Vegetation impact on mean annual evapotranspiration at a global catchment scale

Murray C. Peel,[1] Thomas A. McMahon,[1] and Brian L. Finlayson[2]

Received 22 May 2009; revised 3 May 2010; accepted 11 May 2010; published 4 September 2010.

[1] Research into the role of catchment vegetation within the hydrologic cycle has a long history in the hydrologic literature. Relationships between vegetation type and catchment evapotranspiration and runoff were primarily assessed through paired catchment studies during the 20th century. Results from over 200 paired catchment studies from around the world have been reported in the literature. Two constraints on utilizing the results from paired catchment studies in the wider domain have been that the catchment areas studied are generally (1) small (<10 km^2) and (2) from a narrow range of climate types. The majority of reported paired catchment studies are located in the USA (~47%) and Australia (~27%) and experience mainly temperate (Köppen C) and cold (Köppen D) climate types. In this paper we assess the impact of vegetation type on mean annual evapotranspiration through a large, spatially, and climatically diverse data set of 699 catchments from around the world. These catchments are a subset of 861 unregulated catchments considered for the analysis. Spatially averaged precipitation and temperature data, in conjunction with runoff and land cover information, are analyzed to draw broad conclusions about the vegetation impact on mean annual evapotranspiration. In this analysis any vegetation impact signal is assessed through differences in long-term catchment average actual evapotranspiration, defined as precipitation minus runoff, between catchments grouped by vegetation type. This methodology differs from paired catchment studies where vegetation impact is assessed through streamflow responses to a controlled, within catchment, land cover change. The importance of taking the climate type experienced by the catchments into account when assessing the vegetation impact on evapotranspiration is demonstrated. Tropical and temperate forested catchments are found to have statistically significant higher median evapotranspiration, by about 170 mm and 130 mm, respectively, than non-forested catchments. Unexpectedly, cold forested catchments exhibit significantly lower median evapotranspiration, by about 90 mm, than non-forested catchments. No significant difference was found between median evapotranspiration of temperate evergreen and deciduous forested catchments though sample sizes were small. Temperate evergreen needleleaf forested catchments were found to have significantly higher median evapotranspiration than evergreen broadleaf forested catchments though sample sizes were small. The significant temperate forest versus non-forest difference in median evapotranspiration was found to persist for catchments with areas <1,000 km^2, but not for catchments with areas ≥1,000 km^2, which is consistent with the suggestion that the vegetation impact on evapotranspiration diminishes as catchment area increases. In summary, the results presented here are consistent with those drawn from reviews of paired catchment results. However, this paper demonstrates the value of a diverse hydroclimatic data set when assessing the vegetation impact on evapotranspiration as the magnitude of impact is observed to vary across climate types.

Citation: Peel, M. C., T. A. McMahon, and B. L. Finlayson (2010), Vegetation impact on mean annual evapotranspiration at a global catchment scale, *Water Resour. Res.*, *46*, W09508, doi:10.1029/2009WR008233.

1. Introduction

[2] Research into the role of catchment vegetation within the hydrologic cycle has a history stretching back at least to the first century AD with the observations of Pliny the Elder [*Andréassian*, 2004]. Relationships between vegetation type and catchment evapotranspiration and runoff were primarily assessed through paired catchment studies during the 20th century. Beginning with experiments at Wagon Wheel Gap, Colorado between 1910 and 1926, results have been reported

[1]Department of Civil and Environmental Engineering, University of Melbourne, Melbourne, Victoria, Australia.

[2]Department of Resource Management and Geography, University of Melbourne, Melbourne, Victoria, Australia.

0043-1397/10/2009WR008233

from over 200 paired catchment studies from around the world [e.g., *Bosch and Hewlett*, 1982; *Sahin and Hall*, 1996; *Andréassian*, 2004; *Farley et al.*, 2005; *Brown et al.*, 2005]. Single catchment studies, where the impact of vegetation changes on evapotranspiration and runoff are assessed, have also provided insight [e.g., *Siriwardena et al.*, 2006; *Silveira and Alonso*, 2009]. Generally paired catchment and single catchment studies fall within four broad categories of controlled experiment or observation: (1) afforestation (conversion of short vegetation to forest); (2) deforestation (conversion of forest to short vegetation); (3) regrowth (forest removal and regrowth); and (4) forest conversion (replacement of one forest type with another) [*Brown et al.*, 2005].

[3] By design, paired catchment experiments minimize two key confounding influences experienced by single catchment studies, (1) climate variability and (2) inter-basin variability [*Andréassian*, 2004]. However, two constraints on generalizing paired catchment results to a wider domain have been that the catchment areas studied are generally (1) small (<10 km^2) and (2) from a narrow range of climate types. Reviews of paired catchment studies do not always describe the climate type experienced at each site (see *Brown et al.* [2005] for an exception). The majority of reported paired catchment studies are located in the USA (~47%) and Australia (~27%) [see *Bosch and Hewlett*, 1982; *Andréassian*, 2004; *Brown et al.*, 2005]. In the USA, the climate types represented in these studies are mainly temperate (Köppen C) and cold (Köppen D), whereas in Australia the vast majority of studies are in temperate regions. An updated Köppen-Geiger climate map, presented by *Peel et al.* [2007], shows that, globally, temperate and cold climate types represent 13.4% and 24.6% of the Earth's land surface, respectively.

[4] Recently, *Oudin et al.* [2008] approached the issue of identifying the vegetation impact on catchment water balance from an alternative perspective. Rather than using information from paired catchment or single catchments studies, where controlled or uncontrolled vegetation change is known to have occurred, they used 1508 catchments from France, Sweden, the United Kingdom and the United States to assess whether the addition of land cover information significantly improved estimates of mean annual water balance using simple water balance formulas. They found that the addition of land cover information did make a small, but significant, contribution to improving the efficiency of those formulations, particularly for catchment areas less than 1000 km^2. In their study the range of catchment areas is larger than in paired catchment studies, while the range of climate types experienced was again mainly limited to temperate and cold regions.

[5] The results of *Oudin et al.* [2008] largely confirm the expected influence of vegetation on catchment water balance suggested by *Donohue et al.* [2007] in their overview of the potential role of vegetation within the Budyko curve model. *Donohue et al.* [2007] noted that at large spatial scales ($\gg$1,000 km^2) climatic variables, rather than vegetation, are the primary drivers of long-term catchment water balance. However, they suggest that incorporating vegetation into the Budyko model may improve its predictive ability for smaller spatial and temporal scales. They also note that previous studies aiming to explain deviations from the Budyko curve model often employ an extra parameter possibly related to vegetation (for example, the *w* parameter of *Zhang et al.* [2001, 2004].

[6] Here we present a global analysis of the impact of vegetation type on catchment water balance, represented by mean annual evapotranspiration, using a significantly improved version of the global data set of *Peel et al.* [2001, 2004] and *McMahon et al.* [2007]. Like *Oudin et al.* [2008], this analysis utilizes a large data set of catchment land cover information rather than known land cover changes within a catchment to draw broad conclusions about the vegetation impact on catchment water balance. Although based on fewer catchments than in the work by *Oudin et al.* [2008], the distribution of catchments used in this study is significantly broader in terms of location, size and climate type. Catchment average values of mean annual precipitation, temperature and potential evapotranspiration are estimated for 861 catchments around the world, along with estimates of percentage catchment area covered by different vegetation types and climate types.

[7] Analysis of this large global data set of hydroclimatically diverse catchments permits the following questions to be addressed.

[8] 1. Is climate type important when assessing the vegetation impact on mean annual evapotranspiration?

[9] 2. Are differences in evapotranspiration between forested and non-forested catchments observed globally?

[10] 3. Are differences in evapotranspiration between evergreen and deciduous forested catchments observed globally?

[11] 4. Are differences in evapotranspiration between evergreen broadleaf and evergreen needleleaf forested catchments observed globally?

[12] 5. If differences in evapotranspiration due to vegetation type are observed are they related to catchment area?

[13] The outcome of the first question partially determines the methodology adopted for answering the subsequent questions. If climate type is important then the catchments will be stratified by climate type prior to further analysis. If climate type is not important then the catchments may be analyzed as a single group, which would be consistent with previous investigations into the impact of vegetation on catchment water balance [e.g., *Bosch and Hewlett*, 1982; *Sahin and Hall*, 1996; *Andréassian*, 2004; *Farley et al.*, 2005; *Brown et al.*, 2005; *Zhang et al.*, 2001, 2004]. Although paired catchment studies by design minimize climate variability between each pair, they do not minimize climate variability between groups of paired catchments. However, since the vast majority of reported paired catchment studies are located within temperate and cold climate types, as noted previously, this potentially confounding influence may have had minimal impact on the conclusions drawn from those earlier investigations.

[14] Following this introduction we describe in section 2 the data set used in this analysis, highlighting several key additions since *Peel et al.* [2001, 2004] and *McMahon et al.* [2007]. In section 3 each of the five research questions above are assessed and the results discussed to identify any impact of vegetation type on catchment mean annual evapotranspiration. The main conclusions of this analysis are presented in section 4.

2. Data

[15] Data for 861 catchments were available for analysis and their locations are shown in Figure 1. These catchments,

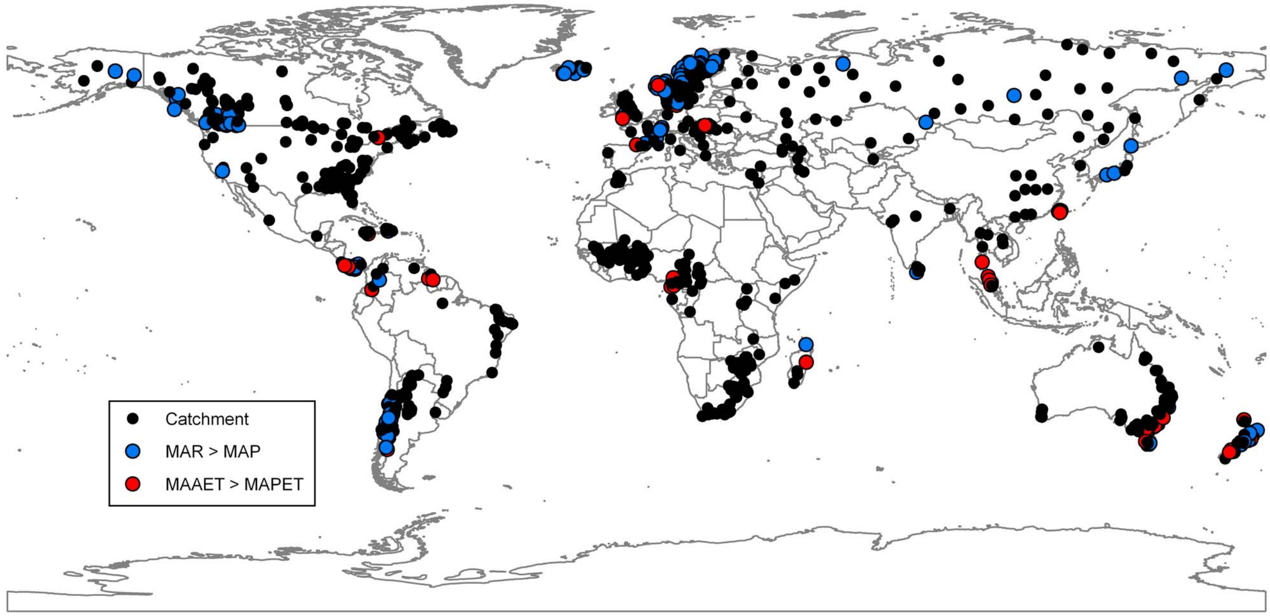


Figure 1. Location of all catchments including catchments where the water balance appears implausible (mean annual runoff > mean annual precipitation; MAR > MAP or mean annual actual evapotranspiration > mean annual potential evapotranspiration; MAAET > MAPET). MAAET is calculated as MAP – MAR.

a sub-set of the data set described by *McMahon et al.* [2007], are reasonably well distributed globally although some regions have little or no data, e.g., arid regions of Mediterranean north Africa, the Middle East, southwestern Africa, central Australia and tropical regions of central America, non-coastal Brazil, Peru, Bolivia and Ecuador.

