OFFICE OF ENVIRONMENT AND HERITAGE

REVISED 2016 DESIGN RAINFALLS INVESTIGATIONS INTO THE NEED FOR AND DERIVATION OF LOCAL TECHNIQUES

FINAL REPORT

JULY 2018

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LIST OF ACRONYMS

AEP	Annual Exceedance Probability
ARI	Average Recurrence Interval
ALS	Airborne Laser Scanning
ARR	Australian Rainfall and Runoff
BOM	Bureau of Meteorology
DECC	Department of Environment and Climate Change (now OEH)
DNR	Department of Natural Resources (now OEH)
DRM	Direct Rainfall Method
DTM	Digital Terrain Model
GIS	Geographic Information System
GPS	Global Positioning System
IFD	Intensity, Frequency and Duration (Rainfall)
mAHD	meters above Australian Height Datum
OEH	Office of Environment and Heritage
PMF	Probable Maximum Flood
SRTM	Shuttle Radar Topography Mission
TUFLOW	one-dimensional (1D) and two-dimensional (2D) flood and tide simulation software (hydraulic model)
WBNM	Watershed Bounded Network Model (hydrologic model)

EXECUTIVE SUMMARY

As part of the revision of Australian Rainfall and Runoff (ARR, Ball et al, 2016), the Bureau of Meteorology (BOM) updated the Intensity-Frequency-Duration (IFD) design rainfalls using more modern methods and incorporating significantly more data than the design rainfalls derived for Australian Rainfall and Runoff 1987 (ARR1987) (Pilgrim 1987). In general, the additional data and new methods create significantly better estimates than the previous instalment, however the changes in IFD values can be quite significant and will have a large impact on design flood estimates.

While the 2016 IFDs are based on a much larger dataset and more up to date techniques than the 1987 IFDs and are generally considered more reliable throughout NSW, in some areas with a significant flood problem Councils have questioned the new estimates. For some areas on the coastal strip, such as near Wollongong, and Coffs Harbour, the rapid variation in the terrain can result in unique local rainfall driving mechanisms, such as orographic enhancement, that could significantly influence rainfall frequency estimates, in addition to elevation. The long-term concern with rainfall gradients in these areas has lead the NSW government to invest in a network of rainfall gauges that allows localised investigations of design rainfall. These locations are also currently investing in flood mitigation and are concerned that under-estimation of IFD values could lead to poor design of works.

It has been suggested that these localised factors may not be able to be adequately represented in approaches that were fit for purpose for a broad-scale national approach used to derive the IFDs and that local approaches that have historically been used for these short duration catchments might need to be continued.

To investigate whether localised approaches may be worthwhile into the future, the Office of Environment and Heritage engaged WMAWater Pty Ltd to examine the IFDs in these sensitive locations to determine whether consideration of local techniques may be warranted, and if so, to examine the development of local techniques that would enable the derivation of finer scale IFD grids that may better represent the significant variation in at-site data in these locations.

This report compares at-site data with the 2016 IFD and demonstrates that in the flatter areas of Wollongong away from the escarpment there is slight overestimation of site data with the 2016 IFD but in the immediate vicinity of the escarpment the 2016 IFD estimates tend to underestimate for durations around 3 hours. A modified approach based on the techniques used in the 2016 IFD has been developed area which captures the localised effect of the escarpment. Figure 38 shows the 2016 IFDs overestimate at-site data in flatter areas of Wollongong away from the escarpment, while Figure 41 and Figure 42 show underestimation in the escarpment areas and how the new methods address this issue. Figure 40 to Figure 42 also show that the previous 1987 IFD generally overestimated and some of the reduction is due to the removal of this bias.

The comparison of at-site data with 2016 IFDs in the Coffs Harbour area revealed that like Wollongong the low-lying areas were being overestimated and the gauges along the escarpment were being underestimated. An approach using aspects of the method that created the 2016 IFD was used to derive IFD estimates in the area that mitigates risk from using potentially underestimated values in this area. Figure 48 through Figure 50 compares the regionalised estimates used for the escarpment with site data. Figure 56 highlights the differences between the proposed Coffs Harbour IFDs and the techniques used for the 2001 Coffs Creek Flood Study (Webb, Mckeown & Associates, 2001), highlighting that the proposed values are higher than both the 2016 IFDs and techniques used in the past.

Although the input data and the methods of the 2016 IFDs yield significant improvements to the 1987 IFDs on a broad scale, for the areas of Coffs Harbour and Wollongong, improvements in estimates have been made using the methods described in this report. Australian Rainfall and Runoff (Ball et. al, 2016) recommends the use of improved information where available, and it is therefore recommended to either use the estimates made in this study or the envelope of these estimates and the 2016 IFDs.

> "*Therefore, where circumstances warrant, designers have a duty to use other procedures and design information more appropriate for their design flood problem"*

1. INTRODUCTION

As part of the revision of Australian Rainfall and Runoff (ARR, Ball et al, 2016), the Bureau of Meteorology (BOM) updated the Intensity-Frequency-Duration (IFD) design rainfalls using more modern methods and incorporating significantly more data than the design rainfalls derived for Australian Rainfall and Runoff 1987 (ARR1987) (Pilgrim 1987). In general, the additional data and new methods create significantly better estimates than the previous instalment, however the changes in IFD values can be quite significant and will have a large impact on design flood estimates in many areas of NSW.

This study was funded by the Office of Environment and Heritage (OEH) to help councils understand the differences between local rainfall data and the old and new IFD estimates. The role of OEH is to provide technical advice to councils so they can make informed policy decisions.

The BOM released interim IFDs in 2013 and revised IFDs in 2016. In the 2016 revision more frequent AEPs and shorter durations still use the 2013 method. However, the 2016 revision used a revised method for the 2% and 1% AEP estimates for durations of 1 – 7 days. This involved using stations with longer periods of record and increasing the station pooling from 500 years to a desired amount of 2000 years. LH2 moments were also used in place of zero shift L-moments (which are used for AEPs of 5% and more frequent and for durations less than 1 day) to better fit at-site rainfall data at the rarer end of the GEV distribution. These changes also impacted durations shorter than 1 day, as new polynomials needed to be fitted to the changed data, which resulted in a slight change in IFD values for the shorter durations at these AEPs.

The 2016 IFDs are based on a much larger dataset and more up to date techniques than the 1987 IFDs, and will in general yield better estimates for most of NSW. However, it was recognised that for some areas on the coastal strip, such as near Wollongong, Gosford and Coffs Harbour the rapid variation in the terrain can result in unique local rainfall driving mechanisms, such as orographic enhancement, that could significantly influence rainfall frequency estimates, in addition to elevation.

It could be expected that these localised factors may not be able to be adequately represented in approaches that were fit for purpose for a broad-scale national approach used to derive the IFD and at the grid density at which these are provided nationally. It should be noted that local approaches have been used in NSW in certain areas, including Coffs Harbour for many years. All editions of Australian Rainfall and Runoff allows and in fact encourages designers to adopt alternative design inputs where they better fit local data (ARR, Ball et. al, 2016).

> "*Therefore, where circumstances warrant, designers have a duty to use other procedures and design information more appropriate for their design flood problem"*

To investigate whether localised approaches may be worthwhile into the future, the Office of Environment and Heritage engaged WMAWater Pty Ltd to examine the IFDs in these sensitive locations to determine whether consideration of local techniques may be warranted, and if so, to examine the development of local techniques that would enable the derivation of finer scale IFD grids that may better represent the significant variation in at site data in these locations.

Section 2 of this report outlines the available data. Sections 3 and 4 discuss the differences between 1987 IFD, 2016 IFD and at site data. Section 5 provides a synopsis of the results and recommendations of this initial assessment into the fitness for purpose of IFDs derived using the broad-scale technique at Wollongong, Coffs Harbour and Gosford. In response to the recommendations outlined in Section 5, an examination of local techniques for deriving finer scale IFD grids for Wollongong respectively to address local biases and then compare these to the 2016 IFDs are outlined in Section 6. Section 7 examines the use of local data to address local bias in the IFD grids for the Coffs Harbour area and proposes values that would mitigate the impact of underestimating IFDs.

The recommendations of this investigations will be made available to the relevant local councils and relevant state agencies for their consideration in relation to whether to use the derived IFD information in decision making.

2. AVAILABLE DATA

2.1. 1987 IFD Grids

The design rainfall intensity grids that were used in conjunction with ARR87 were obtained from the Bureau of Meteorology website (BOM, 2017). These grids were available at the durations and ARIs listed in Table 1, at a resolution of 0.025° covering the entire country. These grids were not naturally aligned with the 2016 IFD grids, so the 1987 IFD grids were re-extracted at the cell centres of the 2016 IFD grids to do direct comparisons.

