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Extreme weather events in the Sneeuberg, Karoo, South Africa: a case study of the floods of 9 and 12 February 2011

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Abstract

Two destructive flood events occurred in rapid succession in the semi-arid Sneeuberg Mountains of the Karoo, South Africa in February 2011. The temporal and spatial characteristics of these two extreme events are examined in this paper through analysis of data from an unusually dense, and reliable, network of farm rain gauges. These analyses add to our understanding derived from existing rain gauge information. Comparisons are then made with patterns from a range of modeled products derived from remote sensed information: the Modern-Era Retrospective Analysis for Research and Applications (MERRA), the Tropical Rainfall Measuring Mission (TRMM) and the Global Land Data Assimilation System (GLDAS). We found that the first flood event was widespread and precipitation was related strongly to altitude. The second was highly localised, with no relationship to altitude. Both had very sharply peaked rainfall intensities. These findings are of significance to the studies of flooding and landscape change in the area as such events have become more pronounced over the past 50 yr and it is likely that this trend will accelerate. The modeled patterns are derived largely from remote sensing and we found that they are reliable for drawing out monthly and annual variations but they make noticeable underestimates. They are poor estimates, however, both for the spatial distribution of precipitation, and the short term trends as they struggle to estimate the impact of topography and other local forcing factors. This finding corroborates information derived from other analyses at broader spatial scales using more widely spread, established rain gauge stations. Ten percent of southern Africa has been classified as mountainous and these areas provide much of our water resources so our findings are significant to water managers throughout this and similar mountainous regions.

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1 Introduction

The Gats and Wilgerbosrivier rivers, two tributaries of the Sundays River that drains the Sneeuberg Mountains in the Eastern Cape of South Africa, experienced two extreme rainfall events on 9 and 12 February 2011. Severe flooding occurred in this semi-arid mountain catchment, destroying weirs, bridges and irrigation infrastructure, inundating meadowlands and drowning livestock on the downstream farm of Ganora. Figure 1 (left panel) shows the main road bridge over the Wilgerbosrivier above Ganora Farm completely submerged under a wave of flood water. Figure 1 (right panel) was taken 90 min later immediately downstream of the bridge showing the flood water surging through the canyon where Ganora's farm buildings and associated irrigated lands lie. The storm of 9 February 2011 had a peak flow that we estimated at 600 $m^3 s^{-1}$. The wall of a two meter high diversion weir was breached; it is completely submerged by several meters of water in Fig. 1 (right panel). Two other weirs were also significantly damaged, siphons carrying water under the river bed were destroyed and furrow systems damaged. A second flood hit on 12 February 2011 generating substantial amounts of storm runoff.

The impact these floods was felt over the wider Sundays catchment and caught the attention of the local media. It was reported that one farmer in the nearby town of Nieu Bethesda estimated a cost of R 500 000 (c. US$ 50 000) to rebuild his dam and that it could take some farmers a decade to recover (S.A. Weather and Disaster Information Service, 2011). The Cqwebe Dam, upstream of the town of Graaff-Reinet and approximately 50 km downstream of Ganora Farm and Nieu Bethesda, overflowed for the first time since 1974.

These events have happened before in this part of the Eastern Cape Province of South Africa. Ganora Farm's main weir was swept away previously in 1961. In 1974 the nearby town of Nieu Bethesda's diversion weir was similarly destroyed. This weir feeds the furrow system that the residents of the old areas of the town use for market gardening of vegetables. Downstream from the town, small scale farmers have flood-irrigated lands on which they depend for growing Lucerne and feeding sheep and cattle. It usually takes a minimum of two years for the weir and furrow systems to be reconstructed and so these events are a major disruption to local lifestyles.

Mason et al. (1999) have shown that the rainfall stations in proximity to our study area have experienced significant increases in extreme events between 1931 and 1990. They estimate that the area experienced a 20–30 % increase in the intensity of 10 yr rainfall events. A recent analysis of rainfall patterns from two well established stations with reliable records (Cranemere 90 km South-East and Middleburg 50 km North-East of Ganora) by Foster et al. (2012) shows evidence of a shift in the magnitude–frequency relationship of daily rainfall since 1950. At Cranemere the magnitude of the 10 yr daily rainfall increased from 54 to 64 mm and the 50 yr daily rainfall from 71 to 84 mm. Middelburg showed greater changes with a shift of the 10 yr daily rainfall from 50 to 82 mm and the 50 yr daily rainfall from 70 to 115 mm. Despite these greater extremes, the long term mean rainfall appears to be constant. These shifts in the character of the rainfall can have important consequences not only for farming enterprises but also for land degradation, biodiversity and the wider rural economy.

The Sneeuberg Mountains to the north of the Cambedoo Plains between Pearston and Graaff-Reinet have been the focus of geomorphological research since the late 1990s. Holmes (1998, 2001) investigated palaeo-environments, with special attention to valley fills. Boardman et al. (2003) and Keay-Bright and Boardman (2006, 2007, 2009) shifted the research focus to soil erosion during the period of historical records. Foster et al. (2012), Foster and Rowntree (2012) and Rowntree and Foster (2012) have added studies of catchment sediment yield based on sediment deposits in small farm dams. The consensus arising from this research is that catchment scale erosion is responding to a complex set of drivers including land management (pressures from livestock grazing and cultivation), climate and intrinsic structural changes to connectivity (Foster et al., 2012). The sediment record from farm dams indicates elevated sediment delivery since the 1950s that is coincident with the increased severity of storm rainfall. The flood of 2011, described in this paper, caused significant geomorphological

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change in the channel downstream of the weir and a monitoring programme has been set up to study the post flood response.

There are five farms in the 277 km^2 catchment above Ganora that keep daily rainfall records and we ourselves installed an autographic gauge at Ganora Farm in April 2009. Additional daily records are available from farms immediately outside the catchment area. This relatively dense rain gauge network presented an opportunity to investigate the spatial and temporal pattern of storm rainfall in February 2011. While the traditional source of precipitation data is from a rain gauge, new sources of data derived from satellite imagery are becoming readily available. These provide a continuous spatial cover that is lacking from the point coverage provided by a rain gauge network. Furthermore, the number of active stations is becoming depleted (Lynch, 2004). These satellite derived data have become increasingly accessible through servers such as Giovanni: the Goddard Earth Science Data and Information Services Centre's web tool (Kempler, 2013a). A question that we ask in this paper is: does this new data source have potential to aid the investigation of extreme events such as the one observed in February 2011? We make a comparison of recorded precipitation and modeled data from three programmes accessed from Giovanni through examining both the short term rain series (daily and hourly rainfall) over the period of the extreme events from 9–12 February 2012 and the long term (annual and monthly rainfall) over the past 30 yr. The spatial variability and the affect of altitude will all be examined.

There are a number of other studies that have compared or combined modeled with existing rain gauge information on the African continent. Hewitson and Crane (2005), for example, evaluated the performance of General Circulation Models with data interpolated from existing ground stations throughout southern Africa. Hughes (2006) took four much larger drainage basins than we are concerned with: the Kafue, Okavango, Thukela and Kat. His focus was on attempting to combine satellite information, such as from the Global Precipitation Climatology Project (GPCP) with historical rain gauge data. Romilly and Gebremichael (2011) related a number of different satellite rainfall estimates to Ethiopian river basins. All three studies stress the significance of topogra-

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phy and local forcing factors and show that there is a great need to critically examine how satellite derived, modeled information performs in comparison to land based data.