[16] The analyses described in this paper require long-term areal catchment average estimates of annual precipitation, temperature, potential evapotranspiration, and runoff, the monthly distribution of average daily temperature range as well as the catchment vegetation type and climate type. All of these values are made available in the auxiliary material.[1] To determine areal catchment average data, it was necessary to delineate catchment boundaries for each catchment. The following sub-sections outline the data in detail and how they were obtained.

2.1. Delineation of Catchment Boundaries

[17] The HYDRO1k digital elevation model (DEM) of the world was used to delineate the catchment boundaries of all catchments, except those in Australia. HYDRO1k has a resolution of 1 km × 1 km and is derived from the USGS GTOP030 DEM (see http://edcdaac.usgs.gov/gtopo30/hydro/ for details of GTOP030 and HYDRO1k). The DEM used to delineate Australian catchment boundaries was the GEODATA 9 s DEM version 2.1 [*Hutchinson*, 2002], which has a resolution of approximately 250 m × 250 m. Only catchments with a DEM based boundary area within 5% of the published catchment area were used in this paper.

2.2. Streamflow Data

[18] This study is based on 861 monthly streamflow records that are a sub-set of the global data set recently described by *McMahon et al.* [2007]. First collated in the 1980s, with subsequent revisions and additions over time [see *McMahon et al.*, 1992; *Peel et al.*, 2001, 2004], this data has been checked and corrected where possible for obvious errors like transcription errors, errors relating to catchment area and location. Data impacted by known major water withdrawals or known upstream reservoirs have been removed. Measurement errors relating to rating curves have not been addressed. The annual streamflow data are based on water years (defined as beginning at the month with the lowest average monthly streamflow) and are expressed as depth per unit area (mm) and denoted as runoff. The range of streamflow record length is from 10 to 172 years with a median of 32 years predominately measured over the period 1950 to 1985. Comparison of a summary statistic (eg: mean) estimated from a range of sample sizes is not ideal, due to the inconsistent standard error of the sampling distribution between each case. However, in this analysis restriction of the data to a common period (temporal sample size) would significantly reduce the number of catchments available for analysis. Therefore, all available data at each catchment have been used in this analysis, which needs to be kept in mind when interpreting later catchment based summary statistic results. The data set represents a wide range of catchment areas, from 3.6 to 4,640,300 km^2 with a median value of 1,620 km^2.

2.3. Observed Precipitation and Temperature Data

[19] The areal catchment average precipitation and temperature data used in this study are estimated directly from observed station records, rather than through gridded products (see *Fekete et al.* [2004] for a discussion of the impact of uncertainties in gridded precipitation products on runoff estimates). The choice of station, as opposed to gridded, based estimates of areal precipitation and temperature is guided by the following criteria: (1) consistent approach

[1] Auxiliary materials are available in the HTML. doi:10.1029/2009WR008233.

across all catchments; (2) methodology can be supported by the available data; and (3) provides a local assessment of the quality of the areal estimate.

[20] Station based and gridded products can both satisfy the first criteria. However, the extent to which gridded products satisfy the second and third criteria, across all catchments, is often difficult to assess. Information about the spatial and temporal consistency of the input data to the gridding process is generally only available at the global, rather than local, level. Thus, for each catchment, the appropriateness of a gridded product (e.g., the number of observations in or nearby a catchment, the period of record observed or infilled, etc…) is generally unknown. As the spatial density and temporal consistency of precipitation and temperature stations around the world is highly variable, a simple 2D Thiessen polygon [*Thiessen*, 1911] areal estimate of precipitation and temperature was adopted. Although the Thiessen polygon method may not provide the optimal areal estimate in more data rich environments, it is able to satisfy all three criteria at all catchments around the world. For example, in station rich locations a 3D estimate, which includes elevation, could be supported by the data. However, in order to be consistent across all catchments, the simpler 2D Thiessen polygon approach is adopted. A consequence of this decision is that the areal precipitation and temperature estimates are blind to orographic influences not represented in the station records.

[21] Long-term station records of monthly precipitation and monthly temperature were obtained from the Global Historical Climatology Network (GHCN) version 2.0 data set [*Peterson and Vose*, 1997]. The steps followed to determine the areal catchment average precipitation and temperature for each catchment were as follows. (1) Identify stations located within or just outside the catchment boundary. Since the monthly correlation distance between precipitation stations is generally shorter than between temperature stations, precipitation stations within 200 km and temperature stations within 500 km of the catchment boundary were selected for further analysis. (2) Select stations from step 1 with data for ≥50% of the period of streamflow record. (3) Calculate Thiessen polygon weights for each station from step 2. (4) Infill any missing monthly precipitation and temperature data over the period of streamflow record for stations with nonzero Thiessen weights from step 3. Infilling was achieved by linear regression against a nearby station with the highest monthly correlation, based on ≥5 years of concurrent monthly data. For precipitation, stations within 300 km were candidates for regression, and for temperature, stations within 500 km were candidates. Keep infilling each station as required with progressively lower correlation stations until complete or the next best correlation falls below 0.5 for precipitation or 0.7 for temperature. The lower correlation limit for precipitation than temperature is indicative of the generally lower monthly correlation observed between precipitation records than between temperature records. If data are still missing then inspect the available data and select from the following options the one most acceptable; (a) trim the observed streamflow period of record to match the available precipitation and temperature, (b) reallocate small Thiessen weights for stations with missing data to a nearby station without missing data, (c) expand the range of nearby stations for an acceptable correlation or, if these three methods are not successful, (d) infill with the monthly average value. Finally, (5) calculate the areal catchment average precipitation and temperature time series by summing the product of the station time series and their Thiessen weight.

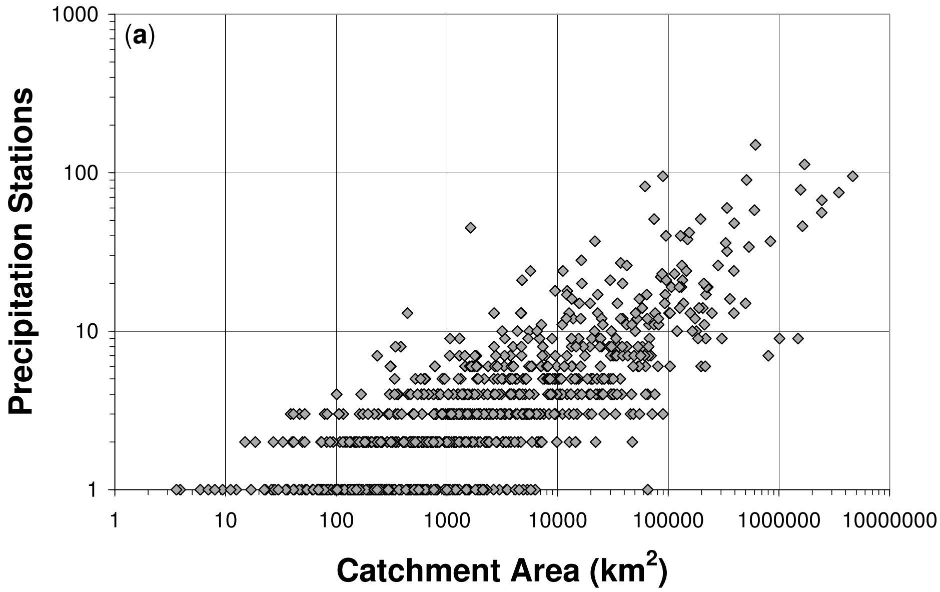
[22] A total of 3,342 separate precipitation and 1,739 separate temperature stations were used to estimate areal catchment average precipitation and temperature for the 861 catchments. The number of precipitation and temperature stations used in each catchment increases with catchment area as expected (see Figure 2). Catchment average values are based on a single precipitation station for 24% of catchments and a single temperature station for 39% of catchments. Generally, the number of precipitation and temperature stations available for use in a catchment is lower in less densely populated areas like the high latitude regions of Alaska, Canada and Russia.

[23] Figure 3 shows the percentage of catchments where the proportion of catchment Thiessen weight (maximum of 1) based on observed (not infilled) precipitation or temperature is equal to or exceeds a given proportion. The proportion of a catchment's Thiessen weight due to observed data was calculated by summing, across all Thiessen weight stations for that catchment, the product of each station's Thiessen weight and the proportion of the precipitation or temperate record that is observed (not infilled). For precipitation, just over 60% of catchments had 0.9 (90%) of their Thiessen weight based on observed data, whereas for temperature just over 45% of catchments satisfied this condition. Temperature data required more infilling than precipitation data, with the average proportion of Thiessen weight based on observed data being 0.89 for precipitation and 0.85 for temperature. The quality of the precipitation correlation against a nearby station was recorded as "high" (0.8–1.0), "medium" (0.7–0.8) or "low" (0.5–0.7). High quality precipitation infilling was used at 577 catchments, with an average proportion of Thiessen weight infilled of 0.064, while 360 catchments had medium quality infilling (average proportion of 0.027) and 263 catchments had low quality infilling (average proportion of 0.014). Only 122 catchments required infilling based on the monthly average precipitation of a station and the average proportion infilled was 0.0006 (0.06%). In the case of temperature the quality of the correlation against a nearby station was recorded as "high" (0.9–1.0), "medium" (0.8–0.9) or "low" (0.7–0.8). High quality temperature infilling was used at 692 catchments, with an average proportion of Thiessen weight infilled of 0.127, while 89 catchments had medium quality infilling (average proportion of 0.008) and 74 catchments had low quality infilling (average proportion of 0.012). Only 82 catchments required infilling based on the monthly average temperature of a station and the average proportion infilled was 0.024 (2.4%).

[24] Once the catchment average monthly precipitation and temperature time series were constructed, the annual precipitation and temperature values for a catchment were estimated using the same water year definition as the streamflow data.