Table 1: ARIs and durations of the available ARR87 IFD grids

AEP (%)	Durations (minutes)
1EY, 39.35, 18.13, 10, 5, 2, 1	5, 10, 30, 60, 120, 180, 360, 720, 1440, 2880, 4320

For AEPs of 50%, 20% and 10% 1987 IFD grids were not available, so these values were interpolated using Equation 1

$$Rainfall_x = Rainfall_{AEP1} - \frac{Rainfall_{AEP1} - Rainfall_{AEP2}}{GumbAEP_{AEP1} - GumbAEP_{AEP2}} \times (GumbAEP_{AEP1} - GumbAEP_{AEPx}) \quad (1)$$

$where$: $GumbAEP_x = -log\left(-log(1 - AEP_x)\right)$

$AEP_x = AEP\ of\ interest$

$AEP_1 = AEP\ above\ AEP\ of\ interest$

$AEP_2 = AEP\ below\ AEP\ of\ interest$

2.2. IFD 2016 Grids

The design rainfall grids that are recommended for use with ARR2016 were obtained from the Bureau of Meteorology website (BOM, 2017). These grids were extracted at all durations and the AEPs listed in Table 3. These grids are also at a resolution of 0.025° and cover the entirety of the country.

2.3. Bureau of Meteorology Daily Read Rain Gauge Data

Data for daily read and pluviography gauges in the Wollongong area were obtained. These gauges had record lengths ranging from 20 to 128 years. Daily read gauges record rainfall that falls between 9am and 9am, as such these totals will not necessarily reflect the maximum 24-hour total that is not restricted to a time window. To account for this standard restricted to unrestricted conversion factors are applied to the data as listed in Table 2.

Table 2: Restricted to unrestricted factors for daily read rainfall gauges

Duration (days)	Restricted to Unrestricted Factor
1	1.15
2	1.11
3	1.07
4	1.05
5	1.04
6	1.03
7	1.02

2.4. Manly Hydraulics Laboratory and Other Agency Pluviometer Data

Data for 79 Manly Hydraulics Laboratory (MHL) pluviometers were provided by MHL. These gauges have record lengths from 2 to 33 years and their data is in 5 minute increments. The records extend to early 2017.

Pluviometer data was obtained from Sydney Water and Water NSW this gauging network lies mostly on the escarpment and has similar records to the 2016 IFDs.

There are additional stations with short record lengths in the area that were not included in the analysis due to there not being enough Annual Maximum Series (AMS), although they could be used for validation.

2.5. Quality Controlling Rainfall Data

All Manly Hydraulics and other agency pluviometer data was quality controlled using both automated and manual methods. Years with more than 165 days missing had their values rejected unless they were in the top 10% of AMS for that site. The selected AMS were manually compared to nearby sites and BoM daily rainfall totals to further support their values. Fitted distributions and AMS were visually inspected and outliers were re-checked against neighbouring sites. Any values that were not supported by neighbouring stations were removed and replaced by another event.

For the BoM rainfall data, it was assumed that the quality control procedures implemented by the BoM were sufficient. Large rainfall values flagged as an accumulation were disaggregated using the rainfall of the nearest BoM gauge with values for the aggregated days.

Appendix D shows the record length and amount of missing data for each of the gauges used.

2.6. Shuttle Radar Topographic Mission DEM

The Consortium for Spatial Information's 90m- Shuttle Radar Topographic Mission (SRTM, NASA 2017) DEM data was used to derive covariates for gridding and regionalisation. This 90m resolution DEM is not of comparable accuracy to LiDAR however, given the uncertainty in IFD analysis, it is considered appropriate for use with IFD data as it gives a wide scale picture of elevation variations, which is suitable for deriving covariates.

3. GRID DIFFERENCES BETWEEN 1987 AND 2016 IFDS

3.1. Methodology

Since design flood estimates are often based on design rainfall inputs, significant changes in the design rainfalls can have a large impact on design flood estimates. To determine the magnitude of the changes between the 2016 and 1987 IFDs, percentage differences were calculated using Equation 2. This was done for the durations and exceedance probabilities listed in Table 3.

$$Percentage\ difference = \frac{2016IFD - 1987IFD}{1987IFD} \times 100 \qquad (2)$$

Table 3: Exceedence probabilities and durations for which percentage differences were calculated.

Annual Exceedance Probabilities	Durations (min)
1EY, 50%, 20%, 10%, 5%, 2%, 1%	5, 10, 30, 60, 120, 180, 360, 720, 1440, 2880, 4320

In general, there is more divergence between datasets at rarer AEPs and shorter durations. This can be attributed to the expansion of the dataset for the 2016 IFDs and differences in the methods to derive the grids. The trend for rarer AEPs having more pronounced differences is likely due to the increased sensitivity these values have to changes in data and method. Both rarer AEPs and shorter durations have higher uncertainty in their estimates and hence will exhibit more variability, this higher variability is another possible explanation for the more pronounced differences.

For durations shorter than 1 day, the 1987 design rainfalls were based on rainfall data from 600 sub-daily gauges with 6 years of record or greater (Green 2015). Sub-daily estimates were derived at daily stations using principal component analyses, using sub-daily stations with greater than 12 years of record. There were very few sub-daily sites with this length of record at the time of this analysis, resulting in high levels of uncertainty for the sub-daily estimates.

The 2016 IFDs used 2,280 sub-daily stations with 8 years of record or greater (Green 2015), estimates were derived at daily stations using a Bayesian least squares regression (BGLSR) regionally. The extra stations and better regression in the 2016 IFDs resulted in significantly more accurate IFD estimates for durations shorter than 1 day, compared with those derived for AR&R87. Comparisons between the 2016 IFDs and the AR&R87 values were undertaken by the BoM as part of the IFD process and sensitive areas or areas with high impact were targeted in the gridding process to ensure optimal results.

There are a range of durations that could be assessed, however to simplify the considerations and focus on the values with highest impacts, one duration was chosen as a representative case study in each area. In Coffs Harbour and Wollongong there is a high density of sub-daily stations and these areas can experience significant impacts of flooding from high intensity short duration rainfalls. Therefore, a duration of 3 hours was chosen as a case study in these areas as it can have a significant impact on design flood estimates and the differences at the 3-hour duration represents the differences over the rest of the applicable durations for the area well. The area surrounding Gosford has comparatively less sub-daily stations, which would limit analyses at shorter durations, and is home to the Tuggerah lake catchment, which can experience flooding at longer durations. Hence a duration of 1 day was chosen as a case study in this area.

The IFDs at rarer AEPs are most likely to have the most pronounced differences to at-site data, however they are also the least accurate, making it more difficult to highlight problems with the method of deriving IFD grids. The 5% AEP has been chosen for investigation as it is directly comparable to the 20 year ARI of the 1987 IFD grids and will have more accuracy than the 1% and 2% AEPs.

The differences between these datasets is indicative of areas that may be highly impacted by the IFD changes and does not help to indicate which values are the most correct. When the potential impact of differences is high, there is likely benefit from further scrutiny of IFD estimates to ensure they are as accurate as possible. Being that the 2016 IFDs utilise a much larger dataset and more advanced method it is likely that they are more correct for the vast majority of areas, however it is possible that certain local areas may be better represented by the 1987 IFDs.

3.2. IFD grid differences in the Wollongong area

In the Wollongong area percentage differences between the 2016 and 1987 IFDs at the 3-hour duration and 5% AEP (Figure 1) reveal that the 2016 IFDs are significantly lower than the 1987 IFDs in most of the area near Wollongong. The areas that are most affected are along the foot of the escarpment and in the corner of the range to the SW, where the 2016 IFDs are more than 30% lower than the 1987 IFDs. This change has implications for event frequency, for example at the Wollongong grid cell a 5% AEP using the 2016 IFDs would only translate to an AEP of approximately 20% using the 1987 IFDs. These differences persist throughout most durations over this area, and will significantly impact design flood estimates.

3.3. IFD grid differences in the Coffs Harbour area

In the Coffs Harbour area for the 3-hour duration and 5% AEP (Figure 1), the 2016 IFDs are generally larger or very close to the 1987 IFDs. The magnitude of the differences along the coast is generally between 5% and 10%, and in the more elevated areas near the top of the catchment the differences are less than 5%. In terms of event frequency, implications are relatively minimal. For example, a 5% AEP using the 2016 IFDs would translate to an AEP of approximately 4% using the 1987 IFDs.

Although grid differences are small in this area, the 1987 IFDs were generally considered to be low around the escarpment in the past, which resulted in local techniques being used to make flood frequency estimates (Webb, Mckeown & Associates, 2001). There are therefore potential for impacts for flood estimation in this area and the validity of local estimates needs to be reconsidered.

3.4. IFD grid differences in the Gosford area

In the Gosford area the 1 day duration 5% AEP rainfall in the upper Tuggerah Lake catchment is significantly lower in the 2016 IFDs compared with the 1987 IFDs. Differences range from 0 to 30% and tend to increase with elevation. This change has moderate implications for event frequency. For example, in some areas of the Tuggerah Lake catchment, a 5% AEP using the 2016 IFDs would translate to an AEP of approximately 8% using the 1987 IFDs. These differences may cause some impact to design flood estimates in the Tuggerah Lakes catchment, but are not widespread and are very small in many areas.