2 Study area and local rainfall data sources

The study area lies on south draining slopes of the Great Escarpment approximately 150 km north of South Africa's southern coastline. The area selected for analysis extended from 31.625 to 32.125° S and from 24.125 to 24.875° E; this was compatible with the extent of the Giovanni sourced data described below, and encompassed the area of the quaternary catchment of the upper Sundays River (N12A) within which the floods were generated. Quaternary catchments are identified by the Department of Water Affairs, South Africa (Department of Water Affairs, 2011), as hydrologically homogenous units used for water resource planning at the national scale. There are 1946 quaternary catchments in the country. N12A is a 738 km^2 catchment with its northern boundary on the drainage divide between rivers that flow north and west to the Atlantic Ocean and those that flow south to the Indian Ocean (Fig. 2). The estimated mean annual rainfall of 450 mm (our analysis; see below) and the mean annual runoff of 12.9 mm (Middleton and Bailey, 2009) indicate the semi-arid nature of this mountainous area. Snow and hail are small components of precipitation in the catchment and the major component is undoubtedly rain: we use the term rainfall to embrace all precipitation events.

The elevation ranges from 1000 to 2500 m (Fig. 3); these altitudes are typical of the Great Escarpment that runs right across the country from 20 to 30° E. The study area meets all three criteria used by Brown et al. (2004) to define mountain areas in southern Africa: a lower elevation of 850 m; slopes more than 5°; and an elevation range of over 300 m. The Sneeuberg Range forms the northern limit of the quaternary catchment, Compassberg is its highest point at 2508 m, the tributaries of the Sundays River such as the Gats River and Wilgerbosrivier flow down from the high mountains

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through broad valleys, joining just south of Nieu Bethesda. Ganora Farm lies on the Wilgerbosrivier.

We sourced rainfall data from seven farms in this catchment: Ganora (1382 m) Wilgebosch (1420 m), Weltevreden (1443 m), Dalvene (1538 m), Quaggasvlei (1580 m), The Rest (1595 m) and Request (1713 m). The majority of these farms lay in the eastern half of the catchment, in or close to the 108 km^2 sub-catchment that generated the flood passing through Ganora farm, our main area of interest. Wellwood (1180 m), Gordonville (1717 m) and Highlands (1772 m) lie just outside the quaternary catchment but inside the area specific boundary for which we accessed MERRA (Modern-Era Retrospective Analysis for Research and Applications), TRMM (Tropical Rainfall Measuring Mission) and GLDAS (Global Land Data Assimilation System) satellite data.

Wellwood has the longest record of rainfall, stretching back to 1874. It was one of South Africa's first rainfall stations supplying information to the South African Weather Service until the country metricated between 1971 and 1973. The reliability of these farm records is very important since we base our analyses on them. Before deriving our own long term average we correlated and ran regressions of cumulative rainfall between three other stations and Wellwood. Weltevreden and Quaggasvlei have data back to at least 1950, The Rest started recording in 1969. We wanted to establish that there were no marked breaks, sudden increases or decreases in the records indicative of a change in recording method, change of farmer, moving of the rain gauge, etc. The relationships were all very close to a straight line with very strong R^2 values as follows:

- Wellwood and Weltevreden $y = 1.02x - 393$ $R^2 = 0.998$
- Wellwood and Quaggasvlei $y = 1.12x - 367$ $R^2 = 0.999$
- Wellwood and The Rest $y = 1.45x - 10\,250$ $R^2 = 0.994$
- Quaggasvlei and The Rest $y = 1.28x - 9421$ $R^2 = 0.996$.

We took these values to indicate that there was little variation between the pairings over long periods and this led us to assume that the records are reliable measurements.

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Daily and hourly rainfall totals were used for the short-term analysis. Daily totals for the storm period of 9 to 12 February 2011 were used to construct a picture of events within the catchment. In this case we used triangulation to authenticate the daily totals. This was accomplished through interviewing each farmer, corroborating his account against that of his neighbours, his own records of precipitation past and present, and the records we had recorded at Ganora using an autographic rain gauge installed in April 2009 to provide detailed five minute monitoring of rainfall events in the catchment. This gauge was vital in the triangulation process as it gave us comprehensive data with which we could interrogate Ganora's own record and those of the adjacent stations further up the catchment.

Figure 4 shows that the rainfall stations for which we have secured data give a good representation of the altitudes of the catchment. Seventy percent of the area of the catchment lies between the elevations of Ganora and Request. We can expect, therefore, that relationships between precipitation and altitude will be typical for the catchment as a whole. For the broader study area 90 % of the altitudes are encompassed: Wellwood at lower altitude, Gordonville and Highlands at the higher altitudes.

3 The Giovanni data

Derived rainfall data was accessed from three programmes: the Modern-Era Retrospective Analysis for Research and Applications (MERRA), the Tropical Rainfall Measuring Mission (TRMM) and the Global Land Data Assimilation System (GLDAS). The three sets of remote sensed observations are instances of data that can now be accessed, visualized and analyzed using Giovanni: the Goddard Earth Science Data and Information Services Centre's web tool (Kempler, 2013a).

TRMM dates back to 1997 and was the first satellite mission to carry precipitation radar specifically designed for earth orbit (Kummerow et al., 2000). There have been many interpretations published using TRMM products, for example Adler et al. (2000), Adeyewa and Nakamura (2003), Rozante et al. (2010) and Romilly and Gebremichael

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(2011). In the present context, one relevant study is that conducted in China by Liu et al. (2012) who looked specifically at the applicability of the TRMM products we use below. MERRA is NASA's latest Earth Observation System re-analysis of its satellite imagery to improve upon the hydrological cycle's representation and to provide near real-time analysis of climate and weather (Rienecker et al., 2011). Lastly, GLDAS is an integrative programme incorporating both satellite and ground-based observations; it is comprehensively documented by Rodell et al. (2004). Our local level case study relates output from these products, accessed through Giovanni, with comparable time-series and spatial distributions. The spatial resolution of MERRA is $\frac{2}{3}$ degree of longitude and $\frac{1}{2}$ degree of latitude, for TRMM it is $\frac{1}{4}$ degree and for GLDAS it is $\frac{1}{4}$ of a degree.

4 Data treatments

4.1 Short term time series

- The daily record was analyzed for 9–12 February 2011 from seven of the stations. The stations are: Wellwood (the most southerly station), Ganora, Wilgebosch, Dalvene, Quaggasvlei, The Rest and Request.
- The hourly record from the autographic rain gauge at Ganora was analyzed for the same period (9–12 February 2011).
- The MAT1NXFLX.5.2.0 hourly time-series product was accessed from the Giovanni data server for comparative purposes. This product is part of the MERRA Hourly History Data Collection (Kempler, 2013b).

4.2 Spatial comparison

- Rainfall maps of the 9 and 12 February events were produced, bounded by the stations of Wellwood, Ganora, Wilgebosch, Dalvene, Quaggasvlei, The Rest, Request and Highlands.

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- A comparison was made of the rainfall maps with the maps we produced using data exported from:
  - The TRMM_3B42.007 product of accumulated precipitation for 9 February;
  - The GLDAS 0.25° GLDAS_NOAH025SUBP_3H.001 product of accumulated precipitation for 9 and 12 February.