2.4. Estimating Catchment Average Potential Evapotranspiration

[25] The catchment average annual potential evapotranspiration (*PET*) used in this analysis is a reference crop



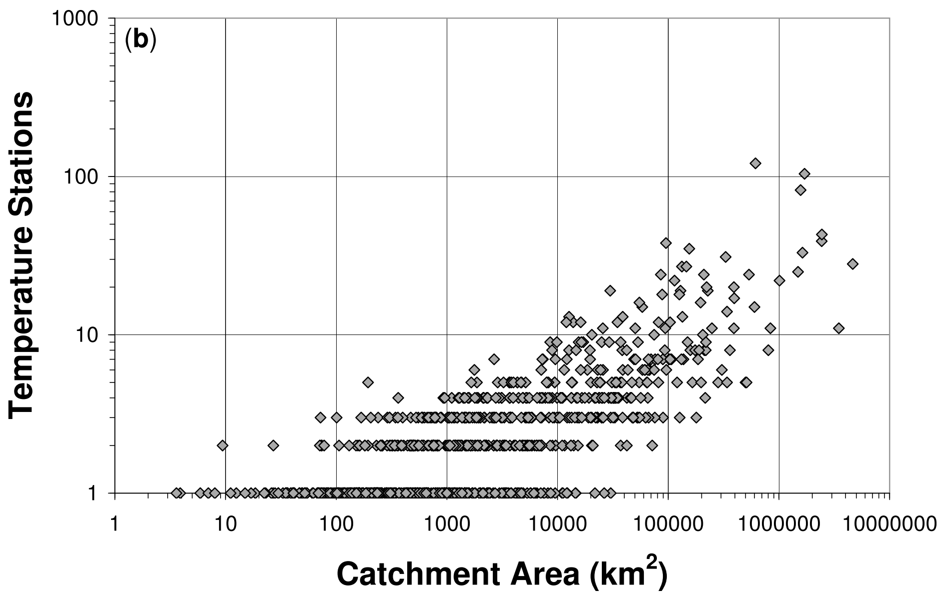


Figure 2. Number of (a) precipitation and (b) temperature stations used in each areal catchment average data calculation by catchment area.

estimate based on the modified Hargreaves method of *Droogers and Allen* [2002], which was adapted by *Adam et al.* [2006] and described in equation (1):

$$PET_j = 0.0013 S_0 (T_j + 17.0)(TD_j - 0.0123 P_j)^{0.76} \tag{1}$$

where, for each month j, PET_j is the estimated potential evapotranspiration, T_j is the monthly temperature (°C), TD_j is the difference between mean daily maximum and mean daily minimum (°C), P_j is the monthly precipitation (mm), and S_0 is the mean water equivalent for extraterrestrial solar radiation (mm per day). In equation (1) values of T_j and P_j are based on the observed catchment monthly temperature and precipitation described in the previous section, while TD_j values are based on catchment averages from the CRU (10 min × 10 min) gridded mean monthly diurnal temperature range product of *New et al.* [2002]. In equation (1) the P_j is used as a surrogate for relative humidity [*Droogers and Allen*, 2002]. *Adam et al.* [2006] adapted the method of estimating mean water equivalent for extraterrestrial solar radiation (S_0), which they estimated by

$$S_0 = 15.392 d_r (\omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s) \tag{2}$$

where ϕ is the latitude of the streamflow gauging station in radians, d_r is the relative distance between the earth and the sun, given by

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \tag{3}$$

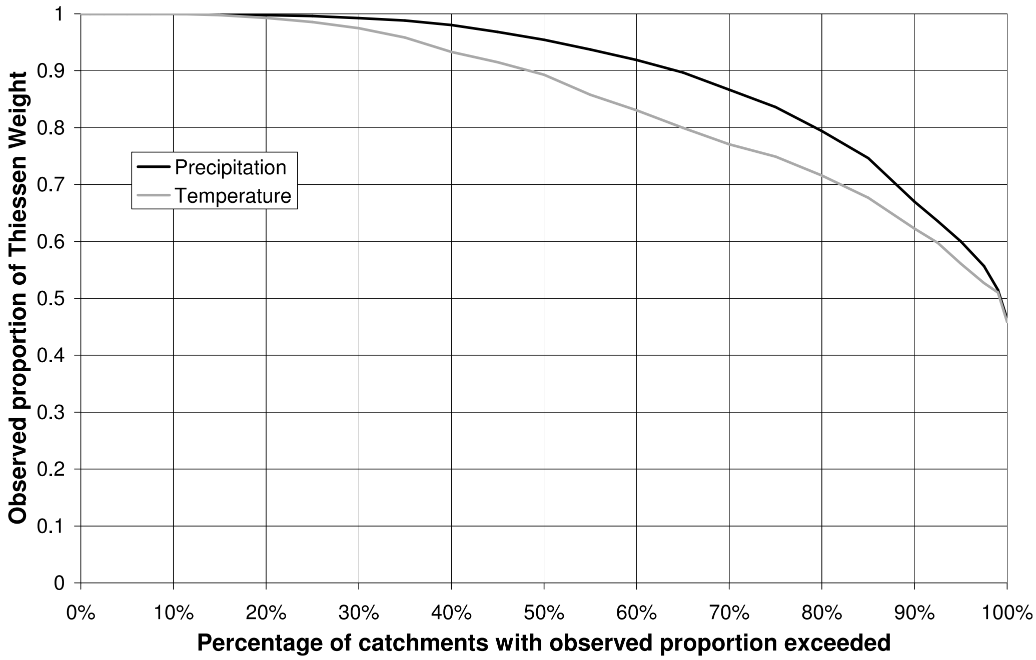


Figure 3. Percentage of catchments where the proportion of catchment Thiessen weight based on observed (not infilled) precipitation or temperature is exceeded or equal to a given proportion.

where J is the Julian day number. ω_s is the sunset hour angle in radians (see *Adam et al.* [2006] for boundary conditions), given by

$$\omega_s = \arccos(-\tan\phi\tan\delta) \tag{4}$$

and δ is the solar declination in radians, given by

$$\delta = 0.4093\sin\left(\frac{2\pi}{365}J - 1.405\right) \tag{5}$$

Once estimated, S_0 was multiplied by the number of days in the month to obtain a monthly value.

[26] For each catchment the annual PET was estimated as the sum of the monthly values of PET_j, based on monthly precipitation, temperature and associated average monthly diurnal temperature range and S_0.

2.5. Assessment of Catchment Water Balance

[27] Prior to addressing the research questions stated in the Introduction, the hydrologic plausibility of the water balance at each catchment is assessed. Following *Le Moine et al.* [2007], we represent each catchment in a non-dimensional plot (Figure 4) of aridity (mean annual potential evapotranspiration/precipitation) against runoff ratio (mean annual runoff/precipitation). Catchments were runoff ratio is > 1.0 indicate that the mean annual runoff is greater than the mean annual precipitation received by this catchment. Over the long-term, where changes in catchment storage are assumed to be zero, this is a physically implausible situation if the catchment is a closed system. Likely reasons for this situation being observed are: (1) underestimation bias / error in the catchment average precipitation estimate; (2) unknown error in the runoff observations; (3) unknown anthropogenic inter-basin transfer into the catchment; or (4) unknown subsurface inter-basin transfer (not a naturally closed system) into the catchment. Of these four possible reasons, the most likely is the first. Two major biases commonly associated with catchment average precipitation estimates are underestimation in high relief catchments and underestimation in regions that experience snow. First, stations within or near a catchment are frequently located in the lower parts of the catchment and, therefore, any orographic effects on precipitation are poorly represented in the observed data [*Milly and Dunne*, 2002]. Second, snow depth precipitation gauges often underestimate actual precipitation depth because of wind-induced undercatch [*Milly and Dunne*, 2002; *Adam and Lettenmaier*, 2003]. In Figure 1, the location of 114 catchments where the runoff ratio is >1.0 (labeled as R > P) are shown. Many of these catchments are in locations where they are likely to have underestimates of catchment average precipitation due to significant orographic effects and or wind-induced undercatch of snow.

[28] The second group of implausible water balance catchments shown in Figure 4 are those where the catchment average actual evapotranspiration (mean annual precipitation minus runoff) > potential evapotranspiration. Again, over the long-term this is a physically implausible situation if the catchment is a closed system. Likely reasons for this situation being observed are: (1) overestimation bias / error in the catchment average precipitation estimate; (2) unknown error in the runoff observations; (3) unknown anthropogenic inter-basin transfer from the catchment; or (4) unknown subsurface inter-basin transfer (not a naturally closed system) from the catchment. Inspection of the spatial distribution of the 48 catchments where actual evapotranspiration is greater than potential evapotranspiration shown in Figure 1 (ET > PET) does not reveal a consistent pattern, thus of the four likely reasons suggested we are unable to conclude which is the most likely overall.

[29] The third group of 699 catchments shown in Figure 4 are those where the mean annual runoff ratio is <1.0 and

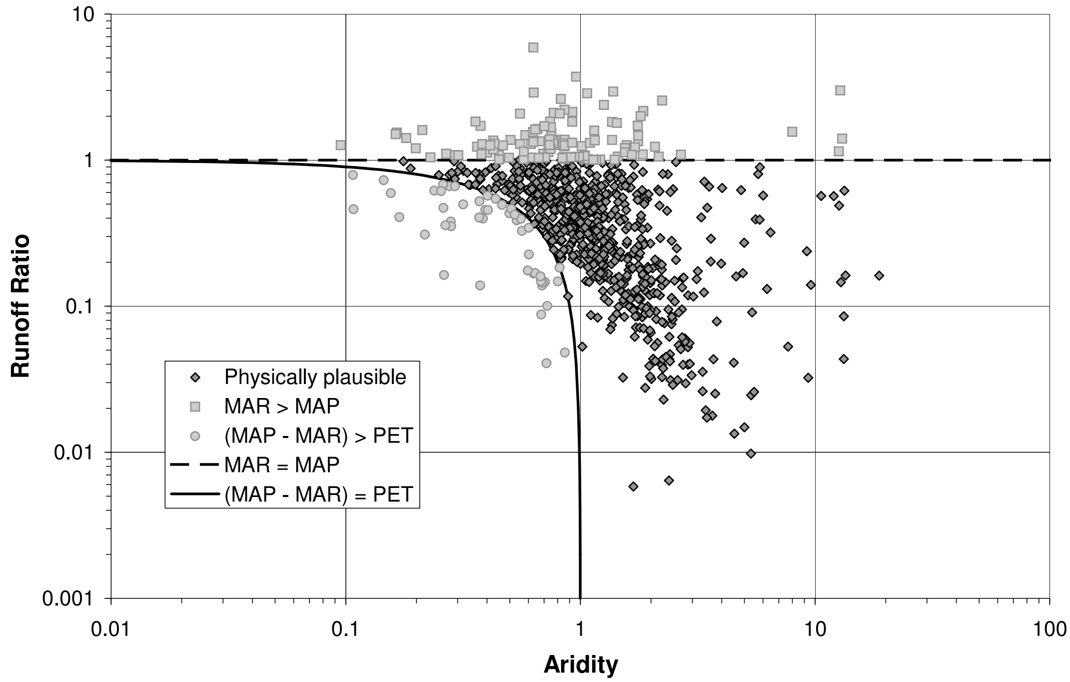


Figure 4. Catchment mean annual runoff ratio (MAR/MAP) versus aridity index (PET/MAP) for 861 catchments.

ET < PET. These catchments are labeled as physically plausible in Figure 4, since they are not clearly implausible. However, as seen in Figure 4 some of these catchments are close to the limits of plausibility. This point needs to be kept in mind in the later analyses.

[30] Although it may be possible to correct some catchment average values for the first two groups of catchments discussed in Figure 4, this has not been pursued in this study. Catchments where corrections could be applied, due to data error or anthropogenic inter-basin transfers, would need to be separated from those where the seemingly implausible water balance is a natural occurrence (not a naturally closed system). In order to identify appropriate catchments for correction, a detailed study of each catchment's water balance would be required, which is beyond the scope of this study. Therefore, these 162 catchments have been removed from further analysis, leaving the 699 physically plausible catchments for further analysis.

[31] A summary of the hydrologic characteristics of the 699 catchments at the annual time step is presented in Table 1. Compared with other studies examining the role of vegetation on catchment water balance [*Bosch and Hewlett*, 1982; *Holmes and Sinclair*, 1986; *Turner*, 1991; *Hornbeck et al.*, 1993; *Sahin and Hall*, 1996; *Zhang et al.*, 2001, 2004; *Andréassian*, 2004; *Farley et al.*, 2005; *Oudin et al.*, 2008], the number of catchments is larger (except in the work by *Oudin et al.* [2008]) and the range of hydrologic conditions represented in this data set is wider. However, this data set differs from most of the prior studies in that it is not based on paired-catchment experiments.