4. DIFFERENCES BETWEEN 2016 IFDS AND SITE ESTIMATES

4.1. Methodology

The method used to derive 2016 IFDs drew on data from 8074 BOM daily read rainfall stations and 2280 sub-daily stations to create estimates a grid resolution of 0.025° over Australia (Green 2015). To derive these IFD grids, L-moments were derived at each site using the annual maximum series (AMS). The higher order L-moments, L-CV and L-skew, were then regionalised by doing a weighted average based on number of AMS at several sites (Green 2012c). Regionalisation increases the effective record length of rainfall frequency estimates which is the driving factor for increased confidence at rarer AEPs (Hosking and Wallis 1997). Generalised Extreme Value distributions (GEV) were then fitted using these L-moments and the parameters of these distributions were gridded using ANUSPLIN gridding software (Beesley et. al. 2014a). Since the final grids are essentially representing aggregated site data from the area, differences between site estimates and the 2016 IFD grids can highlight biases that arise from this method.

To assess these differences IFD estimates were derived at rainfall stations in the area of interest. The AMS was extracted for each site and a GEV was fitted to the AMS using L-moments. Using the fitted GEV distributions, rainfall estimates were extracted for the AEPs listed in Table 3. Percentage differences to the 2016 IFD grid were then calculated using Equation 3, shown in Figure 2 and Figure 3.

$$Percentage\ difference = \frac{IFD2016 - Site}{Site} \times 100 \tag{3}$$

Individual sites generally have short records and cannot provide accurate rare AEP rainfalls. The regionalisation and gridding steps aim to address this problem by substituting time with space, which should create a scatter of low and high differences in at-site estimates. However, consistently low or high differences can indicate a bias in the method or over-smoothing of the data. Like the grid differences, they are in general higher for rarer AEPs and shorter durations due to higher levels of uncertainty and more noise in the data.

While the percentage differences help to give an indication of the differences in 2016 IFD at at-site estimates, they do not accurately reflect the statistical significance of the differences, since they fail to account for higher levels of uncertainty at rarer AEPs and for gauges with shorter record lengths. To investigate the statistical significance of these differences, confidence limits of the fitted at-site GEV distributions were derived using bootstrapping of the AMS. This process involves randomly sampling an AMS pool of the same size as the observed AMS from the observed AMS 500 times. This created sets of AMS with random years repeated and others excluded. GEV distributions were then fitted using L-moments to the 500 sets of AMSs, and values at the relevant exceedance probabilities were extracted. Quantiles of 2.5% and 97.5% were then taken from these sets of 500 values to get the 95% confidence limits. It was then determined which proportion of the samples were smaller than the 2016 IFDs. Values close to 50% correspond to the 2016 IFDs being close to the site estimates. These values can be seen in Figure 5.

The first L-moment, known as index rainfall, is the average of the AMS. This value has a high correlation to the 50% AEP design rainfall, so a general indication of the difference between site and gridded index rainfall can be determined by investigating the differences at the 50% AEP. Accurate representation of index rainfall is important for deriving rainfall frequency estimates since it is the best representative for local conditions and even small sets of AMS will give accurate values. Percentage differences, calculated using Equation 2, are shown in Figure 2.

The second and third L-moments, L-CV and L-skew, define the gradient and shape of the GEV distribution. While these are the parameters that are regionalised, they are closely dependent on one another. A low L-CV can be compensated for with a high L-skew and vice versa, so this interdependence creates more noise in the data. Hence to consider these values together, the 5% AEP rainfall was divided by the 50% AEP rainfall, as this basic gradient will be impacted by both L-CV and L-skew. Percentage differences between at-site growth factors and 2016 IFD growth factors were calculated using Equation 3, and are shown in Figure 4.

4.2. Wollongong Area

The area surrounding Wollongong has some pronounced topographical features that drive rainfall distribution magnitude. There is a steep escarpment facing the coast which can force moist air, that is traveling from the east, to rise and produce rainfall. This is known as orographic enhancement. This causes significantly higher mean annual rainfalls on the escarpment than in the relatively flat terrain below, and causes significant rainfall events to be especially large in the area.

There are patches of significant local bias in 2016 IFDs compared with the at-site rainfalls for the 3-hour duration 5% AEP rainfalls. These rainfalls at stations surrounding Lake Illawarra are significantly overestimated by the 2016 IFDs, as evidenced by the fact that 97.5% of the bootstrapped sample gives estimates below the 2016 IFDs in much of this area (Figure 5). On the escarpment, the at-site design rainfalls are underestimated by 2016 IFDs, although this is not as severe as the overestimation in the low-lying areas.

Index rainfall and the higher order L-moments show similar biases in this area as can be seen in Figure 2 and Figure 4. The use of regressed values at daily stations could be causing some of these differences, since the proportion of the regional AMS pool taken by daily stations in this area is high (Figure 8) and using regressed values will in general bring estimates closer to the average for the dataset.

4.3. Coffs Harbour

Coffs Harbour and the surrounding area is also home to some pronounced topographical features that drive rainfall distribution. While the escarpment at Coffs Harbour also produces orographic enhancement of rainfall, rainfall magnitudes are much more dependent on wind direction. Moist air coming from the NE will generally cause more rainfall to fall on the NE facing sections of the escarpment to the north of Coffs Harbour, and less rainfall to fall on the south facing area. Moist air coming from the SW produces higher rainfalls on the SW facing section of the escarpment and lower rainfalls on the NW. These features mean that design rainfalls in the area can be quite dependent on location and which set of rainfall events are in the dataset of a given gauge, since gauges with short records can easily miss the events with the most significant orographic enhancement.

The 3hr duration 5% AEP rainfalls at sub-daily gauges in the Coffs Harbour area along the escarpment are under-estimated by the 2016 IFDs, while this rainfall at the low-lying airport gauge is overestimated. The gauges where design rainfalls are under-estimated show values well within the site confidence limits. The rainfall at the gauge where design rainfall is over-estimated is close to the confidence limits (Figure 6).

Higher order L-moments in this area show a similar trend, L-moments at gauges on the escarpment being underestimated and the low-lying gauges being overestimated by the method used to derive the 2016 IFDs. Index rainfall in this area appears to be unbiased with a scatter of differences around all the gauges (Figure 2).

There are several long record daily gauges in this area that cover many of the gaps in stations, such as to the North of Coffs Harbour. Regressed values from these stations are likely having a significant impact on 2016 IFD estimates since they take a large proportion of the AMS pool (Figure 8) and may be the cause of the increased rainfall estimates.

4.4. Gosford

The area around Gosford has steep terrain and is home to the Tuggerah Lake catchment. This catchment is large and is sensitive to flooding due to longer duration rainfalls for the lake and shorter duration rainfalls for its tributaries. Since the area has steep terrain it has high annual rainfall and can create some orographic enhancement.

Most of the long record gauges in the Gosford area have at-site design rainfall estimates that are relatively close to the 2016 IFDs. It is difficult to identify a trend in the spatial distribution of the differences between the 2016 IFDs and the bootstrapped sample, which indicates that it is unlikely there is a bias towards higher or lower rainfall estimates in this area. There is also little trend in differences for the L-moments. Therefore, differences in IFD estimates are likely due to the smoothing of the noise in the data via the regionalisation and gridding processes, which is desirable and is the advantage of using these steps.

5. RECOMMENDATIONS OF INITIAL ASSESSMENTS

The 2016 IFD grids are a much better representation of design rainfalls than the ARR87 estimates, due to the additional data used and more advanced methods. The 2016 IFDs were created to achieve the best estimates across Australia. In areas with sharp or unique rainfall frequency characteristics, the 2016 IFDs do not provide the fine scale variation required at the local scale.

Wollongong area has a significant bias away from site estimates, and possible over smoothing of important topographical rainfall features. The Coffs Harbour area has local low biases along the escarpment and high bias for the flatter areas.

On this basis, it was agreed that investigations into local techniques would be undertaken for the Wollongong (Section 6) and Coffs Harbour (Section 7) areas.

6. DERIVATION OF REVISED IFD GRIDS FOR THE WOLLONGONG AREA

Since biases in the 2016 IFD grids were highlighted when compared to site data, potential for improved IFD grids was investigated by deriving revised IFDs using an alternative method. In this section several alternatives were investigated for the various steps in the 2016 IFD process, and the steps with the best performance were chosen (referred to as revised IFDs). This method could be adapted for other areas with biases in the 2016 IFDs, however it has been optimized for Wollongong and would need to be adapted to account for local conditions in other areas. A summary of the final processes for the two methods can be seen in Diagram 1, Diagram 2 and in Table 4.These diagrams and tables do not include the 2016 IFD method for deriving 1% and 2% AEP estimates at durations greater than 1 day.