4.3 Long term time series

- The empirical record (annual, monthly) of the stations with rainfall records from 1986 to 2011 was analyzed: these were Wellwood, Weltevreden, Quaggasvlei, and The Rest. We derived a regional average for the study area from their data. The starting date of 1986 was used to be compatible with data accessed from the Giovanni data server.
- Monthly data was accessed, using the GPCC_RAIN.004 and Monthly GPCP products, from the Giovanni data server (Kempler, 2013a) and compared to the regional average that we had derived. Annual totals were derived from the monthly data.

5 Results

5.1 The short term, daily time series

Figure 5 depicts the daily rainfall totals for Wellwood, Ganora, Wilgebosch, Dalvene, Quaggasvlei, The Rest and Request over the storm period of 9–12 February. The Rest received the heaviest rain on 9 February, Wellwood in the south the lowest. There was moderate rainfall on 10 February and no or low rainfall on 11 February. The high rainfall on 12 February was concentrated over Ganora and Quaggasvlei.

The modeled rainfall estimates from the MERRA hourly history data collection were poorly related to the rainfall stations, they were much lower on days with heavy falls and show significantly less daily variability (Fig. 5). The modeled value was 26 % of the regional average on 9 February, the main storm day in the mountains, and only 11 % of average on 12 February when heavy rain fell to the south and north but Dalvene experienced a much lower total. On 10 February, when moderate falls were recorded, the modeled rainfall was 33 % of the average. On 11 February, when low or zero rainfall was recorded at all stations, the modeled rainfall was higher – 126 % of the average.

Analysis at the hourly time scale used data from the autographic gauge at Ganora Farm and area specific modeled data from the MAT1NXFLX 5.2.0 (MERRA) hourly time-series product. Figure 6 compares the two outputs. (Note that the vertical scale of Fig. 6a captures data from 0–40 mm h^{-1} whilst Fig. 6b is 0–1.8 mm h^{-1}.) Ganora's recorded rainfall is collected at 5 min intervals and the MERRA data comes from hourly estimates for the area. Although the recorded values are only for one station there is no reason to think that the storm profiles would be very different at other points in the catchment over the same period.

There is poor correspondence between the observed and modeled data. Figure 6a shows that the recorded rainfall has high intensities, with the rain concentrated into short time periods (c. 1 h). The maximum recorded intensities were 21.6 and 36.6 mm h^{-1} on 9 and 12 February respectively. In contrast, the maximum modeled intensities (Fig. 6b) were 1.5 and 1.1 mm h^{-1} on 9 and 10 February and the storm duration was longer (c. 10–12 h). Conversely, the MERRA data indicates storms on the 10 and 11 February that are not apparent from the observed data. There is, therefore, not a good match between the timing and intensity of rainfall for the recorded and modeled values.

5.2 Spatial comparison

On 9 February observed rainfall totals were strongly related to the altitude of the stations (R^2 = 0.78, Fig. 7). The rainfall isopleths in Fig. 8 were produced using the kriging

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function in ArcGIS and reveal an obvious south-north trend mirroring the elevation. In contrast, there was no relationship ($R^2 = 0.16$) with altitude on 12 February, the next day of heavy rainfall, indicating that the weather forcing mechanisms were different. Figure 9 shows the rainfall isopleths peaking along the eastern tributaries of the catchment where Quaggasvlei is located.

The modeled data did not demonstrate these observed spatial trends. Figures 10 and 11 compare the spatial patterns derived from the TRMM and GLDAS products for 9 February. Both have a considerably lower range of values than that observed. TRMM predicts a maximum of 33 mm and GLDAS 26 mm when the recorded maximum was slightly under 100 mm. This is understandable as the modeled data are area averaged values rather than point data. Quite clearly, however, the GLDAS prediction is a much better estimation of spatial variation with altitude than TRMM.

Figure 12 shows the isopleths derived from the GLDAS products for 12 February. GLDAS was used because of the better fit to the observed spatial distribution on 9 February. On 12 February, however, it has a poor correspondence with the isopleths shown on Fig. 9. This is quite possibly due to the very localized pattern of heavy rainfall on 12 February in comparison to 9 February (Figs. 8 and 9).

One problem with the interpretation of the spatial variation is that the number of data points used to produce the maps are different: eight rain gauges in the catchment vs. twelve derived data points in the TRMM and GLDAS products. The modeled data also spans a wider area. The difference between the two products is, however, clear and the correspondence (or lack of correspondence) with the observed spatial variation is obvious. This is an area for future research where data from farms on the western side of the catchment area could produce a better picture of the spatial patterns across the entire catchment.

In summary, it can be seen that the short term time series accessed from Giovanni did not reliably describe localized, extreme storm rainfall over the mountainous Ganora catchment. This is not unexpected given the spatial and temporal derivation of the modeled data, but it does point to the danger of the indiscriminate use of these readily available data sets. To complete the analysis we compared the data sets at more realistic time and space scales – annual and monthly data averaged over the study area.

5.3 The long term monthly and annual time series

Long term precipitation data were available for four stations in the study area. For Wellwood, Weltevreden, Quaggasvlei and The Rest these data were analyzed from 1986 up to 2011. The Giovanni data server provided area specific modeled data for a comparable period using the GPCC_RAIN.004 and monthly GPCP products. The GPCC_RAIN.004 data is modeled from a global network of rainfall stations whilst the monthly GPCP data integrates the ground station observations from the GPCC with precipitation estimates from satellite information (Fekete et al., 2004). In our study, the area specified for modeled data lies just beyond the quaternary catchment's boundaries at 31.65° S, 24.27° E and 32.00° S, 24.80° E.

Annual rainfall data for the four stations of Wellwood, Weltevreden, Quaggasvlei and The Rest produced an average value of 450 mm for the 25 yr period from 1986. The standard deviation was 136 mm. Figure 13 shows there were two peaks of around 500 mm, two peaks of approximately 700 mm and one peak in 2011 of nearly 900 mm, the 2011 peak being double the annual average.

Both the GPCP and the GPCC data tend to follow the observed regional average of high and low rainfall years (Fig. 13), but consistently under-estimate annual precipitation and, perhaps more significantly, the peaks that create so much damage. The GPCC data for example, gives a mean of 366 mm and a standard deviation of 88 mm and, in 2011, these data estimated an annual total of 492 mm against a recorded catchment average of 875 mm. The mean for the GPCP data was 353 mm with a standard deviation of 93 mm.

The GPCP data gave the highest correlation with the observed annual totals (Fig. 14) with a strong R^2 value of 81 %. There is a consistent underestimation, however, by over

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20 % as can be seen in Fig. 14 where the best fit line for the data falls below the 1 : 1 relationship. The GPCC data gave a lower correlation, with an R^2 value of only 0.54.

We can take our examination of this relationship further by examining the monthly data from 1986 to 2011 for our regional average and the GPCP's modeled precipitation as this had the best correspondence to the annual fluctuations. Figure 15 demonstrates the close correspondence in the pattern of wet and dry months for the GPCP's modeled and the recorded regional average. It appears that these modeled data are a good estimation at the monthly time scale, though there are some noteworthy peaks and troughs where the modeled figures underestimate either the maxima or the minima.

A regression analysis for the monthly data gave a strong coefficient of determination for both data sets. The R^2 was 0.77 for the relationship between the regional average and the modeled monthly precipitation derived from the monthly GPCP area specific product. The relationship was $y = 0.72x + 3.54$ (Fig. 16). The GPCC data gave a slightly lower coefficient of determination of 0.74 with $y = 0.69x + 4.88$. We can conclude, therefore, that both the GPCP and GPCC products provide reliable estimates of monthly totals and their temporal fluctuations. Overall, however, the modeled data underestimates the observed values by around 30 %. This is significant for extreme events.