2.6. Determination of Catchment Vegetation Type

[32] The proportion of each catchment covered by 23 different vegetation types was determined using the Global Land Cover 2000 (GLC2000) data set [*Fritz et al.*, 2003], derived from 1 km SPOT VEGETATION satellite data for the year 2000. Several satellite based high resolution global land cover data sets are freely available. *McCallum et al.* [2006] noted that due to differences in for example sensor type, period of data collection, method of construction and number of classes, comparison of these different data sets is difficult. Here we used the GLC2000 data set because of its higher number of land cover classes. In a validation of GLC2000 against Landsat data, *Mayaux et al.* [2006] found that the GLC2000 had an overall accuracy of 68.6 ± 5% (95% confidence interval).

[33] As a further check we compared the satellite based GLC2000 vegetation type against the map of *Matthews* [1983], which is based on approximately 100 published sources. In 96 Australian catchments and one Israeli catchment GLC2000 regions indicated as "Tree cover, broadleaved, deciduous open" were changed to "Tree cover, broadleaved, evergreen" based on the work of *Matthews*

Table 1. Hydrologic Characteristics of the 699 Catchments

	Mean	Standard Deviation	Maximum	Minimum
Catchment area (km^2)	56,500	292,000	4,640,000	3.9
N (years)	36.0	17.7	172	10
Observed mean annual precipitation (mm)	930	464	3566	71.9
Observed mean annual temperature (°C)	13.2	8.7	28.9	−17.0
Mean annual potential evapotranspiration (mm)	1123	450	2244	243
Mean annual runoff (mm)	395	389	3126	3.4
Runoff coefficient	0.397	0.260	0.992	0.0058

Table 2. Average Proportion of Catchment Area Covered by Vegetation Types Across All 699 Catchments

	GLC2000 Code	Percent Area
Forest	1–10	50.4
Non-forest vegetation	11–18	46.1
Non-vegetation	19–23	3.5
Evergreen forest	1, 4	29.3
Deciduous forest	2, 3, 5	12.7
Mixed forest	6	6.8
Other forest[a]	7–10	1.7
Evergreen broad-leaf forest	1	17.2
Evergreen needleleaf forest	4	12.1
Deciduous broad-leaf forest	2, 3	11.4
Deciduous needleleaf forest	5	1.3
Evergreen vegetation	1, 4, 11	30.7
Deciduous vegetation	2, 3, 5, 12	23.6
Grassland/pasture[b]	13	6.0

[a]Not specified as evergreen, deciduous or mixed (tree cover that is regularly flooded, burnt or other).
[b]Defined as open or closed herbaceous cover.

[1983]. While in 2 catchments in Morocco the GLC2000 regions indicated as "Tree cover, broadleaved, deciduous closed" were changed to "Tree cover, broadleaved, evergreen." The distribution of vegetation type by average proportion of catchment area covered, across all catchments, is presented in Table 2 for the 699 catchments. It shows that, on average, across all of the catchments over half the catchment area is forested with a further 46% being non-forest vegetation consisting of herbaceous and shrub cover and cultivated and managed areas. Of the forest cover, 58% is evergreen, 25% is deciduous, 14% is mixed and 3% is unspecified.

[34] It should be noted that neither the satellite based GLC2000 nor *Matthews* [1983] take into account changes in vegetation type or extent over time. Therefore, the vegetation type and extent adopted for each catchment here is assumed to have applied in the catchment during the period of streamflow record. For many catchments this assumption is unlikely to be true, due to land-use changes over time. However, obtaining a time series of vegetation type and extent, during the period of streamflow record, for each catchment is beyond the scope of this analysis.

2.7. Determination of Catchment Climate Type

[35] The proportion of each catchment covered by a given Köppen-Geiger climate type was determined using the recently updated Köppen-Geiger climate map of the world [*Peel et al.*, 2007], which was developed using a 2D interpolation of GHCN version 2 [*Peterson and Vose*, 1997] station based precipitation and temperature data. The distribution of climate type by average proportion of catchment area covered, across all catchments, is presented in Table 3 for the 699 catchments. The dominant climate types represented are Temperate (C) and Cold (D) with 44.2% and 30.8% of the catchment area respectively, followed by Tropical (A, 15.3%), Arid (B, 9.1%) and Polar (E, 0.7%). At the individual climate type level the dominant climate types are Cfb (18.9%), Dfb (16.3%), Aw (12.6%) and Dfc (10.2%). Overall, there are only small proportions of catchment area covered by wet tropical, arid or polar climate types.

3. Results and Discussion

3.1. Is Climate Type Important When Assessing the Vegetation Impact on Mean Annual Evapotranspiration?

[36] The global catchments which are used in this investigation examining the role of vegetation on catchment evapotranspiration occur over a wide range of climate types (see Table 3). Climate is a key driver of catchment evapotranspiration around the world through variations in water and energy availability. To assess whether stratification of the catchments by broad Köppen climate type may be important for subsequent analyses we plotted the mean annual precipitation versus the mean annual actual evapotranspiration (MAAET, defined as mean annual precipitation minus mean annual runoff) and stratified the catchments by broad Köppen climate type (1st letter, $\geq$ 75% area of catchment) in Figure 5. Figure 5 clearly shows the interaction between climate and mean annual actual evapotranspiration and how the Köppen climate classification broadly encapsulates this interaction. In arid (Köppen B climates) water is limited and catchment mean annual actual evapotranspiration increases linearly with increasing water availability

Table 3. Average Proportion of Catchment Area Covered by Köppen-Geiger Climate Types Across All 699 Catchments

Broad	Specific	Description	Percent Area
A		Tropical	15.3
	Af	Rain forest	1.4
	Am	Monsoon	1.3
	Aw	Savannah	12.6
B		Arid	9.1
	BWh	Desert, Hot	0.4
	BWk	Desert, Cold	1.9
	BSh	Steppe, Hot	3.9
	BSk	Steppe, Cold	2.8
C		Temperate	44.2
	Csa	Dry Summer, Hot Summer	2.2
	Csb	Dry Summer, Warm Summer	3.9
	Csc	Dry Summer, Cold Summer	0
	Cwa	Dry Winter, Hot Summer	4.8
	Cwb	Dry Winter, Warm Summer	4.3
	Cwc	Dry Winter, Cold Summer	0
	Cfa	Without dry season, Hot Summer	10.2
	Cfb	Without dry season, Warm Summer	18.9
	Cfc	Without dry season, Cold Summer	0
D		Cold	30.8
	Dsa	Dry Summer, Hot Summer	0.2
	Dsb	Dry Summer, Warm Summer	0.4
	Dsc	Dry Summer, Cold Summer	0.3
	Dsd	Dry Summer, Very Cold Winter	0
	Dwa	Dry Winter, Hot Summer	0.3
	Dwb	Dry Winter, Warm Summer	0.6
	Dwc	Dry Winter, Cold Summer	0.9
	Dwd	Dry Winter, Very Cold Winter	0.1
	Dfa	Without dry season, Hot Summer	1.2
	Dfb	Without dry season, Warm Summer	16.3
	Dfc	Without dry season, Cold Summer	10.2
	Dfd	Without dry season, Very Cold Winter	0.5
E		Polar	0.7
	ET	Tundra	0.7
	EF	Frost	0

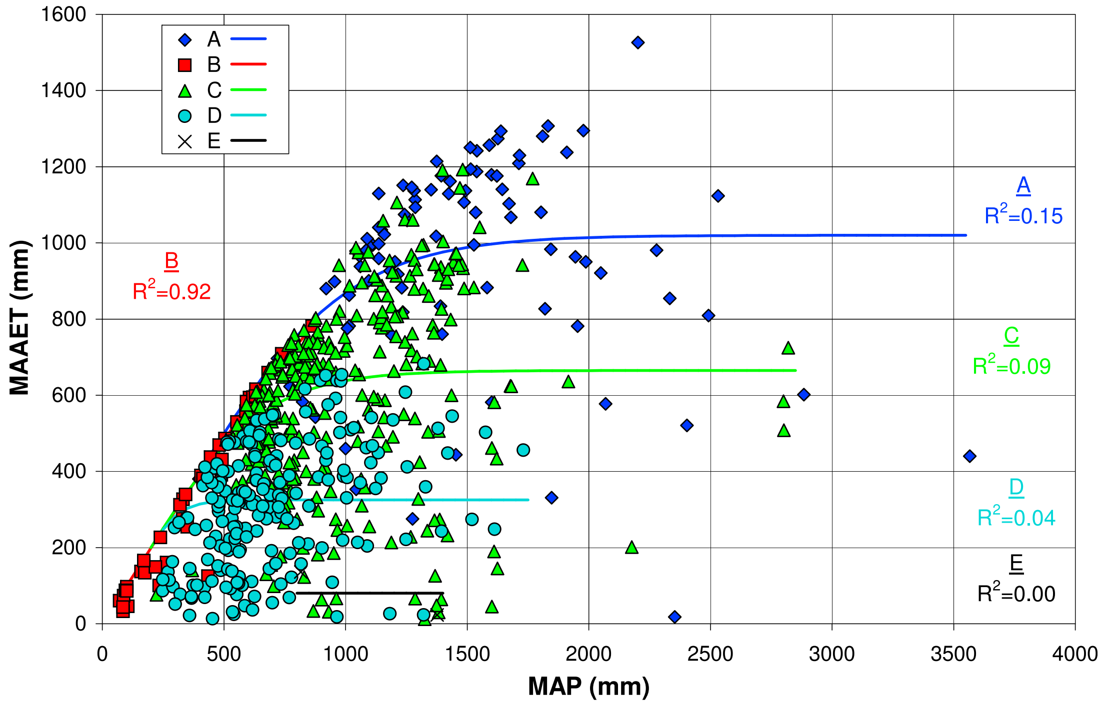


Figure 5. Catchment mean annual actual evapotranspiration (MAAET) versus catchment mean annual precipitation (MAP) stratified by broad (1st letter) Köppen climate type. The 638 catchments represented here have the specified climate type covering ≥75% of their catchment area. Lines of best fit are Tanh functions following *Boughton* [1966] and *Grayson et al.* [1996].