Diagram 1: 2016 IFD workflow

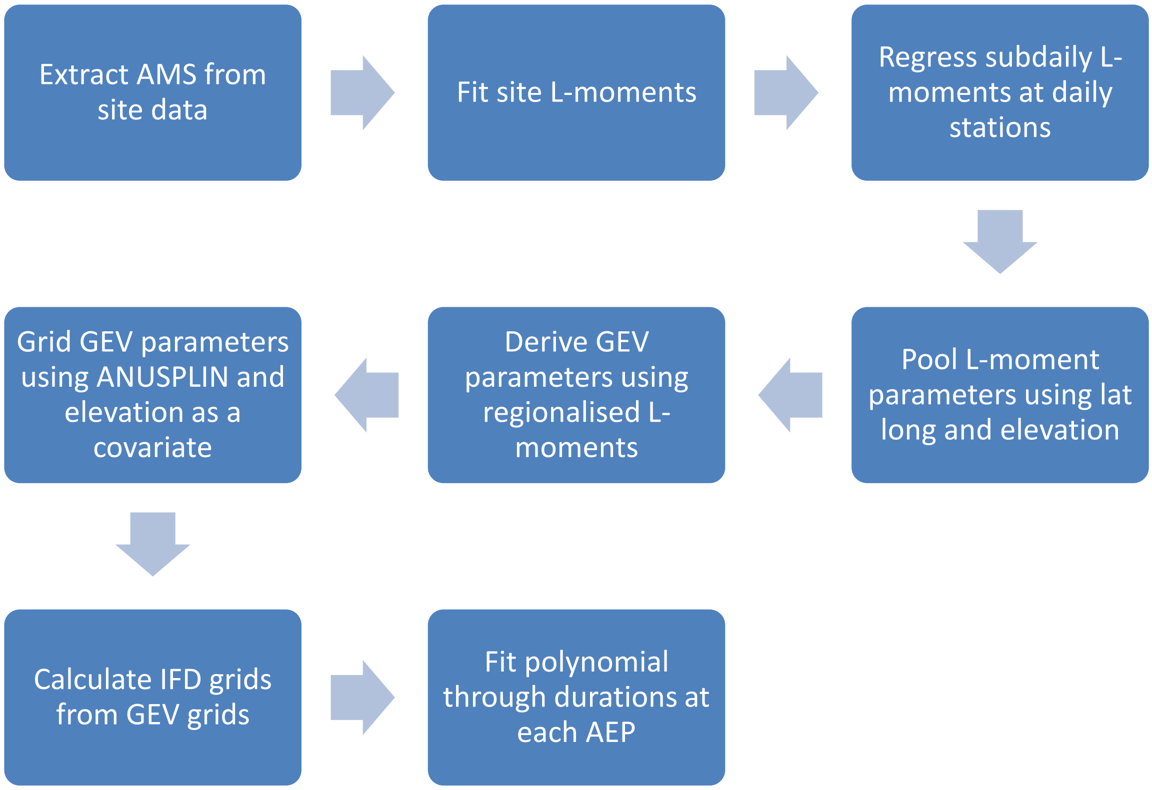


Diagram 2: Revised IFD workflow

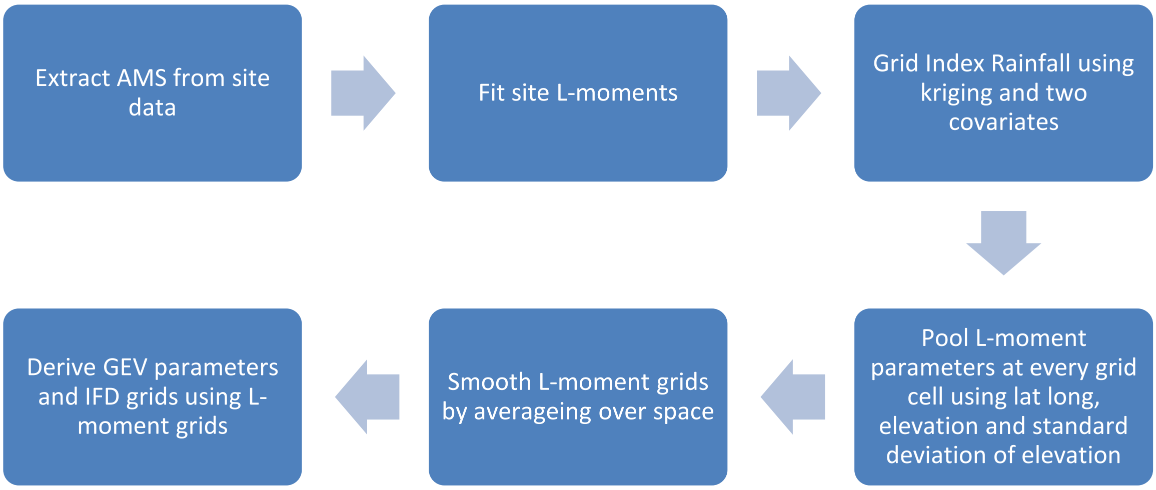


Table 4: Comparison of methods for 2016 IFD and the Wollongong revised IFDs

Step	2016 IFD	Revised IFDs
Extract AMS	Uses data to 2012	Uses data to 2012 with additional data to 2016 at MHL gauges
Fit Site L-moments	Standard LH0 fit of L-moments (sub-daily estimates and for AEPs more frequent then 2%)	Standard LH0 fit of L-moments
Regress L-moments at daily stations	BGLSR used to get sub-daily L-moment estimates at daily stations	No regression
Regionalisation	Pool of 500 AMS, calculating distance in latitude longitude and elevation to get site estimates of L-moments, then use them to calculate GEV parameters	Pool 6 stations, calculate distance in latitude longitude elevation and the standard deviation of elevation to get estimates of L-moments at all grid cells
Gridding	Grid GEV parameters using ANSUPLIN and elevation as a covariate	Grid index rainfall using kriging and elevation and SDE as covariates. Smooth L-moment grids using spatial averaging
IFD grids	Calculate IFDs using gridded GEV parameters	Calculate IFDs using GEV parameters derived from gridded L-moments
Post processing	Fit polynomials through durations at each quantile and ensure consistency by increasing values of higher durations that are inconsistent	No post processing

6.1. Regressing sub-daily parameters to daily stations

For the 2016 IFDs a Bayesian Generalised Least Squares Regression was used to give estimates of L-moment parameters at daily read rainfall gauges for durations less than 1 day (Green et al 2012a). In many areas of Australia there is very low density of sub-daily gauges and using only sub-daily gauges will yield very poor results. Therefore, filling these gaps with regressed values provides much better estimates of sub-daily IFDs. These regressed parameters will, in general, be closer to the mean of the training sample than observed values. In areas such as central NSW, this increased uniformity is a trade-off with the lack of sub-daily rainfall data, and the method will yield better estimates than not using regressed parameters (Green et al 2012a).

In areas such as Wollongong however, there is a high density of continuous rainfall gauges with relatively significant periods of record, so it is less clear whether the addition of regressed values increases the level of spatial information or if it brings all estimates closer to the mean, diminishing the representation of local features. It is also important to consider that daily gauges in this area are given relatively high weightings in regionalisation, given the large number of daily gauges available (shown in Figure 8). This is possibly obscuring the detail at the sub-daily stations.

To assess these possibilities some simple regressions were carried out using L-moment parameters for the 1, 2 and 3 day durations as predictor values. For durations from 5min to 12hrs in Figure 8, a standard linear regression and a random forest regression (Liaw and Wiener 2002), which is a random regression tree that is easily applied, were used to make estimates of index rainfall.

The performance of these regressions was assessed by calculating the coefficient of determination (R^2), the standard error of the estimate (SEE) and the confidence limits. This was done for the predicted values using the entire sample set and by deriving regressions leaving one station out of the regression and making estimates at that station. As can be seen in Table 5, Table 6 and Figure 9, rederiving regressions by leaving out a station yields much lower R^2 values, indicating significant overfitting of both regressions. The performance of the regressions also quickly diminishes as duration decreases so that using regressed parameters for the very short durations would give poorer estimates.

Table 5: Standard linear regression statistics

Duration	Training set	Leave one out		
	R^2	R^2	SEE	Confidence limits (%)
5	0.34	-0.24	1.48	31.56
10	0.47	-0.12	1.58	21.89
15	0.45	-0.05	1.88	20.95
30	0.49	0.15	2.84	22.91
60	0.57	0.25	4.71	28.32
120	0.68	0.43	6.34	28.37
180	0.77	0.62	6.57	24.49
360	0.91	0.84	6.35	16.83
720	0.97	0.95	5.27	10.02

Table 6: Random forest regression statistics

Duration	Training set	Leave one out		
	R^2	R^2	SEE	Confidence limits (%)
5	0.75	-0.06	1.37	29.18
10	0.83	0.09	1.42	19.69
15	0.83	0.11	1.73	19.29
30	0.84	0.17	2.81	22.62
60	0.86	0.28	4.61	27.71
120	0.90	0.48	6.04	27.03
180	0.92	0.61	6.58	24.52
360	0.96	0.82	6.85	18.16
720	0.98	0.92	6.42	12.21

Using these regressions to make estimates of L-CV and L-skew further reduces performance and increases the likelihood that local characteristics are oversmoothed by bringing parameters closer to the mean. Hence a regression was not used for the revised grids.