6 Conclusions

This analysis of rainfall in the upper Sundays River catchment has achieved two outcomes. The first is a description of the temporal and spatial distribution over a sub catchment that produced rare and destructive flood events. The second is a comparison of recorded data with that derived from remotely sensed imagery, freely available from the Giovanni server. The results of this second analysis provide information about the reliability of these data for flood studies, erosion research and other studies that require short-term event data.

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The flood on 9 February 2011 that caused extensive damage on Ganora Farm and downstream was produced by a short lived intensive storm centered over the upper catchment of the western tributary in which Dalvene, The Rest and Wilgebosch are located. Storm rainfall was strongly related to altitude. The autographic gauge at Ganora showed that most of the rainfall, 22 mm, fell within one hour. The total storm rainfall at Ganora was only 28 mm compared to 100 mm in the upper catchment. It is therefore likely that intensities were much higher at the centre of the storm.

The second storm on 12 February was more localized and not related to altitude. The rain was concentrated over the eastern catchment in which Quaggasvlei and Request are located. The record from Ganora shows a similar short lived storm with a higher maximum intensity (37 mm in one hour). This storm also produced local flooding but was not so destructive because the most vulnerable infrastructure had already been destroyed.

This analysis of two consecutive storms is unusual for the relatively dense data set available for the 277 km^2 catchment area over which the storms were located. Semi-arid areas are scientifically notorious for the lack of rainfall data, yet here we acquired daily data from seven gauges within or close to the catchment that produced the flood, one an autographic gauge that recorded at 5 min intervals. This relatively high density of gauges reflects the strong interest that Karoo farmers have in rainfall amounts, and accurate long term records are greatly valued. These data are not archived by the South Africa Weather Service because many farmers have resisted the change from inches to millimeters and the Weather Service will only accept metric data. As noted by Lynch (2004), this has resulted in a loss of official stations over the last forty years. Because of our local contacts with farmers in the area we have been able to tap into this informal data base, along with using our own autographic gauge at Ganora Farm.

It is tempting to believe that data such as that from the Giovanni website can be used to fill the gaps in the record based on ground stations. Our analysis has shown that while these data replicate the annual and monthly regional record with an acceptable degree of accuracy (though generally underestimating totals by 20 to 30 %), they

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are misleading when used at the daily time scale. Both the daily totals, the hourly intensities and the spatial distribution showed a significant mismatch between observed and modeled data.

The Giovanni website (Kempler, 2012) notes in its FAQs concerning using TRMM precipitation products:

Occurrence of precipitation over land tends to be underestimated, because satellite schemes tend to miss light precipitation and precipitation that is enhanced by flow lifting over mountains.

Our own analysis has also found underestimation for different temporal regimes and misrepresentation of spatial variation. These findings conform with Liu et al. (2012) who also found that the TRMM RB42 data were poor estimates of daily rainfall both spatially and temporally and they were especially deficient at estimating large storms. Thus not only do these derived products underestimate light rainfall (Kempler, 2012) but also intense storms.

Our study area typifies mountain areas of South Africa as defined by Brown et al. (2004). Using the criteria of altitude greater than 850 m, a slope angle of 5° or greater and a range of elevation exceeding 300 m, they determined that 8.3 % of the country and approximately 10 % of the broader southern Africa region consisted of mountain areas. Mountain areas of the semi-arid Sneeuberg are important for many reasons. They are vital water sources, areas of upland grazing (Chesterman, 2009) and significant sediment sources (Foster et al., 2012). Our conclusions reinforce those made by researchers who were working at larger spatial scales such as Hewitson and Crane (2005) and Hughes (2006). They speak of the need to corroborate satellite data with ground-based observations so that precipitation estimates become more reliable and more useful for water managers in these disaster prone areas. Catchment managers in such areas must be cognizant of extreme weather events, which are predicted by climate change models for South Africa (Department of Science and Technology, 2011) to become more severe in the future. While being aware of the potential of data

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available through servers such as Giovanni, they must also beware of being seduced into using modeled information without recognizing its limitations.

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References

Adeyewa, Z. and Nakamura, K.: Validation of TRMM radar rainfall data over major climatic regions in Africa, J. Appl. Meteorol., 42, 331–347, 2003.

Adler, R., Huffman, G., Bolvin, D., Curtis, S., and Nelkin, E.: Tropical rainfall distributions determined using TRMM combined with other satellite and rain gauge information, J. Appl. Meteorol., 39, 2007–2023, 2000.

Boardman, J., Parsons, A. J., Holland, R., Holmes, P. J., and Washington, R.: Development of badlands and gullies in the Sneeuberg, Great Karoo, South Africa, Catena, 50, 165–184, 2003.

Brown, T., Fox, R. C., and Funnel, D.: The "invisible" mountains: using GIS to examine the extent of mountain terrain in South Africa, Mt. Res. Dev., 24, 28–34, 2004.

Chesterman, S.: Land use in the Karoo: comparing stock and game farming with regards to veld condition and management, M. Sc. Dissertation, University of Oxford, 79 pp., 2009.

Department of Science and Technology, South Africa: South African Risk and Vulnerability Atlas, available at: http://www.rvatlas.org/download/sarva_atlas.pdf, last access: 27 October 2011.

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Fekete, B. M., Vörösmarty, C. J., Roads, J. O., and Willmott, C. J.: Uncertainties in precipitation and their impacts on runoff estimates, J. Climate, 17, 294–304, 2004.
Foster, I. D. L. and Rowntree, K. M.: Sediment yield changes in the semi-arid Karoo: a palaeoenvironmental reconstruction of sediments accumulating in Cranemere Reservoir, Eastern Cape, South Africa, Z. Geomorphol., 56, 131–146, 2012.
Foster, I. D. L., Rowntree, K. M., Boardman, J., and Mighall, T. M.: Changing sediment yield and sediment dynamics in the Karoo uplands, South Africa: post-European impacts, Land Degrad. Dev., 23, 508–522, 2012.
Hewitson, B. C. and Crane, R. G.: Gridded area-averaged daily precipitation via conditional interpolation, J. Climate, 18, 41–57, 2005.
Holmes, P. J.: Late Quaternary geomorphic palaeoenvironments of some central and marginal Great Karoo Uplands, South Africa, Ph. D. thesis, University of Cape Town, South Africa, 247 pp., 1998.
Holmes, P. J.: Central Great Karoo headwater catchments and valley fills; an overview of short term change, S. Afr. Geogr. J., 83, 274–282, 2001.
Hughes, D.: Comparison of satellite rainfall data with observations from gauging station networks, J. Hydrol., 327, 399–410, 2006.
Keay-Bright, J. and Boardman, J.: Changes in the distribution of degraded land over time in the central Karoo, South Africa, Catena, 67, 1–14, 2006.
Keay-Bright, J. and Boardman, J.: The influence of land management on soil erosion in the Sneeuberg mountains, Central Karoo, South Africa, Land Degrad. Dev., 18, 423–439, 2007.
Keay-Bright, J. and Boardman, J.: Evidence from field-based studies of rates of soil erosion on degraded land in the central Karoo, South Africa, Geomorphology, 103, 455–465, 2009.
Kempler, S.: Precipitation, http://disc.sci.gsfc.nasa.gov/precipitation/additional/faq (last access: 15 April 2013), 2012.
Kempler, S.: Giovanni – interactive visualisation and analysis, http://disc.sci.gsfc.nasa.gov/giovanni (last access: 6 April 2013), 2013a.
Kempler, S.: MERRA hourly history data collection, http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=MERRA_HOUR_2D (last access: 6 April 2013), 2013b.
Kummerow, C, Simpson, J., Thiele, O., Barnes, W., Chang, A., Stocker, E., Adler, R., Hou, A., Kakar, R., Wentz, F., Ashcroft, P., Kozu, T., Hong, Y., Okamoto, K., Iguchi, T., Kuroiwa, H., Im, E., Haddad, Z., and Huffman, G.: The status of the Tropical Rainfall Measuring Mission (TRMM) after two years in orbit, J. Appl. Meteorol., 39, 1965–1982, 2000.