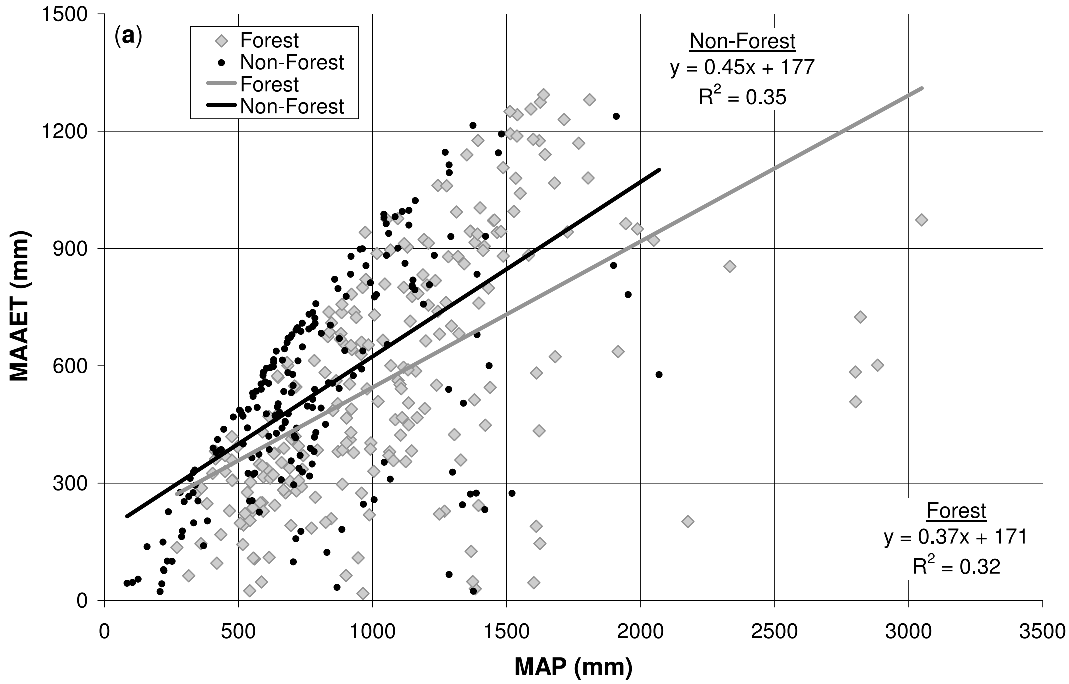
(mean annual precipitation). However, as water availability increases, the role of energy limitation becomes apparent. A spectrum of mean annual actual evapotranspiration response, for a given mean annual precipitation, is apparent in Figure 5. In high energy tropical catchments (Köppen A climates) the highest mean annual evapotranspiration is observed, and as energy availability decreases through temperate (C), cold (D) to polar (E) climate types the catchment mean annual actual evapotranspiration decreases accordingly.

[37] However, within a climate type there remains a wide range of scatter for a given mean annual precipitation (MAP) (Figure 5), which is indicative of the variation of climatic conditions within the broad climate types as well as the potential influence of vegetation type on mean annual actual evapotranspiration (MAAET). This within climate type variation is seen for example in the tropical (A) climate for catchments with high MAP (e.g., MAP ≥ 2000 mm). Of the 11 catchments with MAP ≥ 2000 mm, only 4 have MAAET ≥ 900 mm (2 in Malaysia, 1 in Brazil and 1 in Guinea), whereas 7 catchments have MAAET ≤ 900 mm (4 in Panama, 2 in Jamaica and 1 in Costa Rica). The catchments with lower MAAET all have relatively low mean annual potential evapotranspiration (lowest 15% of tropical catchments) in concordance with a narrow diurnal temperature range throughout the year compared to the catchments with higher MAAET.

[38] Since the Köppen climate classification broadly encapsulates the interaction between climate and mean annual actual evapotranspiration, it will be used to stratify the catchments in the following analyses. When stratified by climate type, only analyses for tropical (A), temperate (C) and cold (D) climate types are possible due to insufficient available data in arid (B) and polar (E) climates. For a catchment to be included in the following analyses, the specific vegetation type must cover ≥ 75% of the catchment area and, when stratified by Köppen climate type, the broad (1st letter) climate type must cover ≥ 75% of the catchment area.

3.2. Are Differences in Evapotranspiration Between Forested and Non-forested Catchments Observed Globally?

[39] In Figure 6a catchment MAAET is plotted against MAP and stratified by forest and non-forest vegetation for all climate types. This plot is presented here since it is comparable with earlier studies [e.g., *Zhang et al.*, 2001, Figure 9], where climate type is not explicitly taken into account. In Figure 6a the non-forested catchments generally have higher actual evapotranspiration than the forested catchments, which is the opposite of earlier conclusions [e.g., *Zhang et al.*, 2001]. The regression coefficients were tested for any significant differences at the 5% (α = 0.05) level of significance using a two-sided t Studentized bootstrap test-statistic (e.g., values of p < 0.025 or p > 0.975 indicate significant differences). Following *Wehrens et al.* [2000], the t test-statistic was calculated for 1000 bootstrap replicates of cases, rather than regression residuals, and the variances of the regression terms for each sample were not assumed to be equal. The regression coefficients of the linear relationships were not significantly different (slope p = 0.827; intercept p = 0.492). Therefore, although the non-forested catchments generally have higher MAAET than forested catchments in Figure 6a, the difference is not statistically significant.



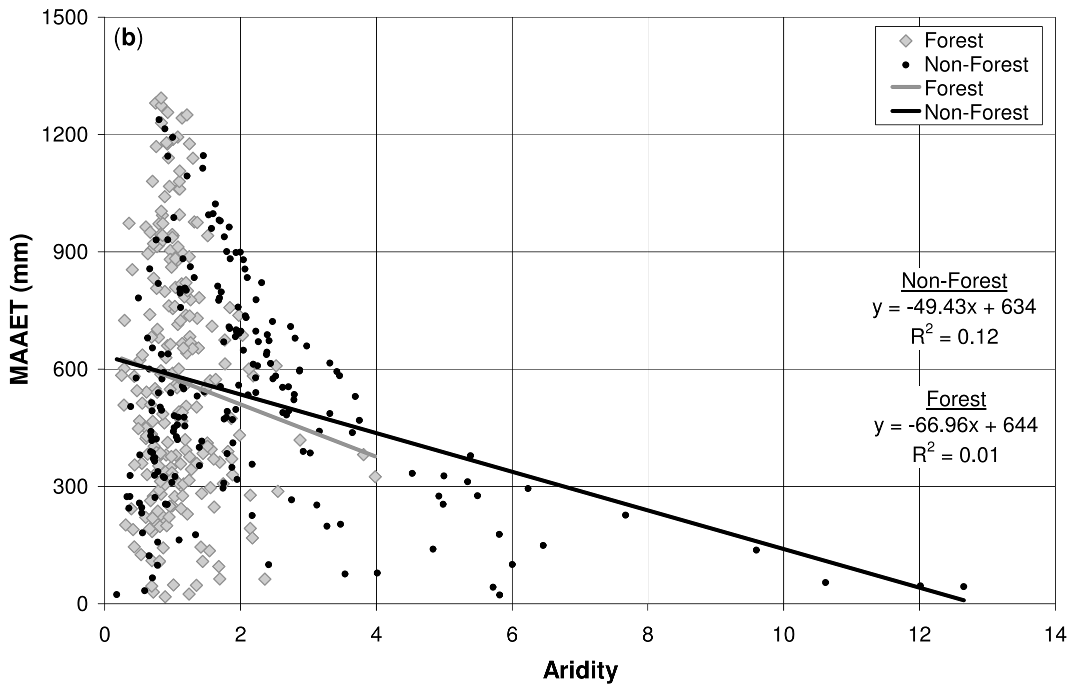


Figure 6. Catchment mean annual actual evapotranspiration versus (a) mean annual precipitation and (b) aridity index, stratified by forest (N = 235) and non-forest (N = 198) vegetation for all climate types.

[40] The energy and water limitation effects on catchment MAAET, noted in Figure 5, are not fully taken into account in Figure 6a, since only MAP is shown. For example, a catchment may receive annual average precipitation of 1000 mm and, depending on the annual average potential evapotranspiration (PET) value, may be water limited or energy limited. The aridity index (PET/MAP) encapsulates this concept, where an aridity index <1 indicates a tendency toward an energy limited environment and an aridity index >1 indicates a tendency toward a water limited environment. In Figure 6b, MAP is replaced by the aridity index and the separation between forested and non-forested catchments observed in Figure 6a is reduced. The linear regression relationships explain little variance, which indicates that the aridity index effectively represents the interaction between energy and water limitation on catchment MAAET. Thus, aridity will be used, instead of MAP, throughout the remaining analyses.

[41] The forested and non-forested regression terms in Figure 6b were not tested for significant differences due to

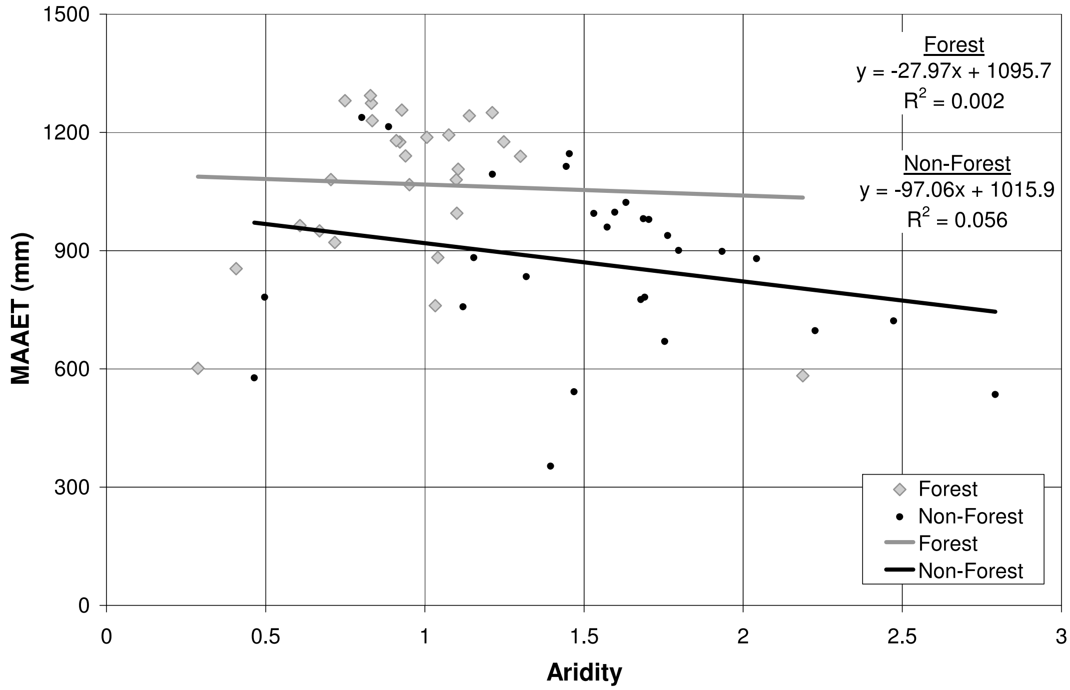


Figure 7. Catchment mean annual actual evapotranspiration versus aridity index stratified by forest (N = 27) and non-forest (N = 28) vegetation for Tropical (A) climate types.

the low variance explained by the regression relationships. Instead, a two-sided *t* Studentized bootstrap difference of median significance test was applied to the forested and non-forested median MAAET values. Following *Wehrens et al.* [2000], the *t* test-statistic was calculated for 1000 bootstrap replicates and the variances of each sample were not assumed to be equal. The median MAAET for forested catchments (541 mm) was not significantly different (p = 0.116) from the median MAAET for non-forested catchments (509 mm). Again, this result is inconsistent with previously reported results, where forested catchments are generally observed to have higher MAAET than non-forested catchments [e.g., *Zhang et al.*, 2001].