6.2. Gridding index rainfall

To make estimates in areas between rainfall stations, the 2016 IFD method used ANUSPLIN with elevation as a covariate to grid index rainfall and the alpha and kappa GEV parameters. As part of assessing the performance of the 2016 IFDs in the areas of interest, gridding of index rainfall was undertaken using elevation and the standard deviation of elevation (SDE) as covariates (Figure 10 and Figure 11). The standard deviation of elevation grid was derived by taking the standard deviation of elevation of all cells on the SRTM within 0.05° latitude or longitude of the target cell. SDE was chosen to reflect the relationship between sharp features of topography and orographic enhancement. Using SDE as a covariate is similar to the use of the rough and smooth adjustment that was used in the BoM 'Generalised Short-Duration Probable Maximum Precipitation Method' (BoM, 2003), which applies a rough weighting to areas within 20km of a location where elevation changes more than 50m within a horizontal distance of 400m. This parameter may have little or no impact in other areas of the country but may be beneficial in the Wollongong area.

For this project, the gridding process chosen was kriging, as ANUSPLIN is not freely available. This change in gridding technique will yield different results, however the covariates that best represent the spatial changes in rainfall values should be mostly constant across gridding approaches. In addition, a finer grid resolution of 0.005° was chosen to better capture the sharp features of the topography in the area. This should not impact the assessment of the value of using additional covariates.

The 'gstat' package in R was used to carry out the analysis. Fitting a different variogram for every dataset created inconsistent results, so to simplify the method the range was set to 15km and the psill was set to the average gamma for values with a distance greater than 15km. This method created consistent results that achieved estimates that best reflected the known rainfall characteristics of the topography in this area.

Index rainfall grids were derived using:

i. no covariates
ii. elevation (as used in derivation of the 2016 IFDs)
iii. SDE
iv. Combination of elevation and SDE

The potential for elevation and SDE to give better estimates of index rainfall was further highlighted when comparing elevation to SDE and index rainfall as seen in Figure 12. This shows that there are areas where similar levels of elevation and SDE have similar index rainfall values. In general for the 3 hour duration SDE has the highest correlation to index rainfall values.

To assess the performance of the 4 combinations of covariates in the gridding, mean absolute error (MAE), root mean squared error (RMSE) and the coefficient of determination (R^2) were calculated using site values as the observed data and the grid as the predicted dataset. Table 7 and Figure 13 and Figure 10 show that most of the time the combination of SDE and elevation gives the best results. For durations greater than 1 day, elevation appears to have a larger impact, whereas for durations shorter than one day SDE has the most impact. The combination of SDE and elevation as covariates was chosen for gridding across all durations. A comparison between these grids and their site parameters for the 3-hour duration can be seen in Figure 14.

Table 7: Index rainfall gridding statistics

Duration	Covariate	MAE	RMSE	R^2
5	No Covariate	0.40	0.50	0.69
	Elevation	0.40	0.50	0.69
	SDE	0.40	0.50	0.69
	Elevation and SDE	0.39	0.50	0.69
10	No Covariate	0.55	0.72	0.72
	Elevation	0.56	0.73	0.71
	SDE	0.55	0.72	0.72
	Elevation and SDE	0.55	0.72	0.72
15	No Covariate	0.73	0.94	0.74
	Elevation	0.75	0.95	0.73
	SDE	0.72	0.93	0.74
	Elevation and SDE	0.73	0.94	0.74
30	No Covariate	1.16	1.47	0.77
	Elevation	1.17	1.48	0.77
	SDE	1.13	1.45	0.78
	Elevation and SDE	1.13	1.47	0.77
60	No Covariate	1.98	2.45	0.80
	Elevation	1.99	2.47	0.79
	SDE	1.86	2.41	0.80
	Elevation and SDE	1.85	2.42	0.80
120	No Covariate	2.94	3.74	0.80

Duration	Covariate	MAE	RMSE	R^2
	Elevation	2.94	3.75	0.80
	SDE	2.71	3.64	0.81
	Elevation and SDE	2.70	3.66	0.81
180	No Covariate	3.52	4.60	0.81
	Elevation	3.50	4.58	0.81
	SDE	3.21	4.46	0.82
	Elevation and SDE	3.20	4.45	0.82
360	No Covariate	5.24	6.94	0.81
	Elevation	5.06	6.71	0.82
	SDE	4.82	6.68	0.82
	Elevation and SDE	4.76	6.48	0.84
720	No Covariate	7.15	9.85	0.81
	Elevation	7.01	9.35	0.83
	SDE	6.63	9.45	0.82
	Elevation and SDE	6.38	9.01	0.84
1440	No Covariate	15.33	21.62	0.58
	Elevation	14.69	20.71	0.62
	SDE	15.05	21.52	0.59
	Elevation and SDE	14.56	20.54	0.62
2880	No Covariate	21.35	30.30	0.55
	Elevation	20.93	29.33	0.58
	SDE	21.07	30.11	0.55
	Elevation and SDE	20.60	29.03	0.59
4320	No Covariate	23.63	33.58	0.55
	Elevation	23.14	32.44	0.58
	SDE	23.39	33.39	0.55
	Elevation and SDE	22.84	32.14	0.59

6.3. Regionalisation

Regionalisation of L-CV and L-skew parameters was carried out for the 2016 IFDs in order to achieve higher accuracy of quantile estimates at rarer AEPs. The method used to derive the 2016 IFDs calculated Euclidean distance between the target site and all surrounding sites in 3 dimensions using latitude, longitude and elevation in km (Green et al 2012c). This is roughly equivalent to scaling elevation to be 100 times larger. The closest sites were then added until a pooled sample of 500 years for AMS was reached. Using this pool of sites, the weighted averages of L-CV and L-skew were calculated based on each site's AMS length (nAMS) (Equation 3).

$$lcv_{regional} = \sum_{n}^{i=1} \frac{lcv_i \times nAMS}{\sum nAMS} \quad (3)$$

For durations shorter than 1 day, this method generally results in the majority of the weighting being given to daily stations where L-moments have been estimated via a regression, since their AMS is generally much longer than that of the sub-daily stations. The proportion of weighting given to sub-daily stations for each region, at a sub-daily gauge, can be seen in Figure 8. Since regression estimates bring the pool of values closer to the mean, using this method could potential create over- smoothing of local features in the Wollongong area.

Using the requirement of 500 years for AMS would include a very large number of sites in regions when there are no regressed daily sites with large AMS pools. To limit the pooling of sites whose characteristics are too dissimilar, much smaller regions were chosen that always have 6 sites. This was chosen based on the average length of the AMS for sub-daily sites being approximately 21.4 years, resulting in an average AMS pool of over 100 years. This smaller AMS pool will increase uncertainty of estimates at rarer AEPs, but will also make estimates more location specific. Given the high gradients of rainfall features in the area it was thought that more accuracy could be gained by shifting focus towards locality rather than large data pools.

Since the gridding of the index rainfall revealed benefits of using elevation and the standard deviation of elevation, testing of using both parameters in conjunction for regional pooling was carried out. When using both parameters it is unclear what weightings each should be given, so a range of weightings were tested and the combinations of values is shown in Table 8.

Table 8: Weighting ranges tested for optimum regionalisation

Parameter	Lowest Weighting	Highest Weighting	Division size	Number of Divisions
Elevation	0	0.001	0.00002	51
Standard Deviation of Elevation	0	0.0033	0.0001	34

For each combination of parameters, regionalisation was carried out at all sites in the area. R^2 values were calculated using at-site L-CV and L-skew as observed values, and regionalised values as predicted. This yielded the results seen in Figure 18. There is considerable variation in optimal weightings for each duration and it is likely that the significance of these parameters on rainfall characteristics changes with duration. In Wollongong, rainfall durations from 30 minutes to 1 day have the most impact on design flood estimation, so R^2 values were added together for these durations resulting in the values shown in Figure 19. The optimal weightings across multiple durations seem to be at approximately 0.0002 for elevation and 0.001 for the standard deviation of elevation.

To confirm a correlation between these parameters and IFD estimates, site IFD values were plotted against the sum of the scaled covariates, yielding the results shown in Figure 15through Figure 17. This shows that there is a general trend in these parameters although it is not particularly strong. In general, the higher the sum of scaled covariates, the higher the site IFD estimate.

The weighting for elevation is much lower than the 0.001 weighting used in the 2016 IFDs. Some of this difference will be accounted for with elevated areas coinciding with areas that have a high standard deviation of elevation. Another reason for the difference is that in this area there are highly local features that produce high rainfall, so elevation is not as effective at pooling L-moment parameters as it is in some other areas of the country.

6.4. Gridding of L-moments via regionalisation

For the 2016 IFDs regionalised L-moment parameters were used to obtain GEV parameters which were gridded using ANUSPLIN. In the Wollongong area, the rainfall characteristics change considerably over small distances, so there is potential for further gridding after regionalisation to smooth parameters even further. To avoid this, gridding was carried out by using regionalised parameter estimates at each grid cell. The resulting L-CV grid for the 3-hour duration can be seen in Figure 20.