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Liu, J., Zhu, A.-X., and Duan, Z.: Evaluation of TRMM 3B42 precipitation product using rain gauge data in Meichuan watershed, Poyang lake basin, China, J. Resour. Ecol., 3, 359–366, 2012.

Lynch, S. D.: Development of a raster database of annual, monthly and daily rainfall for Southern Africa, Water Research Commission Report 1156/1/04, Water Research Commission, Pretoria, South Africa, 107 pp., 2004.

Mason, S., Waylen, P., Mimmack, G., Rajaratnam, B., and Harrison, J.: Changes in extreme rainfall events in South Africa, Climate Change, 41, 249–257, 1999.

Middleton, B. J. and Bailey, A, K.: Water resources of South Africa 2005, Water Research Commission Report, TT 380/08, Water Research Commission, Pretoria, South Africa, 188 pp., 2009.

Rienecker, M., Suarez, M., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M., Schubert, S., Takacs, L., Kim, G., Bloom, S., Chen, J., Collins, D., Conaty, A., da Silva, A., Gu, W., Joiner, J., Koster, R., Lucchesi, R., and Molod, A.: MERRA: NASA's modern-era retrospective analysis for research and applications, J. Climate, 24, 3624–3648, 2011.

Rodell, M., Houser, P. R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entini, J. K., Walker, J. P., Lohmann, D., and Toll, D.: The Global Land Data Assimilation System, B. Am. Meteorol. Soc., 85, 381–394, 2004.

Romilly, T. G. and Gebremichael, M.: Evaluation of satellite rainfall estimates over Ethiopian river basins, Hydrol. Earth Syst. Sci., 15, 1505–1514, doi:10.5194/hess-15-1505-2011, 2011.

Rowntree, K. M. and Foster, I. D. L.: A reconstruction of historical changes in sediment sources, sediment transfer and sediment yield in a small, semi-arid Karoo catchment, South Africa, Z. Geomorphol. Supp., 56, 87–98, 2012.

Rozante, J., Moreira, D., de Goncalves, L., and Vila, D.: Combining TRMM and surface observations of precipitation: technique and validation over South America, Weather Forecast., 25, 885–894, 2010.

S.A. Weather and Disaster Information Service: Nieu Bethesda farmers count flood costs, http://saweatherobserver.blogspot.com/2011/02/nieu-bethesda-farmers-count-flood-costs.html (last access: 2 April 2013), 2011.

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Fig. 1. The first flood, Wilgerbosrivier 9 February 2011: at 17:23 LT (left panel), right at 18:55 LT (right panel).

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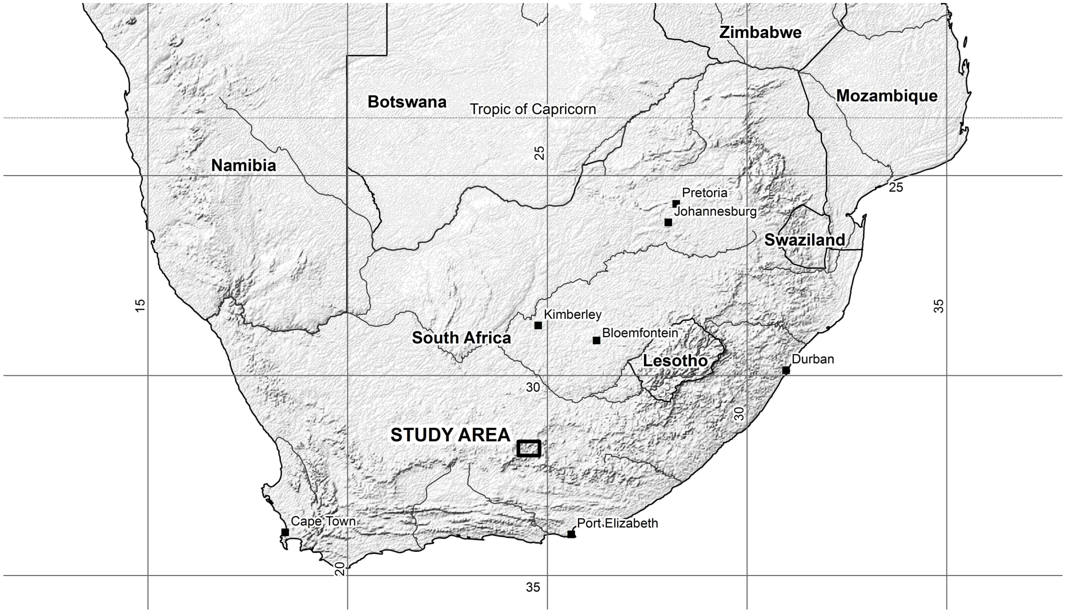

Fig. 2. Location of the study area.

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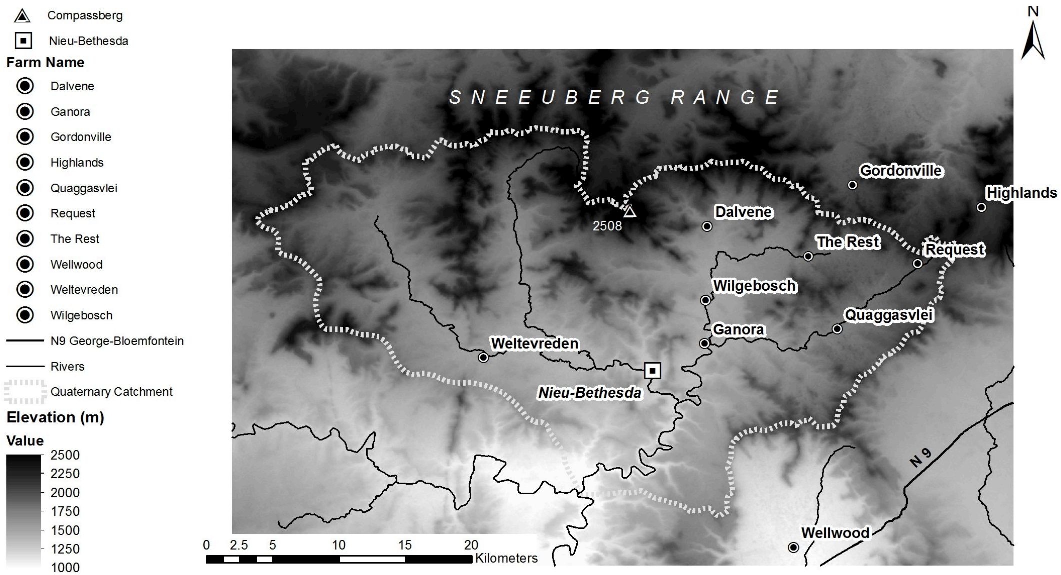

Fig. 3. The study area showing topography and rainfall stations.

