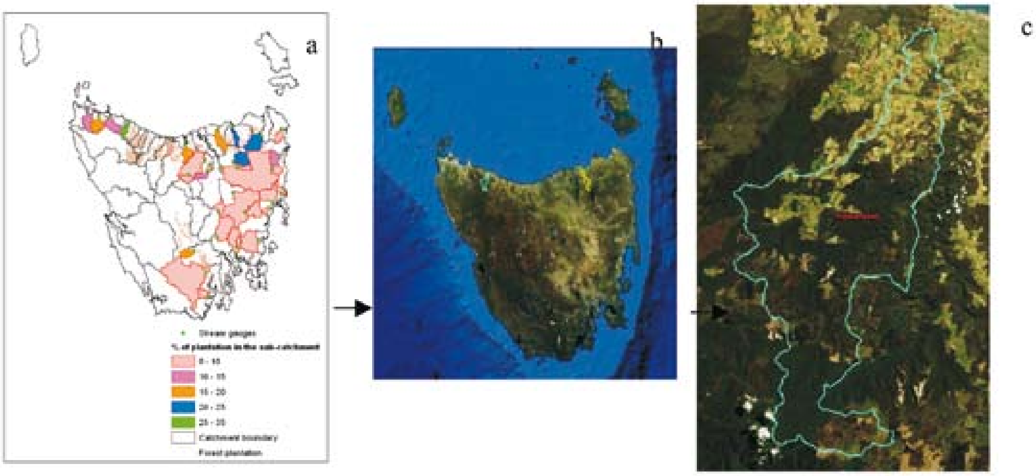


**Figure 2.** (a) Tasmanian catchments with long term streamflow measurements, different colours show percentage of the area of the catchment covered with forest plantations, (b) Two electable experimental catchments (Flowerdale(blue) and Brid (yellow)) and (c) detailed view of the Flowerdale catchment

budget limitations we decided to concentrate the analyses and instrumentation on the Flowerdale catchment in the first phase of the project (Figure 2c).

The Flowerdale catchment has 15,175 ha with 33% of the land occupied with forest plantations predominantly *Eucalyptus nitens*, 49 % is native forest and 18% is pasture and minor areas with annual crops. An important aspect of this catchment is the increasing area of plantations during the last twenty years. The classification of satellite images from 2000 and 2009 shows that most of the expansion of the plantations occurred in areas occupied previously with native forests.

Table 2 shows the land use change occurred during this period. The area of plantation increased by 30% and the area of native forest was reduced by 13% in relation to 2000. We considered that this level of change will be sufficient to quantify the effects of the change in the water availability.

Figures 3 (a) and (b) show the LANDSAT satellite images for 2000 and 2009 respectively of Flowerdale catchment where it is possible to see that most of the changes occurred in the southeast and central east and part of central west regions. Figure 3 (c) shows the difference of altitude across the catchment, with highest areas in the South and lowest areas

**Table 2.** Comparison of land use in the Flowerdale catchment from 2000 to 2009

| | **Year 2000** | | **Year 2009** | | **Difference (2009 - 2000)** | |
|---|---|---|---|---|---|---|
| Land use | Area (ha) | Use % | Area (ha) | Use % | Area (ha) | Change % |
| Agriculture | 2,747 | 18.1 | 2,725 | 18.0 | -22 | -0.8 |
| Native Forest | 8,571 | 56.5 | 7,436 | 49.0 | -1,135 | -13.2 |
| Forest plantation | 3,857 | 25.4 | 5,014 | 33.0 | 1,157 | 30.0 |
| Total | 15,175 | 100.0 | 15,175 | 100.0 | | |