Using this approach creates sharp boundaries, where neighbouring grid cells can have considerably different L-CV and L-skew values. Sharp changes in rainfall characteristics are unrealistic and could have significant impact on design, so smoothing of the regionalised L-moment grids was carried out. The smoothing involved averaging L-moment parameters of all grid cells within 0.01° of the target grid cell.

6.5. Derivation of revised IFD grids

The calculated index rainfall and L-moment grids were then converted to IFD grids by using these parameters to fit a GEV distribution at each grid cell for each duration and extracting values for the desired AEPs of 1EY, 50%, 20%, 10%, 5%, 2% and 1%. These grids for the 3-hour duration and 50%, 5% and 1% AEPs can be seen in Figure 21 through Figure 23.

6.6. Differences to 2016 IFD grids

Percentage differences were calculated between the 2016 IFDs and the derived revised IFD grids using Equation 4, shown in Figure 24 through Figure 26.

$$Percentage\ difference = \frac{Revised\ IFD - IFD2016}{IFD2016} \times 100 \quad (4)$$

In general, along the escarpment the revised IFD grids are higher than the 2016 IFDs and in the low areas or the elevated areas behind the escarpment, the revised IFDs are lower than the 2016 IFDs. Since a bias toward over-estimation in the low areas and underestimation around the escarpment was identified in the 2016 IFDs, the changes in grids are as desired. These changes can be quite significant for the 1% AEP, with differences on the escarpment as high as 30% and differences as low as -30% in the low areas.

6.7. Site differences

Percentage differences were calculated between the revised IFD grids and the site IFD estimates using Equation 5, and can be seen in Figure 27 through Figure 29.

$$Percentage\ difference = \frac{Revised\ IFD - Site}{Site} \times 100 \quad (5)$$

Although percentage differences can still be high for the 3-hour duration, there is little local bias for the revised IFDs. At the 1% AEP there is some bias along the top of the escarpment near Wollongong, however given the method of regionalising some smoothing of the highest and lowest parameters will always be present. Most areas show a reasonable scatter of both high and low percentage difference points indicating that the revised grids are performing reasonably well. Quantiles of percentage differences for the stations in the Wollongong area were calculated for both 2016 IFD grids and the revised IFD grids (Figure 30 through Figure 32). Medians and quartiles are more consistent across duration and closer to zero, further highlighting that the revised IFD grids are better representing at-site data.

The site with the largest negative percentage difference to the revised grids for the 3 hour and 1% AEP (Figure 29) is the Little Lake gauge operated by MHL. It is located near the east coast just south of Lake Illawarra. Sites with similar topographical characteristics from the surrounding area demonstrate much lower IFD estimates, which is why this gauge is so much higher than the revised grids. Examples like this are to be expected as there is large variability in data from individual sites since a small number of erroneous events can have very large impacts on rare estimates, and in this case, there are 2 very large suspicious events skewing the dataset. This is why pooling is used instead of site estimates, as the impact of erroneous data is minimised and additional confidence in estimates can be attained from nearby gauges.

Since the aim of creating the revised grids was to lower site residuals, MAE, RMSE and R^2 were calculated using both the revised IFDs and the 2016 IFDs as the predicted dataset, and the site IFD estimates as the observed. This produced the results shown in Figure 33 through Figure 35. For all AEPs and durations MAE, RMSE and R^2 showed better performance with the revised IFDs than the 2016 IFDs. On average the revised method has created grids that better represent site estimates and hence the local features of the terrain.

6.8. Comparison of revised IFD grids to grids of site quantile estimates

Any of the steps of the process used to create the revised IFDs could be introducing biases that compound throughout the process. To determine if this was occurring, site quantile estimates were gridded and compared to the revised IFD grids. These gridded quantiles were created using the same method to grid index rainfall (using kriging and elevation and SDE as covariates).

Figure 36 through Figure 38 shows the percentage difference between the two sets of grids for the 3-hour duration. For the more frequent AEPs there is very little differences in the grids, however for the rarest AEPs there are local area with percentage differences as high as 20%-30%. These differences are, in general, centred around single gauges with dissimilar characteristics to their neighbours. Given the pooling used to create higher accuracy at rare AEPs, these differences are expected. Since there are no significant trends in the differences it was concluded that there is no significant bias introduced in the revised IFD estimates.

6.9. Conclusions

Revised IFD grids were calculated in Wollongong to achieve better location specific IFD estimates using a similar dataset to the 2016 IFDs, with some additional data. The method used to create these grids highlighted the benefit of using predictive parameters that are specific to rainfall characteristics of the area.

Figure 39 shows the IFD comparison sites that represent the flat land near Wollongong, the southern escarpments and northern Illawarra where the escarpment is very close to the coast. Figure 40 to Figure 42 show the 3 hour duration IFD comparisons which is representative of the response time of most Illawarra catchments. Figure 40 shows in the flatland areas where the 2016 IFD and the revised IFD are similar. Figure 41 shows the southern escarpment where the 1987 IFD is generally above the at-site upper confidence limit while the 2016 IFD is generally near the lower confidence limit. The revised IFD is midway between the two and fits the at-site data and mean well. Figure 42 shows that the 2016 IFD is well below the at-site data while the 1987 IFD generally slightly high with a flatter gradient, while the revised IFD fits the at-site data well. A full set of these Figures for every gauge within the Illawarra IFD region can be seen in Appendix A.

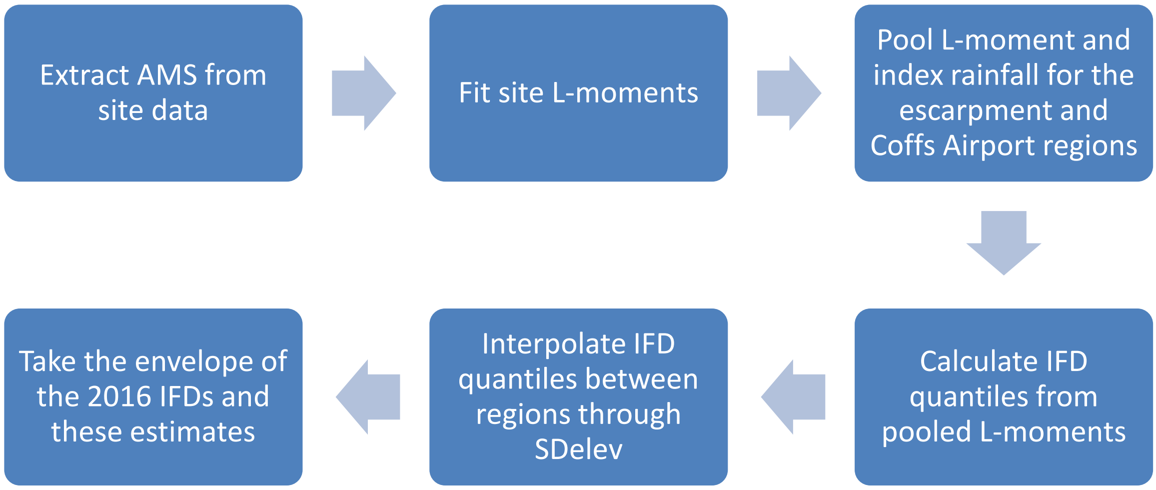
The Revised IFD grids are applicable for use in the surrounding Wollongong area in catchments that drain east to the coast.

7. DERIVATION OF REVISED IFD VALUES FOR THE COFFS HARBOUR AREA

Since bias was evident in the 2016 IFDs, the potential for alternative IFDs was investigated for the Coffs Harbour area. For the 3-hour duration at the 1% AEP 2016 IFDs are consistently more than 30% lower than site estimates along the Coffs Harbour escarpment. This implies that the 2016 IFDs are likely underestimates of true IFDs and that future infrastructure based on them could be significantly under-designed. Considering this and that the available local dataset would be too small to achieve high confidence in rare rainfall frequency estimates, the approach aimed to be conservative by being more location specific and taking an upper bound of IFD estimates.

The steps used to derive these estimates involved setting two IFD regions, one for the escarpment and one for the flatter area surrounding Coffs Harbour Airport. A summary of the method to derive conservative IFD estimates in Coffs Harbour can be seen in Diagram 3.

Diagram 3: Coffs Harbour IFD workflow



7.1. Regionalisation

To increase the effective record length of the sites along the escarpment at Coffs Harbour, the potential for pooling index rainfall and higher order L-moments was investigated. Initially this involved deriving GEV distributions for sites in the area and comparing the distributions and the growth curves of the sites to one another, which is shown in Figure 43 and Figure 44. This highlighted a strong relationship between the escarpment gauges and the divergence of these estimates from the Coffs Harbour Airport gauge.

The Perry Drive gauge has a visibly different fit despite being on the escarpment. It has a shorter record length that did not include the large 1996 event, and has an unusually low reading for the large 2009 event that was present at nearby sites. Therefore this site was not included in the region. The BoM gauge 059026 which is positioned behind the escarpment also has a considerably different fit to the escarpment gauges, which could be due to the orographic effect that is driving rainfall on the escarpment , not driving rainfall over the range. Hence this site was also left out of the Coffs Harbour escarpment region.