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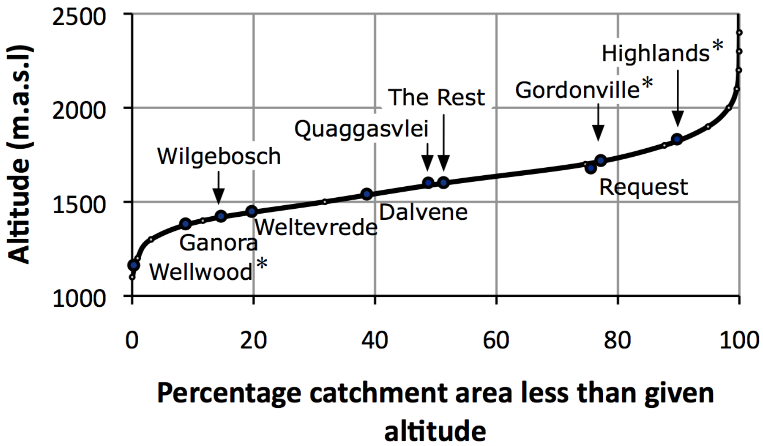

Fig. 4. Hypsometric graph: distribution of catchment area by altitude. (Wellwood, Gordonville and Highlands lie just beyond the catchment boundaries but within the broader study area.)

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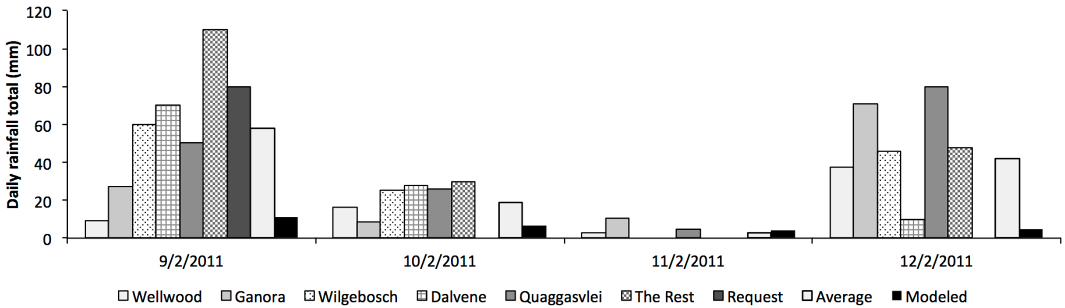

Fig. 5. Daily rainfall over the storm period 9–12 February 2012.

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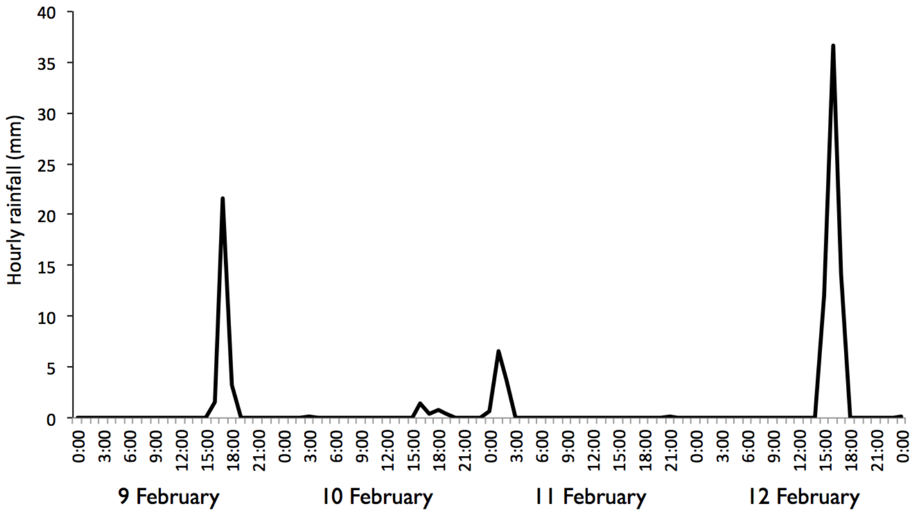

Fig. 6a. Ganora Farm autographic rain gauge: hourly rainfall over the storm period.

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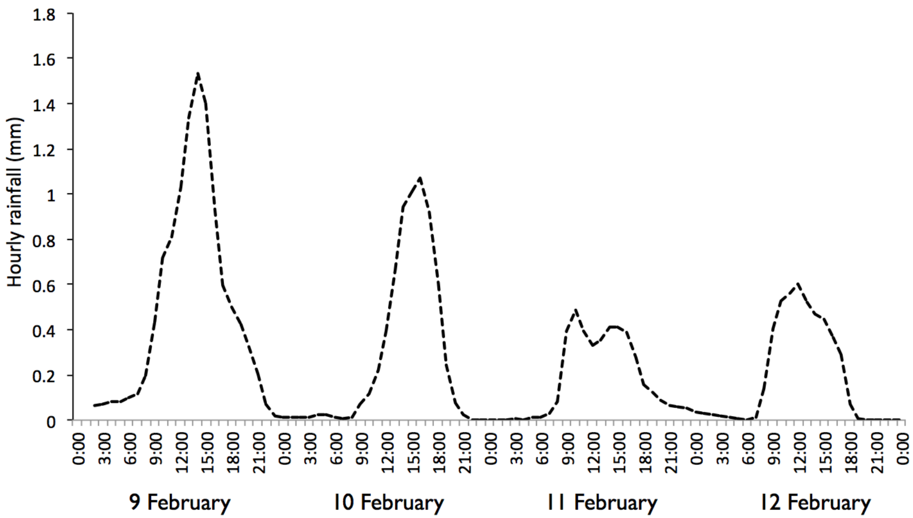

Fig. 6b. Modeled hourly rainfall over the storm period (from MERRA).

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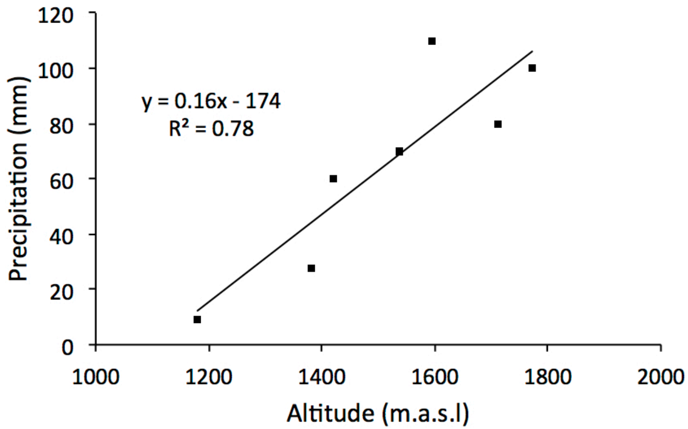

Fig. 7. Relationship between altitude and precipitation on 9 February.