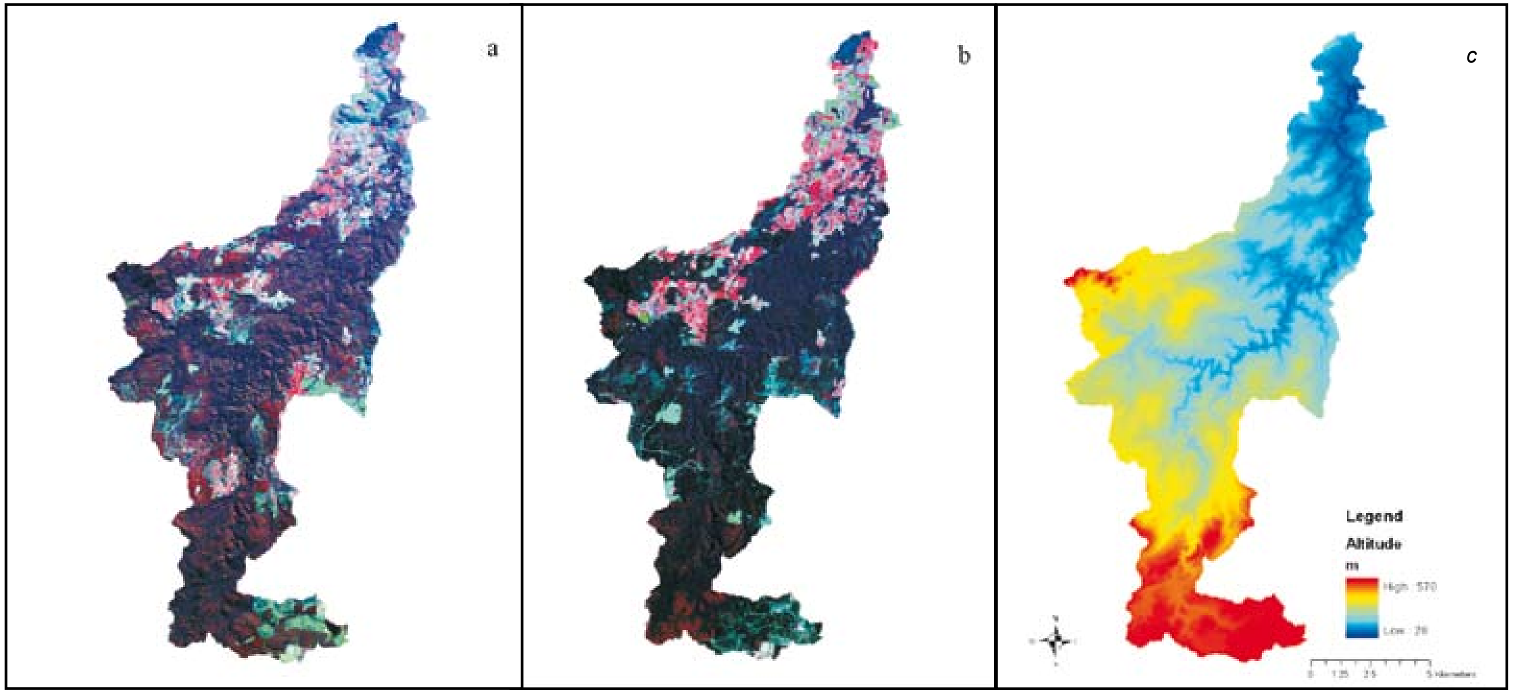


**Figure 3.** Flowerdale catchment: LANDSAT satellite image from (a) 2000, (b) 2009 and (c) altitude map

in the North of the catchment. The higher areas are also the wettest areas. Producing an accurate rainfall distribution across the catchment is essential for catchment studies and requires the collection of data in different parts of the catchment.

In order to estimate the water-use and water-use efficiency of different land use, four experimental sub-catchments, each with a different land use, have been established in the Flowerdale catchment (Table 3). The four sub catchments are occupied by *Eucalyptus nitens*, native forest and pasture and received instrumentation to measure precipitation, soil moisture at hill slope, streamflow, biomass production and leaf area index.

current ratio measured in the weir at the end of the Flowerdale catchment.

Figure 5a shows the annual rainfall and runoff occurred from 1968 to 2009 measured in the weir at the end of the Flowerdale catchment. A small trend of reduction in both, rainfall and runoff was observed (Fig 5.a) the values demonstrate a higher trend of reduction in runoff. A slightly higher trend occurred when the ratio of runoff and precipitation was plotted (Figure 5b). Potential causes of this decline such as climate, irrigation practice and vegetation changes have not yet been elucidated. An analysis at sub catchment scale shall provide a more detailed and comprehensive

**Table 3.** Selected sub-catchments land use, area, location and field measurements

| Sub-catchment name | Predominant land use | Area (ha) | Latitude streamflow | Longitude streamflow | Measurements in each sub-catchment |
|---|---|---|---|---|---|
| Euc1 | *Eucalyptus nitens* plantation | 421 | -41.167° | 145.55° | Rainfall, streamflow, soil moisture, vegetation growth, leaf area index |
| Euc2 | *Eucalyptus nitens* plantation | 220 | -41.071° | 145.57 | |
| Nat | Native forest | 179 | -41.045° | 145.48° | |
| Past | Pasture | 96 | -40.991° | 145.60° | |

Figure 4 shows the location of the sub catchment and land use in each one. The predominance of the specific vegetation is evident in each one of the sub catchment what guarantee comparison between different land use.

Streamflow, rainfall and soil moisture measurements are being undertaken in the four sub catchments to quantify the water use and calculate the water balance for each land use. The rainfall and streamflow measured in each sub catchment will produce a ratio of rainfall / streamflow. These ratios will be applied according with the land use in the entire catchment and compared with the quantification of effects of land use change on water yield.