Sites North and South of Coffs Harbour that are relatively close to the coast and are near a steep escarpment like the one at Coffs Harbour were added to the analysis to investigate the potential for gaining additional data from elsewhere. Their locations can be seen in Figure 45 and their GEV fits and growth curves can be seen in Figure 46 and Figure 47. Unfortunately this highlighted that there were no gauges with similar enough characteristics to Coffs Harbour nearby to increase confidence in rare estimates of the Coffs escarpment region. This also highlighted that there are no nearby areas along the NSW coast where this rainfall producing mechanism has been observed.

Having a singular index rainfall for all sites along the escarpment would allow a simpler transition from the escarpment rainfall frequency distribution to the distribution of the Coffs Harbour Airport gauges. Hence confidence limits of mean AMS, which is effectively the index rainfall, were derived and are shown in Appendix B. For durations from 30 min to 2 days, all mean estimates are within the confidence limits of the mean for all the sites in the region. For the shorter durations, it is possible that the more localised rainfalls that drive these types of events means that the rarer events that create wider confidence limits are missed by some of the sites. Since the BoM estimates for these durations are generally higher than site estimates anyway, it was decided not to derive IFDs outside the range of durations from 30 min to 1 day.

The homogeneity of the Coffs escarpment region was calculated for all durations using the Hosking and Wallis homogeneity test (Hosking and Wallis, 1997), which is shown in Table 9. H values greater than 2 indicate a heterogeneous region, between 1 and 2 indicates a somewhat heterogeneous region, less than 1 indicates a homogenous region and largely negative H values of less than -2 can indicate significant cross-correlation of sites. H_1 relates to L-CV and H_2 relates to L-SK. For durations of 30min and shorter, the region is mostly homogenous and there is not significant cross-correlation. For the durations of interest there is a moderate amount of cross-correlation present, which will diminish the increase in accuracy from the pooling.

Table 9: Hosking and Wallace Homogeneity Measures for the Coffs Escarpment Region

Duration (min)	H_1	H_2
5	3.391	0.736
10	-0.109	-0.315
15	-0.455	-0.743
30	-0.901	-0.982
60	-1.347	-1.680
120	-1.442	-1.788
180	-1.389	-1.734
360	-1.498	-1.922
720	-1.512	-1.900
1440	-1.844	-1.803
2880	-1.548	-1.323
4320	-1.471	-1.580

Bootstrapped confidence limits were derived for the Coffs escarpment region and regionalised estimates were compared to both the 2016 IFDs and the site estimates. These confidence limits will be underestimates of the true confidence limits due to site cross-correlation and the assumption that the site data is representative of the "true" distribution, however it gives a valid indication of the increased certainty that is achieved with regionalisation. As can be seen in Figure 48 through Figure 50, the 2016 IFD estimates generally lie within the confidence limits of the regional estimates but are toward the lower end. This suggests that the 2016 IFD values underestimate the true IFDs but it is not conclusive, further highlighting the value for conservative estimates.

The percentage difference between the Coffs Harbour Airport gauge and the 2016 IFDs can be seen in Table 10. For durations shorter than 1 day, the overall trend is for site estimates to be lower than the 2016 IFDs. Since this approach aims to derive conservative estimates it was decided for these durations it would not be necessary to regionalise since the BoM estimates are already an overestimation. For the 1 day duration however, the 2016 IFDs are underestimating site values, so the site estimates needed to be used to get conservative estimates and hence needed to be regionalised in order to reduce uncertainty.

Table 10: Percentage Difference Between Coffs Airport and 2016 IFD Quantiles

Duration (min)	50% AEP	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP
1	24.78	9.31	-2.67	-14.08	-27.20	-35.79
5	16.62	24.88	29.08	33.25	38.04	41.91
10	15.91	22.45	26.03	28.67	31.43	33.16
15	12.59	18.47	21.77	24.31	26.76	28.42
30	-0.51	5.62	9.92	14.58	20.80	25.89
60	-3.60	1.90	5.66	9.30	14.46	18.53
120	-1.50	4.47	9.08	14.10	21.64	27.91
180	-1.33	3.34	6.56	9.84	14.55	18.23
360	3.17	8.13	8.78	7.97	4.91	1.77
720	5.28	8.73	9.23	8.81	5.99	3.27
1440	10.12	12.49	10.02	5.71	-3.24	-10.67
2880	0.98	0.31	-3.14	-7.70	-15.67	-22.07
4320	1.81	2.82	0.58	-2.83	-9.05	-14.29

Four sites near to the Coffs Harbour Airport gauge that lie close to the coast and are on relatively flat terrain were chosen to derive a regional estimate (Figure 54). Like the Coffs escarpment region the potential for pooling the index rainfall was investigated by calculating the confidence limits of the mean for these sites (Figure 51). Site 059039 did not fit the index rainfall characteristics of the other sites so it was not included in the calculation of index rainfall. The homogeneity measure for this region is H_1=-0.978 and H_2=-0.057, indicating that the region is homogenous and not overly cross-correlated.

Bootstrapped confidence limits were also derived for this region and can be seen in Figure 52. The regional estimates are much closer to the 2016 IFDs than the site estimates at the Coffs Airport gauge, which confirms that using the 1 day 2016 IFDs for the flat areas around Coffs Harbour is unlikely to underestimate the true IFDs.

7.2. Gridding of IFD quantiles

IFD values needed to be interpolated to areas between the escarpment region and the flatlands region. To do this rainfall frequency values need to have a firm relationship with one or more interpolation parameters, some of which are listed in Table 11. The values of these parameters and their mean estimates for the regions can be seen in Figure 53.

Table 11: Advantages and Disadvantages of Potential Interpolation Parameters

Interpolation Parameter	Advantages/Disadvantages
Distance from the coast	Is relatively consistent in the escarpment region and would yield more conservative estimates due to a slower approach towards the Coffs Airport quantiles than is likely to occur. Is inconsistent in the airport region
Latitude and longitude	Is more difficult to implement due to there being two parameters and offers not advantage over Distance from the coast
Elevation	Is consistent in the airport region and has precedence with use from the 2016 IFDs. Has been shown not to sufficiently capture orographic enhancement in the area and is inconsistent in the escarpment region
Slope	Should relate to orographic enhancement. Is inconsistent in both regions and is too noisy to sufficiently relate to anything.
SDE	Is consistent in both regions and has been shown to be effective for the Wollongong area. There is little certainty in the transition in quantiles between the two regions and the choice of buffer may not be optimal.

While any of these parameters could be used for interpolation, there is little known about the transition of quantiles between the two regions, so a subjective decision needed to be made. Considering the advantages and disadvantages listed in Table 11, SDE was chosen. Distance from the coast was a viable alternative but it was felt that it may create results that are overly conservative and transition poorly in areas where the escarpment is closer to the coast.

The Coffs Harbour SDE grid was derived at a resolution 0.005° and the same buffer applied to the grid used in Wollongong. This yielded high SDE values that extended all the way to the Coffs Harbour Airport gauge, so the buffer was halved to 0.025° and the grid was rederived and can be seen in Figure 54.

To get rainfall frequency estimates at all points in the Coffs Harbour area quantiles were interpolated through SDE using Equation 6. The SDE values chosen to represent the region were the minimum values in the region as it is the most conservative. The interpolated grid for the 3-hour duration can be seen in Figure 55.

$$Quantile_i = Quantile_{Esc} - \frac{Quantile_{Esc} - Quantile_{Airport}}{SDelev_{Esc} - SDelev_{Airport}} \times (SDelev_{Esc} - SDelev_i) \qquad (6)$$

$where:\ SDelev_{Esc} \qquad = 72.21$

$$SDelev_{Airport} = 7.13$$

BoM IFD values were sampled at every point on the grid of Coffs Harbour estimates. In cells where the 2016 IFD is higher than the Coffs Harbour IFD, the 2016 IFD value was taken. Figure 55 shows the final Coffs Harbour IFD grid for the 3-hour duration and where the 2016 IFD values were taken in place of the derived Coffs Harbour estimates.

7.3. Differences to Previous Local Techniques

Due to concerns that the 1987 IFDs were underestimating rainfall frequency values along the escarpment around Coffs Harbour, local techniques have been utilized in the past to make flood frequency estimates for Coffs Creek. One example of this is the 2001 Coffs Creek Flood Study (Webb, McKeown & Associates, 2001), which detailed meteorological analysis of rainfall increases with elevation for the area for the 1 day duration. The method applied the 1987 IFDs from Table 12 with the best estimate rainfall gradient from Table 13 to get design rainfall estimates at all durations.