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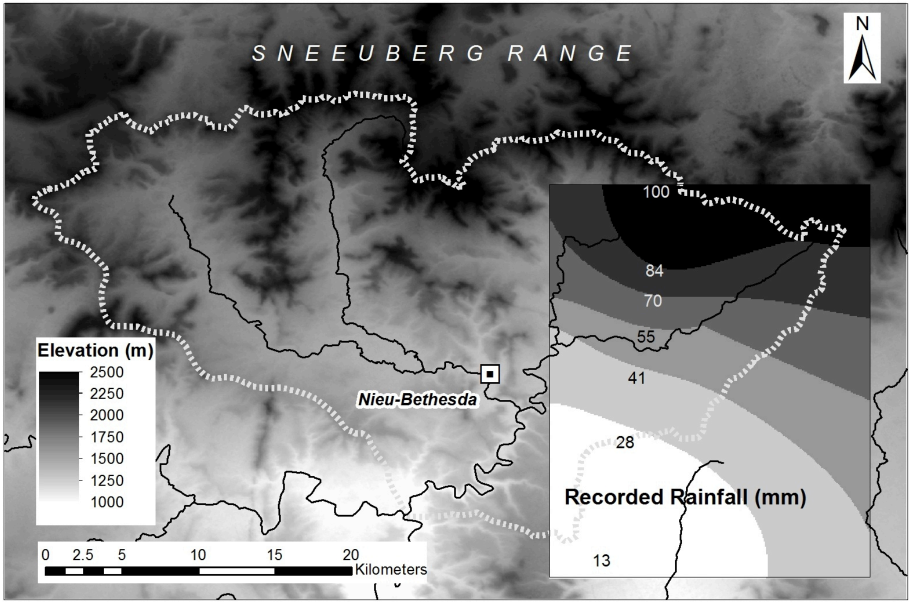

Fig. 8. Rainfall isopleths for 9 February 2011.

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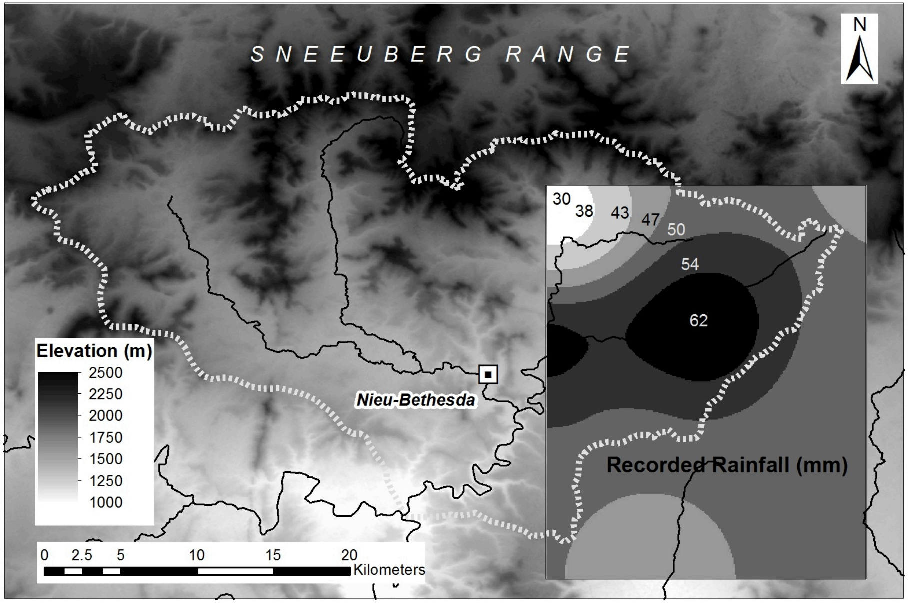

Fig. 9. Rainfall isopleths for 12 February 2011.

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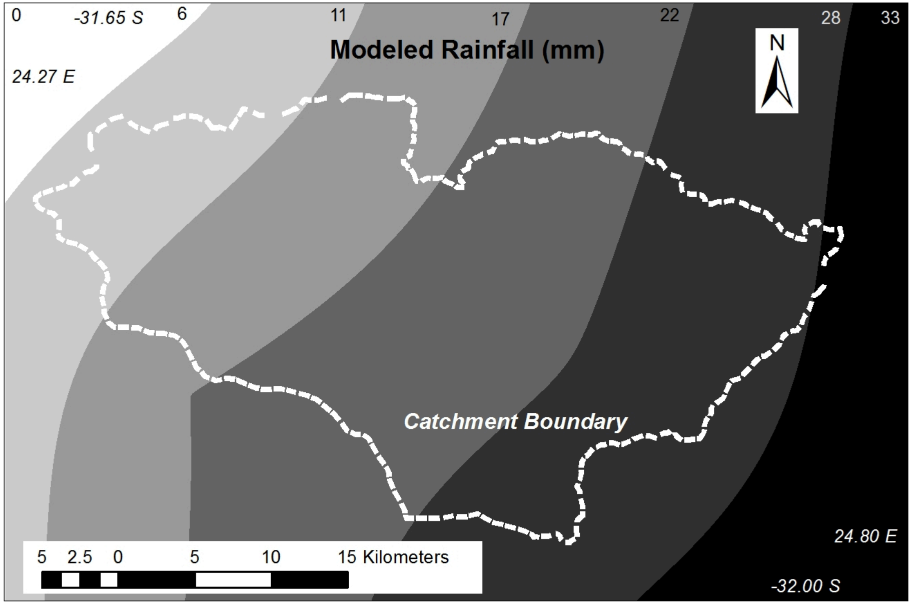

Fig. 10. Rainfall isopleths for 9 February derived from the TRMM product.

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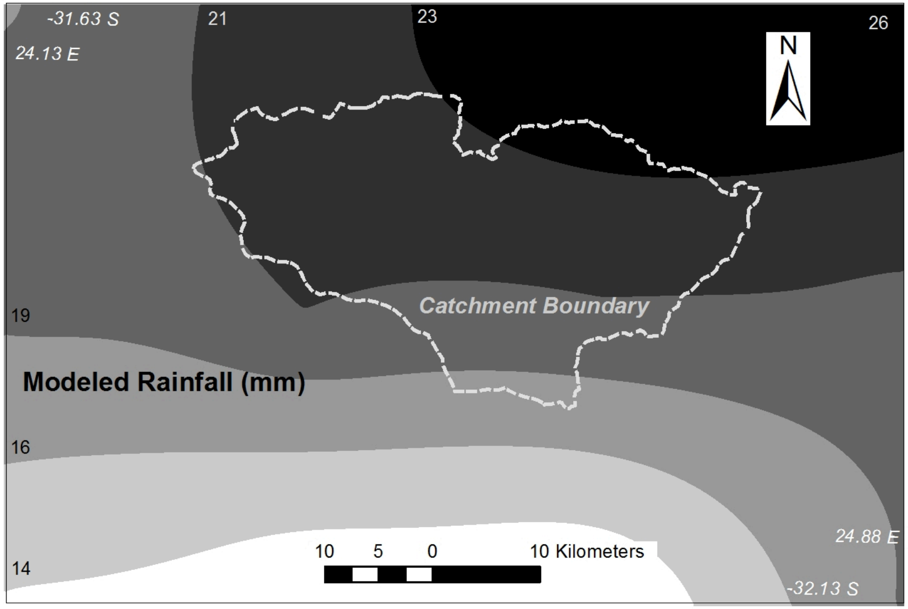

Fig. 11. Rainfall isopleths for 9 February derived from the GLDAS product.