## Final considerations

The methodology presented in this paper has been designed for the express purpose of determining the difference in water use of the dominant vegetation types within the Flowerdale catchment, and hence understand the underlying system affecting the water use of the catchment. To repeat this approach the catchments being studied need to have high quality, long term measurements of rainfall,

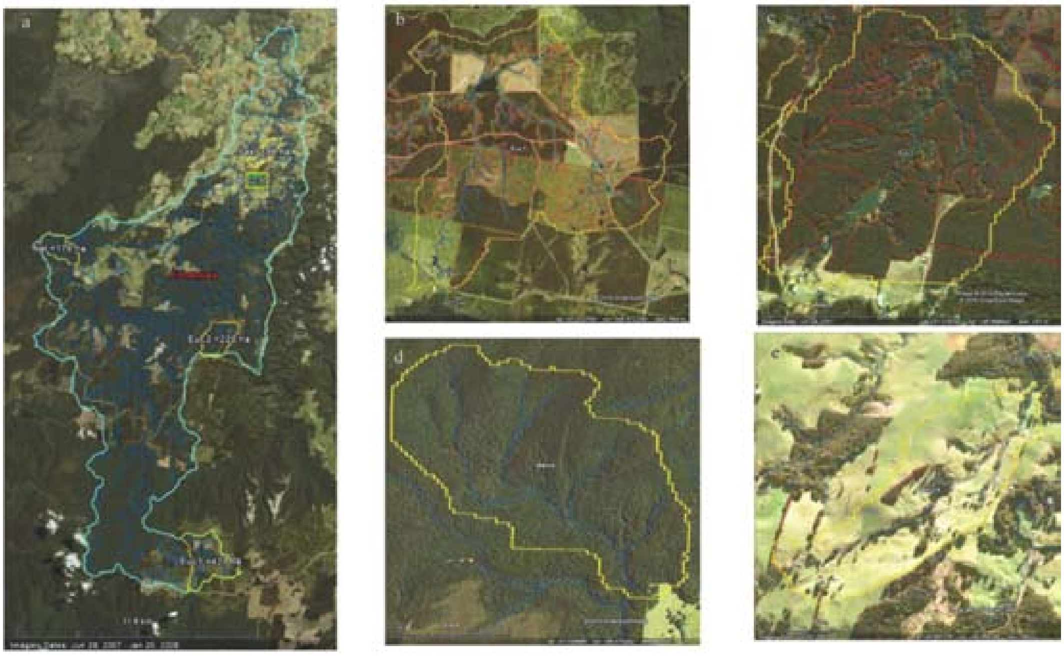

**Figure 4.** (a) Flowerdale catchment and the four selected sub-catchments and predominant vegetation (yellow lines), (b) Eucalyptus nitens, (c) Eucalyptus nitens(2), (d) native forest and (e) pasture

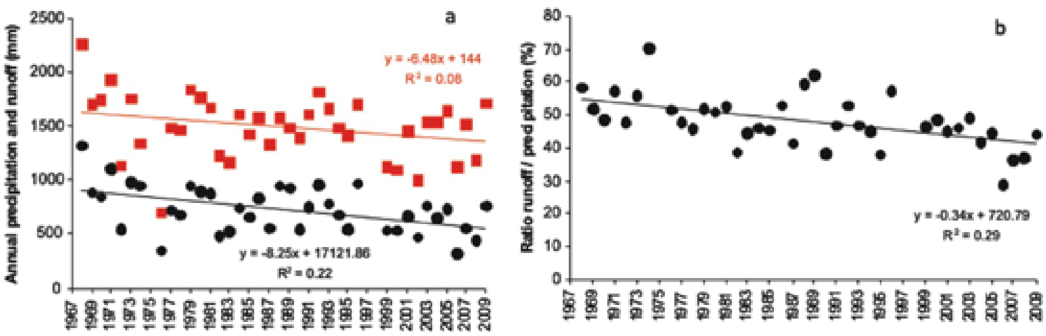


**Figure 5.** Flowerdale catchment (a) observed annual precipitation (red dots) and runoff (black dots) and (b) annual ratio of runoff / precipitation

and streamflow in order to a) establish the link between the amount of water being received by the catchment, and the amount of water leaving the catchment (at the sub-catchment scale) and b) account for any climatic (long term) variations that might otherwise influence the result. Once this difference can been reliably quantified, the factors affecting the loss of water into the streams can be assessed, and it is important to consider these factors at a sub-catchment scale. For the Tasmanian catchment of Flowerdale a wealth of readily attainable data assisted in the delineation of these sub-catchments, chief amongst these being a high quality, medium resolution (25m) digital elevation model. Where pre-existing catchment boundaries are not available, freely available tools such as ArcHydro

(ESRI, 2009) can be used to generate them from a DEM, as well as experimenting with the location of sub-catchments. Tools such as Google Earth are generally suitable for assessing field locations before visiting them in person, and the wealth of LANDSAT data freely available for most regions around the world means that the approaches adopted here should be able to be extended to any location where a DEM is available.

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