[42] When the catchments are not stratified by climate type (Figure 6) the expected differences in MAAET between forested and non-forested catchments were not observed. When catchments are stratified by climate type, the relationship between catchment MAAET and the aridity index, for forest and non-forest vegetation, reveals an outcome more in line with expectations. For tropical (A) climate type catchments (Figure 7), linear regression relationships, although weak, indicate that forested catchments generally have higher MAAET (~170 mm) than non-forested catchments. Since both regression relationships are weak, a two-sided *t* s Studentized bootstrap difference of median significance test was applied and median MAAET for forested catchments (1139 mm) was found to be significantly higher (p = 0.003) than median MAAET from non-forested catchments (890 mm). Higher MAAET of up to 200 mm for forested, relative to non-forested, catchments is largely consistent with earlier findings [*Bosch and Hewlett*, 1982; *Sahin and Hall*, 1996]. However, the result shown in Figure 7 should be interpreted with care, since 89% of the tropical forested catchments are situated in conditions where energy and water are roughly equally limiting (0.5 < aridity index < 1.5) and MAAET will be at a maximum. Whereas, for non-forested catchments, the majority experience water limiting conditions (aridity > 1.5) and associated lower MAAET. It is possible the significant difference in MAAET observed between tropical forested and non-forested catchments is an artifact of their respective distribution along the aridity gradient.

[43] For temperate (C) climate type catchments (Figure 8) average MAAET is generally lower than in tropical catchments (Figure 7) for a given aridity. Linear regression relationships, although weak, indicate that forested catchments have higher MAAET (~130 mm) than non-forested catchments within the 0.5 < aridity < 2.0 range. A two-sided *t* Studentized bootstrap difference of median significance test was applied to the forested and non-forested median MAAET values. The median MAAET for forested catchments (681 mm) is significantly higher (p = 0.001) than for non-forested catchments (504 mm) in temperate climates. Again this result is largely consistent with earlier findings [*Bosch and Hewlett*, 1982; *Sahin and Hall*, 1996].

[44] In cold (D) climates (Figure 9) average MAAET is lower again than in tropical and temperate catchments (Figures 7 and 8) for a given aridity. Contrary to expectations, non-forested catchments appear to have higher MAAET than forested catchments across the aridity range shown. The linear regression relationships, although weak, indicate that non-forested catchments have higher MAAET (~90 mm) than forested catchments within the 0.5 < aridity < 2.0 range. A two-sided *t* Studentized bootstrap difference of median significance test was applied to the forested and non-forested median MAAET values. The median MAAET for forested catchments (319 mm) is significantly lower (p = 0.977) than for non-forested catchments (389 mm) in cold climates. This result is not consistent with earlier findings [*Bosch and Hewlett*, 1982; *Sahin and Hall*,

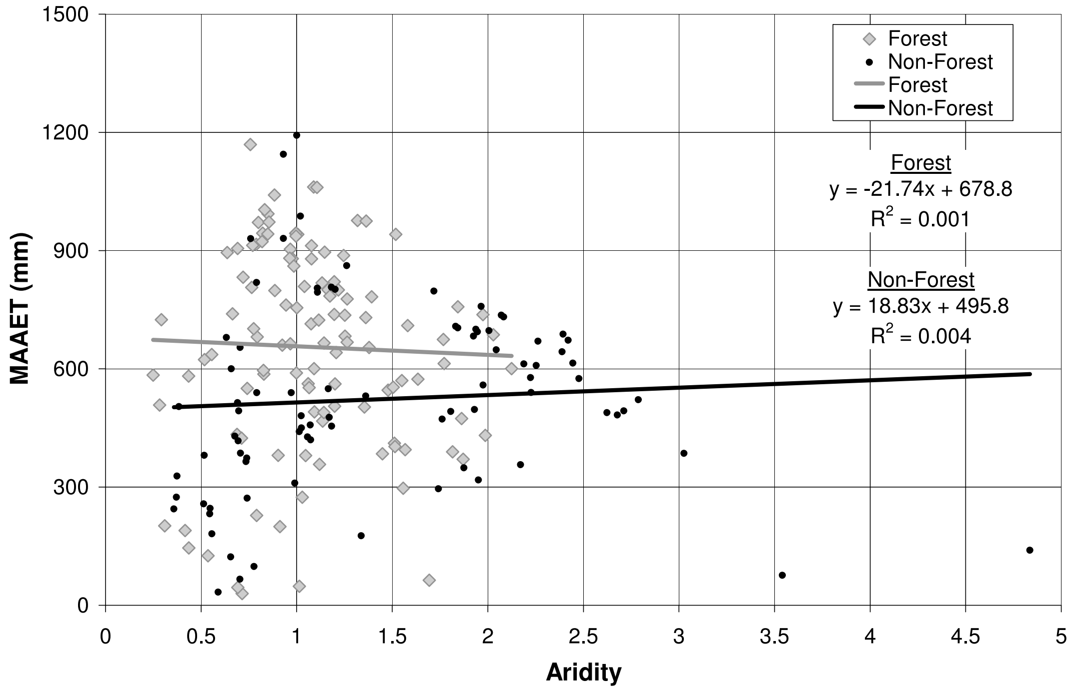


Figure 8. Catchment mean annual actual evapotranspiration versus aridity index stratified by forest (N = 113) and non-forest (N = 85) vegetation for Temperate (C) climate types.

1996]. The difference in MAAET between forested and non-forested catchments is the smallest observed of the three climate types assessed, as expected due to the lower energy availability in cold climates, relative to tropical and temperate climates. However, it was not expected that non-forested vegetation would have significantly higher MAAET than forested vegetation under these conditions. A possible explanation for this observation is seen in Figure 9 where the sample of forested catchments contains more borderline implausible water balance catchments (MAAET close to zero) than the non-forested sample, thus biasing the forested catchments toward lower MAAET. This result requires further study, preferably with a larger sample of catchments located in cold climate regions.

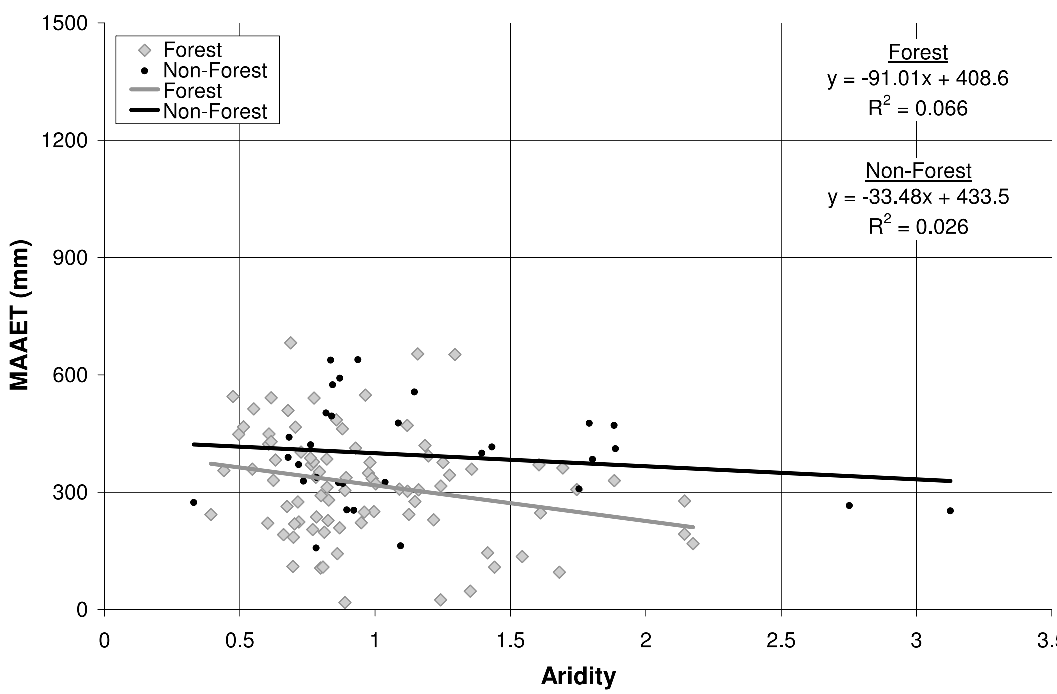


Figure 9. Catchment mean annual actual evapotranspiration versus aridity index stratified by forest (N = 86) and non-forest (N = 31) vegetation for cold (D) climate types.

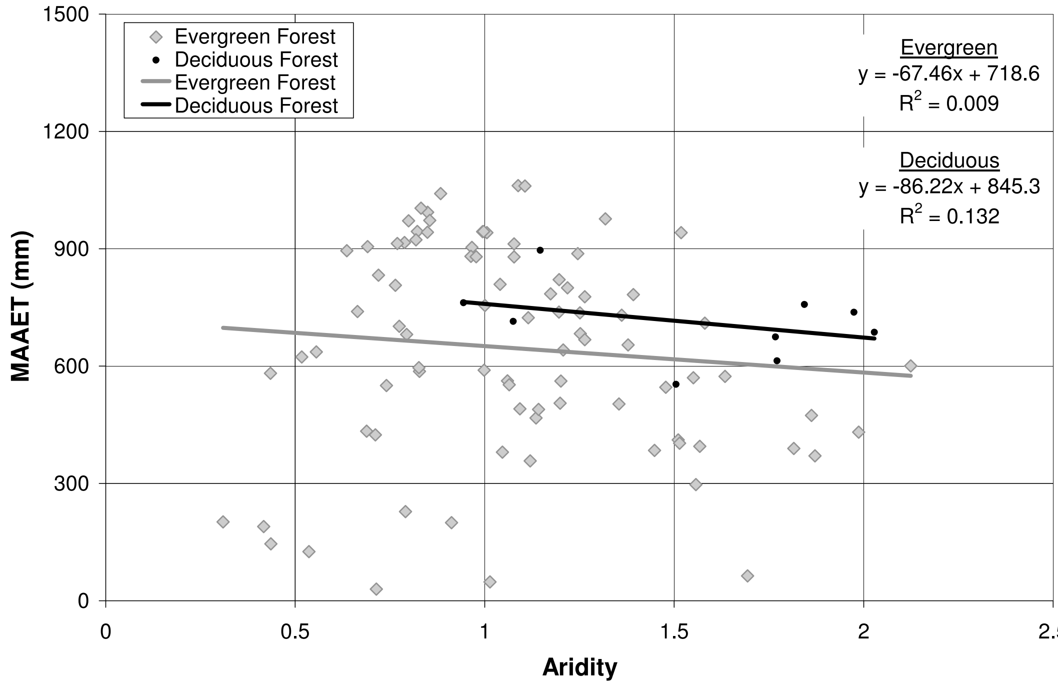


Figure 10. Catchment mean annual actual evapotranspiration versus aridity index stratified by evergreen (N = 87) and deciduous (N = 9) forest for Temperate (C) climate types.

[45] The broad climate type results for A, C and D (Figures 7–9) are consistent at the finer climate classification level (not shown) of Aw (forest = 20, non-forest = 25 catchments), Cfb (forest = 55, non-forest = 42 catchments) and Dfb (forest = 38, non-forest = 24 catchments), which are the dominant climate types within each broad climate type respectively. Finally, the difference in results observed in the analyses based on climate type (Figures 7–9) relative to those not based on climate type (Figure 6) confirm the importance of stratifying catchments by climate type prior to any vegetation impact analysis.

3.3. Are Differences in Evapotranspiration Between Evergreen and Deciduous Forested Catchments Observed Globally?

[46] Forested catchments were sub-divided into evergreen and deciduous forest type to investigate whether any difference in catchment MAAET exists between these forest types. Based on a brief literature review of MAAET differences between evergreen and deciduous forests, *Peel et al.* [2001] noted that evergreen forests could have between 100–200 mm higher MAAET than deciduous forests. This difference is primarily due to reduced transpiration and interception by deciduous forests, relative to evergreen forests, during their leafless period. However, the magnitude of this difference is expected to be influenced by MAP, PET (water or energy limited environment) and the seasonality of precipitation [*Peel et al.*, 2002].