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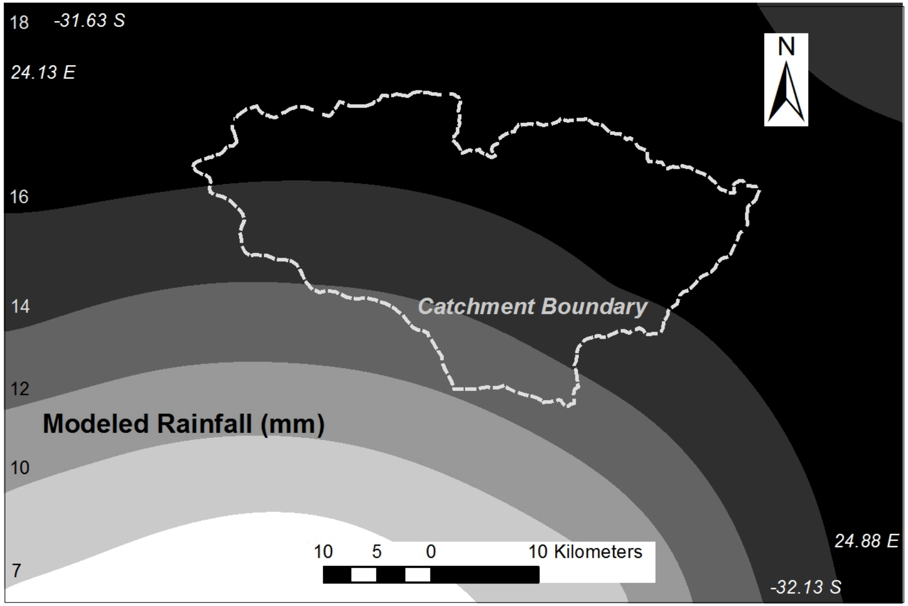

Fig. 12. Rainfall isopleths for 12 February derived from the GLDAS product.

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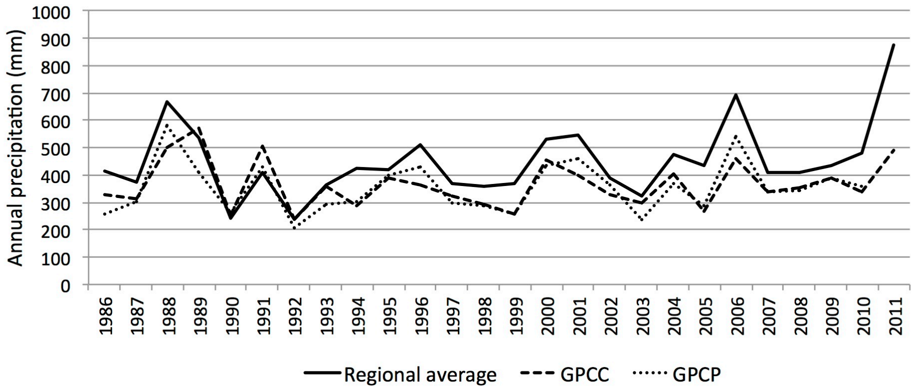

Fig. 13. Longer term annual rainfall trends 1986–2011 (GPCP data to 2010).

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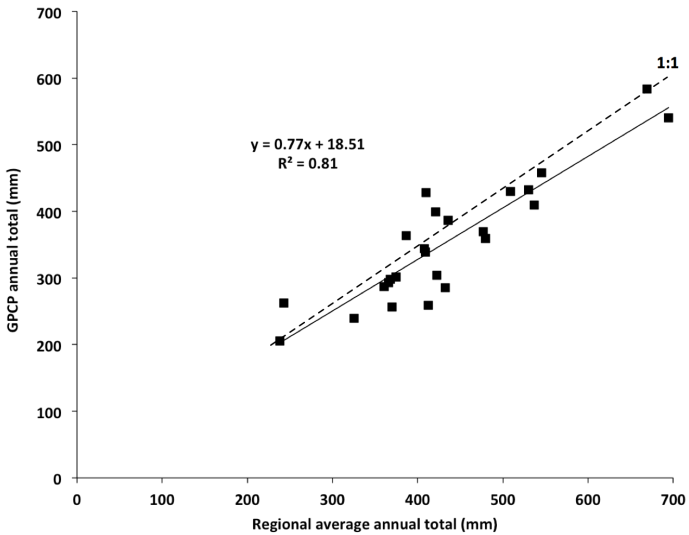

Fig. 14. Relationship between GPCP precipitation and regional average annual totals, 1986–2010.

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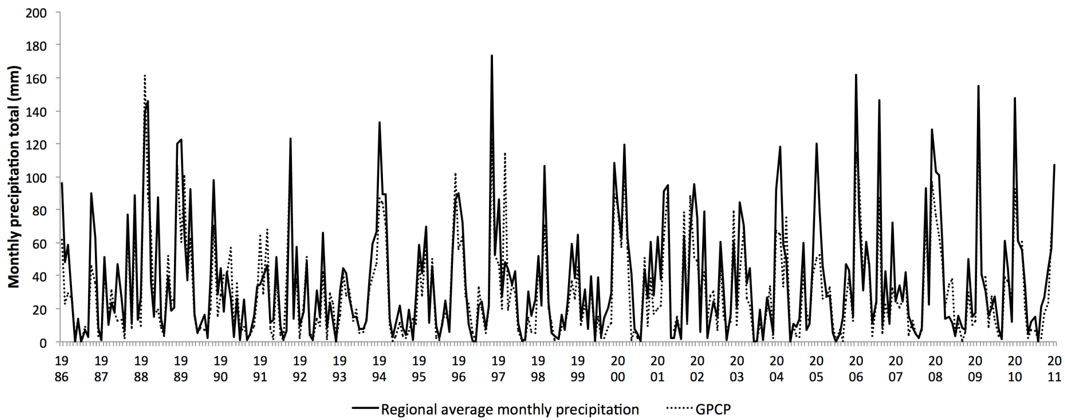

Fig. 15. Monthly precipitation time series GPCP and regional averaged data from 1986 to February 2011.

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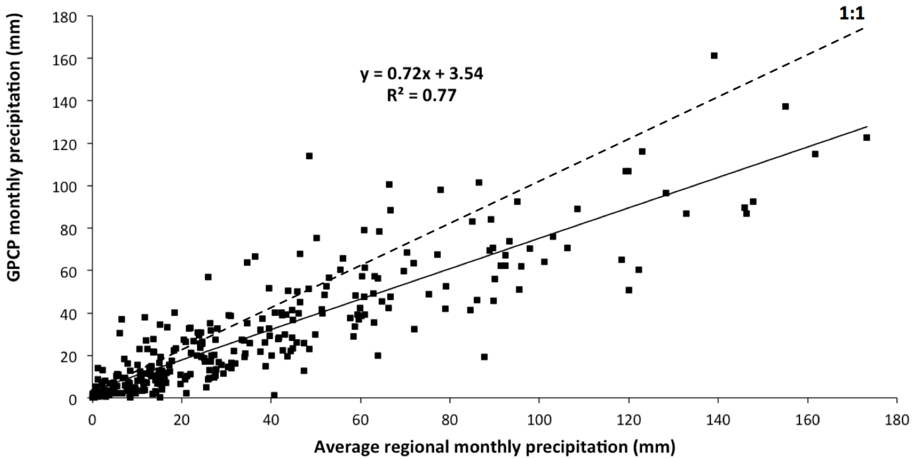

Fig. 16. Relationship between GPCP modeled precipitation and regional average monthly totals, 1986–2010.