[47] In tropical catchments (not shown, due to small sample sizes) the forested catchments formed clear groups along the aridity index, with evergreen forests in more energy limited (aridity < 1) and deciduous forests in more water limited (aridity > 1) environments. This grouping reflects the transition from predominately evergreen in wet tropical rain forests to predominately deciduous (with the exception of northern Australia) in seasonally dry tropical savannah [*Murphy and Lugo*, 1986].

[48] Weak linear regression relationships indicate that MAAET for deciduous forested catchments experiencing temperate (C) climate types is generally higher than for evergreen forested catchments (Figure 10). However, a two-sided t Studentized bootstrap difference of median significance test indicates no significant difference (p = 0.795) between forested evergreen (668 mm) and deciduous (714 mm) median MAAET. A possible reason for the lack of a difference between temperate evergreen and deciduous catchments is that the deciduous catchments in this data set are predominately from the summer dominant precipitation climate types (Cwa and Cwb (N = 7); see Table 3). Evapotranspiration differences between evergreen and deciduous forests are expected to be small under this seasonal precipitation regime since the leaf fall period of the deciduous forest coincides with the winter dry period, when evergreen forests would also have low evapotranspiration. Furthermore, Cw climate types generally border tropical savannah regions and deciduous forests in these regions may be largely facultatively deciduous (variable loss of leaves depending on conditions) rather than obligately deciduous (complete loss of leaves irrespective of conditions) and may maintain some leaf area throughout the year.

[49] The difference in MAAET between temperate evergreen and deciduous forested catchments expected from the literature is not observed in this analysis. The suspected high proportion of facultatively deciduous forests in this sample, relative to obligately deciduous forests, may be masking the expected difference. Alternatively, the expectation of a difference may be incorrect and no difference exists. To answer these questions definitively requires a larger sample of obligately deciduous forested catchments located in Cf

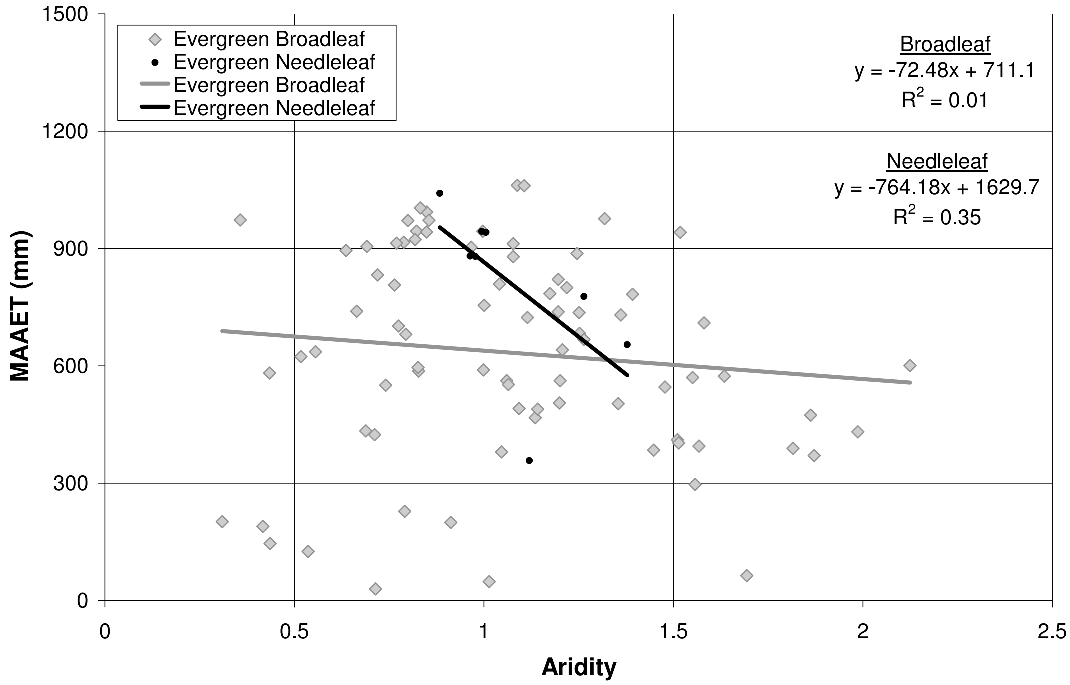


Figure 11. Catchment mean annual actual evapotranspiration versus aridity index stratified by evergreen broadleaf (N = 80) and evergreen needleleaf (N = 8) forest for Temperate (C) climate types.

climate types. Results are not presented for the cold climate type due to the small sample of deciduous catchments (N = 2) available.

3.4. Are Differences in Evapotranspiration Between Evergreen Broadleaf and Evergreen Needleleaf Forested Catchments Observed Globally?

[50] The evergreen forested catchments were further subdivided into broadleaf and needleleaf forest type to investigate whether any difference in catchment MAAET exists between these forest types. *Farley et al.* [2005] found that afforestation of grassland or shrubland catchments with eucalypts produces a proportionally larger reduction in runoff (increase in MAAET) than when afforested with pines. They note that this difference is influenced by climate, with eucalypts having a greater impact in drier regions (due to exploiting deeper soil water stores at a young age) and pines in wetter regions (greater interception losses). Needleleaf forests do tend to intercept more precipitation than broadleaf forests under similar conditions, although drawing general conclusion about interception losses for particular forest types is difficult (see *Crockford and Richardson* [2000] for a review).

[51] Figure 11 shows linear relationships between catchment MAAET and aridity index for temperate (C climate) evergreen broadleaf and evergreen needleleaf forested catchments. Generally, evergreen needleleaf forests have higher catchment MAAET than evergreen broadleaf forests. Although the needleleaf sample size is very small (N = 8), the two-sided *t* Studentized bootstrap difference of median significance test indicates a significant difference (p = 0.999) between the evergreen broadleaf (639 mm) and needleleaf (880 mm) median MAAET values. Due to the small evergreen needleleaf sample size, this result should be treated with caution. However, it is interesting to note that the distribution of needleleaf MAAET values along the aridity gradient (high MAAET for low aridity and low MAAET for high aridity) in Figure 11 is consistent with the expectation of *Farley et al.* [2005].

3.5. If Differences in Evapotranspiration Due to Vegetation Type Are Observed Are They Related to Catchment Area?

[52] In the three previous sub-sections differences in evapotranspiration between catchments with different vegetation types were investigated. Statistically significant results were observed in sections 3.2 (forest versus non-forest) and 3.4 (evergreen broadleaf forest versus evergreen needleleaf forest). In this sub-section the influence of catchment area on these differences is investigated in order to test whether they are observed across all catchment areas or are restricted to smaller catchments (~<1,000 km^2) as *Donohue et al.* [2007] expect. Since the evergreen needleleaf forest sample was very small (section 3.4), it is not assessed here, only the forest versus non-forest results (section 3.2) are assessed.

[53] Tropical forested and non-forested catchments, shown previous in Figure 7, were further sub-divided by catchment area into two groups: (1) catchment area < 1,000 km^2; and (2) catchment area ≥ 1,000 km^2. Results for catchments < 1,000 km^2 were inconclusive (not shown) due to the small sample size of both forested (N = 2) and non-forested (N = 6) catchments. For catchments with area ≥ 1,000 km^2 the results (not shown) are very similar to Figure 7, with the previously noted grouping of forested and non-forested catchments along the aridity gradient more clearly apparent. For tropical catchments the influence of catchment area on forested and non-forested evapotranspiration differences was

not assessable due to the low number of catchments with area $< 1{,}000$ km^2. Furthermore, catchments experiencing a tropical climate type are not good candidates for investigating the influence of catchment area on vegetation related evapotranspiration differences, because the aridity gradient associated clustering of forested and non-forested catchments confound a direct comparison between vegetation types.

[54] In temperate climate types forested and non-forested catchments are more evenly mixed across the aridity range than in tropical climates. Prior to sub-dividing by catchment area, forested median MAAET (681 mm) was significantly higher ($p = 0.001$) than non-forested median MAAET (504 mm) as shown previously in Figure 8. When sub-divided by catchment area ($<$ or $\geq 1{,}000$ km^2) the linear regression relationships between MAAET and aridity are similar to Figure 8. For catchments with area $< 1{,}000$ km^2, the two-sided t Studentized bootstrap difference of median test indicates that the significant difference in median MAAET (forest = 660 mm, N = 77; non-forest = 479 mm, N = 52) is maintained ($p = 0.001$). Whereas, for catchments with area $\geq 1{,}000$ km^2 the forested median MAAET (760 mm, N = 36) is not significantly different from the non-forested median MAAET (648 mm, N = 33) ($p = 0.074$). The significant median difference result for smaller forested and non-forested temperate catchments and the non-significant result for the larger catchments are consistent with the expectations of *Donohue et al.* [2007].

[55] For cold climate types prior to sub-dividing by catchment area, forested median MAAET (319 mm) was significantly lower ($p = 0.997$) than non-forested median MAAET (389 mm) in Figure 9. When sub-divided by catchment area ($<$ or $\geq 1{,}000$ km^2) the linear regression relationships between MAAET and aridity are similar to Figure 9. However, the significant difference in median MAAET between forested and non-forested catchments is not maintained for catchments with area $< 1{,}000$ km^2 (forest = 304 mm, N = 26; non-forest = 380 mm, N = 16; $p = 0.888$) or for catchments with area $\geq 1{,}000$ km^2 (forest = 330 mm, N = 60; non-forest = 400 mm, N = 15; $p = 0.951$) using the two-sided t Studentized bootstrap difference of median test. These median difference results for smaller and larger forested and non-forested cold climate catchments neither support nor contradict the expectations of *Donohue et al.* [2007].

4. Conclusion

[56] In this paper we describe a significant improvement of the global streamflow data set of *Peel et al.* [2001, 2004] and *McMahon et al.* [2007]. Through analysis of this data set, we address five research questions that assess the impact of vegetation type on mean annual evapotranspiration, and hence catchment water balance, for 699 catchments globally. Like *Oudin et al.* [2008], this analysis utilizes a large data set of catchment land cover information, rather than known land cover changes within a catchment (e.g., paired catchment studies) to draw broad conclusions about the vegetation impact on catchment mean annual evapotranspiration.

[57] First, the importance of climate type to the relationship between mean annual actual evapotranspiration and precipitation was investigated in order to assess whether subsequent analyses should be stratified by climate type. Previous reviews of paired catchment results have not explicitly taken climate type into account when assessing the vegetation impact on catchment evapotranspiration. Results from the wide range of climate types represented in this data set indicate that climate type is important and does need to be taken into account in this type of assessment.

[58] Second, when climate type is not taken into account, mean annual evapotranspiration from non-forested catchments is generally higher, though not statistically significant, than from forested catchments when plotted against mean annual precipitation or an aridity index. This result is contrary to previous conclusions from the literature and is indicative of the anomalous results that may be achieved when climate type is not taken into account. When stratified by broad climate type, the significant differences in mean annual evapotranspiration between forested and non-forested catchments are more consistent with results from previous research. For tropical climates, forested catchment mean annual evapotranspiration is approximately 170 mm higher than for non-forested catchments. However, this result may be an artifact of the distribution of forested and non-forested catchments along the aridity gradient. In temperate regions forested catchments exhibit about 130 mm higher mean annual evapotranspiration than non-forested catchments across the range of aridity index values. In cold climates the results are the opposite of expectations, with non-forested catchments exhibiting approximately 90 mm higher mean annual evapotranspiration than forested catchments. This unexpected result may be due to data concerns with some of the forested catchments.

[59] Third, the expected difference in mean annual evapotranspiration between temperate evergreen and deciduous forested catchments was not observed. A combination of small deciduous sample size and potentially a high proportion of facultatively, relative to obligately, deciduous forested catchments may be masking the expected difference.

[60] Fourthly, evergreen needleleaf forested catchments were found to have significantly higher evapotranspiration than evergreen broadleaf forested catchments, although the needleleaf sample size was small and this result should be treated with caution.

[61] Finally, the role of catchment area on the significant forested versus non-forested catchment evapotranspiration difference was investigated. In temperate climates, where sample sizes were largest, the significant difference between higher forested and lower non-forested catchment evapotranspiration was maintained for catchments with area $< 1{,}000$ km^2. For catchment areas $\geq 1{,}000$ km^2 the difference in evapotranspiration between forested and non-forested catchments was reduced and was no longer statistically significant.

[62] In summary, this paper demonstrates the value of assessing the vegetation impact on catchment evapotranspiration through a large, spatially, and climatically diverse data set. Additionally, questions are raised by these analyses that could form the basis of investigations targeted at specific combinations of climate and vegetation type. Climate type is shown to be a significant influence over the results of this type of assessment and it should be utilized in future assessments of vegetation impact on catchment evapotranspiration. Although based on land cover information, rather than known vegetation disturbances, the results presented here are largely consistent with expectations from the existing vegetation disturbance literature.

[63] **Acknowledgments.** Australian Research Council Discovery grants DP0449685 and DP0773016 financially supported this work. The authors would like to thank Lionel Siriwardena for his assistance in compiling the catchment average precipitation and temperature records, David Wilson and Kristin Gardner for assistance with delineating the catchment boundaries and Francis Chiew for useful discussions. The authors appreciate the comments provided by three anonymous reviewers and associate editor Michiaki Sugita, which significantly improved this paper.

References

Adam, J. C., and D. P. Lettenmaier (2003), Adjustment of global gridded precipitation for systematic bias, *J. Geophys. Res.*, *108*(D9), 4257, doi:10.1029/2002JD002499.

Adam, J. C., E. A. Clark, D. P. Lettenmaier, and E. F. Wood (2006), Correction of global precipitation products for orographic effects, *J. Clim.*, *19*, 15–38, doi:10.1175/JCLI3604.1.

Andréassian, V. (2004), Water and forests: From historical controversy to scientific debate, *J. Hydrol.*, *291*, 1–27, doi:10.1016/j.jhydrol.2003.12.015.

Bosch, J. M., and J. D. Hewlett (1982), A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration, *J. Hydrol.*, *55*, 3–23, doi:10.1016/0022-1694(82)90117-2.

Boughton, W. C. (1966), A mathematical model for relating runoff to rainfall with daily data, *Civ. Eng. Trans. Inst. Eng. Aust.*, *8*(1), 83–97.

Brown, A. E., L. Zhang, T. A. McMahon, A. W. Western, and R. A. Vertessy (2005), A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation, *J. Hydrol.*, *310*, 28–61, doi:10.1016/j.jhydrol.2004.12.010.

Crockford, R. H., and D. P. Richardson (2000), Partitioning of rainfall into throughfall, stemflow and interception: Effect of forest type, ground cover and climate, *Hydrol. Processes*, *14*, 2903–2920, doi:10.1002/1099-1085(200011/12)14:16/17<2903::AID-HYP126>3.0.CO;2-6.

Donohue, R. J., M. L. Roderick, and T. R. McVicar (2007), On the importance of including vegetation dynamics in Budyko's hydrological model, *Hydrol. Earth Syst. Sci.*, *11*, 983–995, doi:10.5194/hess-11-983-2007.

Droogers, P., and R. G. Allen (2002), Estimating reference evapotranspiration under inaccurate data conditions, *Irrig. Drain. Syst.*, *16*, 33–45, doi:10.1023/A:1015508322413.

Farley, K. A., E. G. Jobbágy, and R. B. Jackson (2005), Effects of afforestation on water yield: A global synthesis with implications for policy, *Global Change Biol.*, *11*, 1565–1576, doi:10.1111/j.1365-2486.2005.01011.x.

Fekete, B. M., C. J. Vörösmarty, J. O. Roads, and C. J. Willmott (2004), Uncertainties in precipitation and their impacts on runoff estimates, *J. Clim.*, *17*, 294–304, doi:10.1175/1520-0442(2004)017<0294:UIPATI>2.0.CO;2.

Fritz, S., et al. (2003), Harmonisation, mosaicing and production of the Global Land Cover 2000 database (beta version), *EUR 20849 EN*, Joint Res. Cent., Eur. Comm., Brussels.

Grayson, R. B., R. M. Argent, R. J. Nathan, T. A. McMahon, and R. G. Mein (1996), Hydrological recipes estimation techniques in Australian hydrology, Coop. Res. Cent. for Catchment Hydrol., Monash Univ., Melbourne, Victoria, Australia.

Holmes, J. W., and J. A. Sinclair (1986), Water yield from some afforested catchments in Victoria, paper presented at Hydrology and Water Resources Symposium, Inst. of Eng. Aust., Brisbane, Queensland, Australia.

Hornbeck, J. W., M. B. Adams, E. S. Corbett, E. S. Verry, and J. A. Lynch (1993), Long-term impacts of forest treatments on water yield: A summary for northeastern USA, *J. Hydrol.*, *150*, 323–344, doi:10.1016/0022-1694(93)90115-P.

Hutchinson, M. F. (Ed.) (2002), GEODATA 9 second DEM (version 2.1), data user guide, GeoSci. Aust., Canberra.

Le Moine, N., V. Andréassian, C. Perrin, and C. Michel (2007), How can rainfall-runoff models handle intercatchment groundwater flows? Theoretical study based on 1040 French catchments, *Water Resour. Res.*, *43*, W06428, doi:10.1029/2006WR005608.

Matthews, E. (1983), Global vegetation and land-use: New high-resolution data bases for climate studies, *J. Clim. Appl. Meteorol.*, *22*, 474–487, doi:10.1175/1520-0450(1983)022<0474:GVALUN>2.0.CO;2.

Mayaux, P., et al. (2006), Validation of the Global Land Cover 2000 map, *IEEE Trans. Geosci. Remote Sens.*, *44*(7), 1728–1739, doi:10.1109/TGRS.2006.864370.

McCallum, I., M. Obersteiner, S. Nilsson, and A. Shvidenko (2006), A spatial comparison of four satellite derived 1 km global land cover datasets, *Int. J. Appl. Earth Obs.*, *8*, 246–255, doi:10.1016/j.jag.2005.12.002.

McMahon, T. A., B. L. Finlayson, A. Haines, and R. Srikanthan (1992), *Global Runoff—Continental Comparisons of Annual Flows and Peak Discharges*, Catena, Reiskirchen, Germany.

McMahon, T. A., R. M. Vogel, M. C. Peel, and G. G. S. Pegram (2007), Global streamflow—Part 1: Characteristics of annual streamflows, *J. Hydrol.*, *347*, 243–259, doi:10.1016/j.jhydrol.2007.09.002.

Milly, P. C. D., and K. A. Dunne (2002), Macroscale water fluxes: 1. Quantifying errors in the estimation of basin mean precipitation, *Water Resour. Res.*, *38*(10), 1205, doi:10.1029/2001WR000759.

Murphy, P. G., and A. E. Lugo (1986), Ecology of tropical dry forest, *Annu. Rev. Ecol. Syst.*, *17*, 67–88, doi:10.1146/annurev.es.17.110186.000435.

New, M., D. Lister, M. Hulme, and I. Makin (2002), A high-resolution data set of surface climate over global land areas, *Clim. Res.*, *21*, 1–25, doi:10.3354/cr021001.

Oudin, L., V. Andréassian, J. Lerat, and C. Michel (2008), Has land cover a significant impact on mean annual streamflow? An international assessment using 1508 catchments, *J. Hydrol.*, *357*, 303–316, doi:10.1016/j.jhydrol.2008.05.021.

Peel, M. C., T. A. McMahon, B. L. Finlayson, and F. G. R. Watson (2001), Identification and explanation of continental differences in the variability of annual runoff, *J. Hydrol.*, *250*, 224–240, doi:10.1016/S0022-1694(01)00438-3.

Peel, M. C., T. A. McMahon, B. L. Finlayson, and F. G. R. Watson (2002), Implications of the relationship between catchment vegetation type and the variability of annual runoff, *Hydrol. Processes*, *16*, 2995–3002, doi:10.1002/hyp.1084.

Peel, M. C., T. A. McMahon, and B. L. Finlayson (2004), Continental differences in the variability of annual runoff—Update and reassessment, *J. Hydrol.*, *295*, 185–197, doi:10.1016/j.jhydrol.2004.03.004.

Peel, M. C., B. L. Finlayson, and T. A. McMahon (2007), Updated world map of the Köppen-Geiger climate classification, *Hydrol. Earth Syst. Sci.*, *11*, 1633–1644, doi:10.5194/hess-11-1633-2007.

Peterson, T. C., and R. S. Vose (1997), An overview of the Global Historical Climatology Network temperature database, *Bull. Am. Meteorol. Soc.*, *78*(12), 2837–2849, doi:10.1175/1520-0477(1997)078<2837:AOOTGH>2.0.CO;2.

Sahin, V., and M. J. Hall (1996), The effects of afforestation and deforestation on water yields, *J. Hydrol.*, *178*, 293–309, doi:10.1016/0022-1694(95)02825-0.

Silveira, L., and J. Alonso (2009), Runoff modifications due to the conversion of natural grasslands to forests in a large basin in Uruguay, *Hydrol. Processes*, *23*, 320–329, doi:10.1002/hyp.7156.

Siriwardena, L., B. L. Finlayson, and T. A. McMahon (2006), The impact of land use change on catchment hydrology in large catchments: The Comet River, central Queensland, Australia, *J. Hydrol.*, *326*, 199–214.

Thiessen, A. H. (1911), Precipitation averages for large areas, *Mon. Weather Rev.*, *39*(7), 1082–1084, doi:10.1175/1520-0493(1911)39<1082b:PAFLA>2.0.CO;2.

Turner, K. M. (1991), Annual evapotranspiration of native vegetation in a Mediterranean-type climate, *Water Resour. Bull.*, *27*, 1–6.

Wehrens, R., H. Putter, and L. M. C. Buydens (2000), The bootstrap: A tutorial, *Chemometr. Intell. Lab. Syst.*, *54*, 35–52, doi:10.1016/S0169-7439(00)00102-7.

Zhang, L., W. R. Dawes, and G. R. Walker (2001), Response of mean annual evapotranspiration to vegetation changes at catchment scale, *Water Resour. Res.*, *37*(3), 701–708, doi:10.1029/2000WR900325.

Zhang, L., K. Hickel, W. R. Dawes, F. H. S. Chiew, A. W. Western, and P. R. Briggs (2004), A rational function approach for estimating mean annual evapotranspiration, *Water Resour. Res.*, *40*, W02502, doi:10.1029/2003WR002710.

B. L. Finlayson, Department of Resource Management and Geography, University of Melbourne, Melbourne, Vic 3010, Australia. (brianlf@unimelb.edu.au)

T. A. McMahon and M. C. Peel, Department of Civil and Environmental Engineering, University of Melbourne, Melbourne, Vic 3010, Australia. (thomasam@unimelb.edu.au; mpeel@unimelb.edu.au)