Table 12: 1987 IFD Values Used for the 2001 Coffs Creek Flood Study

Duration (hours)	Rainfall Total (mm)					
	10 year ARI	20 year ARI	50 year ARI	100 year ARI	200 year ARI	500 year ARI
1	69	80	94	105	116	131
2	94	110	130	145	161	183
3	113	131	156	175	195	221
4.5	134	157	187	210	235	268
6	152	178	213	240	268	306
9	181	213	256	289	324	371
12	206	242	291	330	370	425
24	277	329	399	454	512	591

Table 13: Rainfall Gradient Scenarios from the 2001 Coffs Creek Flood Study

Elevation (mAHD)	Gradient Ratio (Relative to Airport)		
	Lower Bound	Best Estimate	Upper Bound
20	1	1	1
80	1.05	1.3	1.6
140	1.1	1.6	2.2
200	1.15	1.9	2.8
400	1.2	2.25	3.3

These rainfall gradients and design rainfall values for the 3-hour duration and 100 year ARI were converted to a grid using the SRTM for elevation and were compared to the revised Coffs Harbour IFD grid. Percentage differences were calculated and are shown in Figure 56. At the highest points along the escarpment estimates are very similar, however further from the escarpment and towards Coffs Harbour Airport the revised grids are significantly higher than the 2001 estimates.

This is due to there being additional data for the escarpment gauges to derive rainfall frequency estimates and the use of SDE to interpolate values, which extends high rainfalls much further toward the coast then elevation does. Considering many of the escarpment gauges are on the foot of the escarpment and demonstrate the same high rainfall frequency estimates as the more elevated gauges, these changes result in values that are more representative of the area.

7.4. Conclusions

Revised IFD estimates were created for the Coffs Harbour area to achieve more conservative and location specific IFD estimates along the Coffs Harbour escarpment. The method used to create these grids took the envelope of interpolated regional and the 2016 IFD grids to be conservative and limit the impact on design of errors in IFD estimates. A full set of site IFD comparisons can be found in Appendix C.

These revised IFD grids are appropriate for use in the surrounding Coffs Harbour area in catchments of Coffs Creek, Boambee Creek, Newports Creek, Jordans Creek, the Kororo Basin and Bonville Creek. There is lower confidence in values over the Pine Creek catchment that drains into Bonville Creek, so it may be more appropriate to use 2016 IFD values there. The revised IFDs are not appropriate west of the escarpment in areas that drain into the Orara River.

8. FINAL RECOMMENDATIONS

Although the 2016 IFD grids are vastly superior to the 1987 IFD grids since they incorporate better fitting techniques and considerably more data, there are some areas with sharp elevation changes that may be prone to local bias. The large region sizes and the incorporation of a regression to estimate sub-daily rainfalls at daily gauges yields better large-scale accuracy but is not optimal for areas with high sub-daily gauge density and sharp elevation changes that drive localised high rainfall gradients.

Revised IFD grids have been developed for the Illawarra and Coffs Harbour areas that place much higher weighting on the local sub-daily data and achieve more location specific estimates. It is therefore recommended that for these areas the revised grids be utilised when deriving flood frequency estimates as the 2016 IFD grids are locally biased. If more conservative estimates are desired, it would be valid for practitioners to use the envelope of the revised IFD grids and the 2016 IFDs.

For other areas that are likely to have local bias in the 2016 IFDs the introduction to ARR 2016 provides some relevant guidance (ARR, Ball et al, 2016). In the context of using the 2016 IFDs, they are currently the best estimates and should be used, however if it is evident that local bias is having significant impact on flood frequency estimates it is appropriate, and even encouraged, to develop or utilise new methods that better represent the IFDs in the area of interest.

> "*In development of this guidance, it was recognised that knowledge and information availability is not fixed and that future research and applications will develop new techniques and information. This is particularly relevant in applications where techniques have been extrapolated from the region of their development to other regions and where efforts should be made to reduce large uncertainties in current estimates of design flood characteristics.*
>
> *Therefore, where circumstances warrant, designers have a duty to use other procedures and design information more appropriate for their design flood problem. The authorship team of this edition of Australian Rainfall and Runoff believe that the use of new or improved procedures should be encouraged, especially where these are more appropriate than the methods described in this publication. Assessment of the relative merits of new procedures and design information should be based on the following desirable attributes:*
>
> - *based on observed data relevant to the specific application;*
> - *consistent with current knowledge of flood processes;*
> - *able to reproduce observed flood behaviour in the area of interest; and*
> - *where possible, endorsed by a peer review process*"

9. CLIMATE CHANGE CONSIDERATIONS

The work carried out in this report assumes that the climate is stationary and rainfalls observed in the past are representative of what will be observed in the future. Climate change is however accepted as occurring and will likely have impacts on IFD relationships (Bates et al, 2015). Therefore, the IFD estimates provided as part of this report will be likely underestimates once climate change starts having significant impacts on IFD relationships. Unfortunately there is not enough data in the areas studied in this report to make confident estimates about the effect of climate change on IFDs.

ARR 2016 (Bates et al, 2016) provides guidance on adjusting IFD estimates to account for climate change. Expected changes in heavy rainfalls are between 2% and 15% per °C of warming, and the recommended adjustment is to increase rainfall by 5% per °C of warming. ARR 2016 also details guidelines on how to make decisions in the design of an asset on the extent of climate change. It is highly recommended to follow these guidelines when developing significant infrastructure that will have impacts on flooding in the future.

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Figures

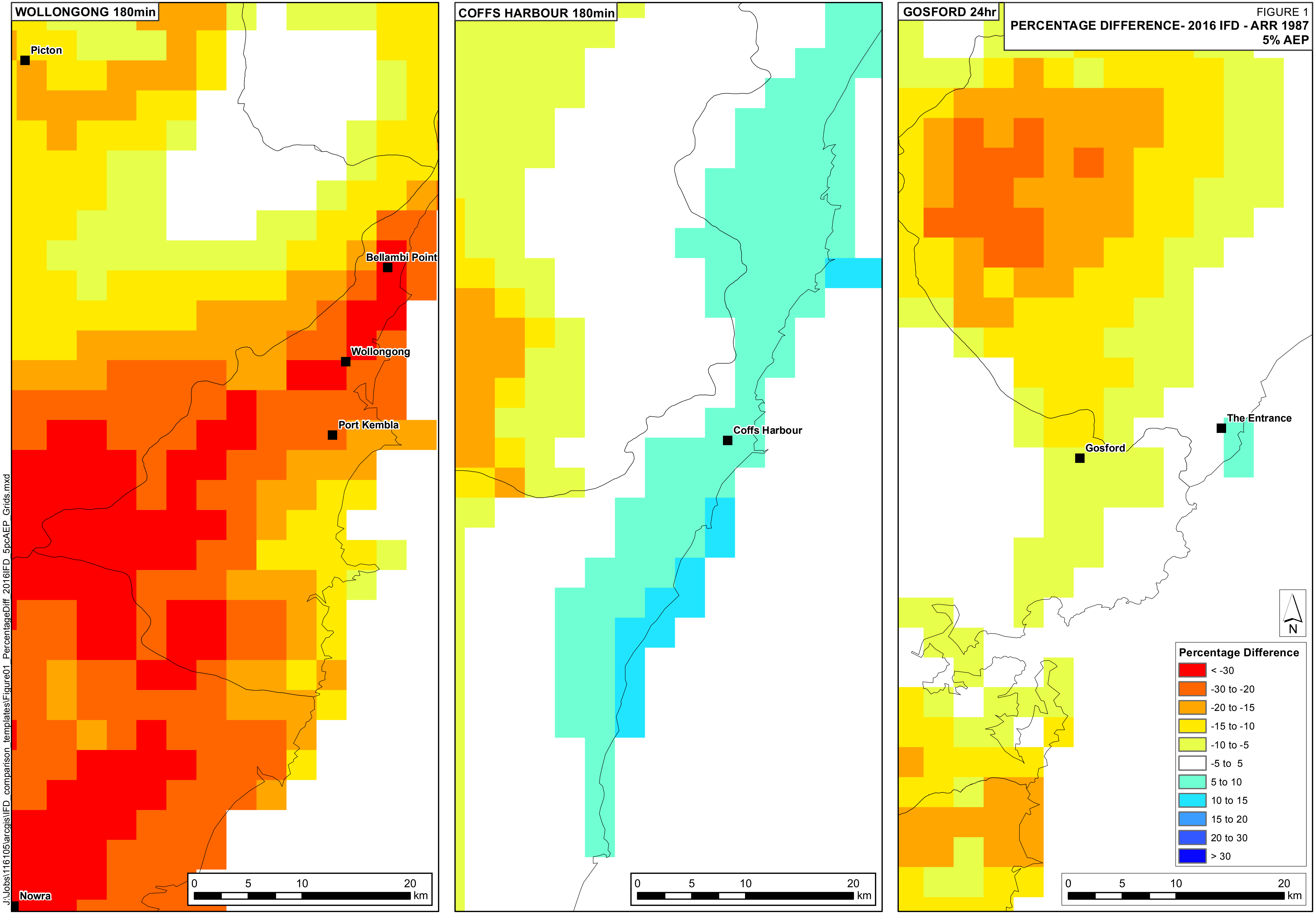

FIGURE 1
PERCENTAGE DIFFERENCE- 2016 IFD - ARR 1987
5% AEP

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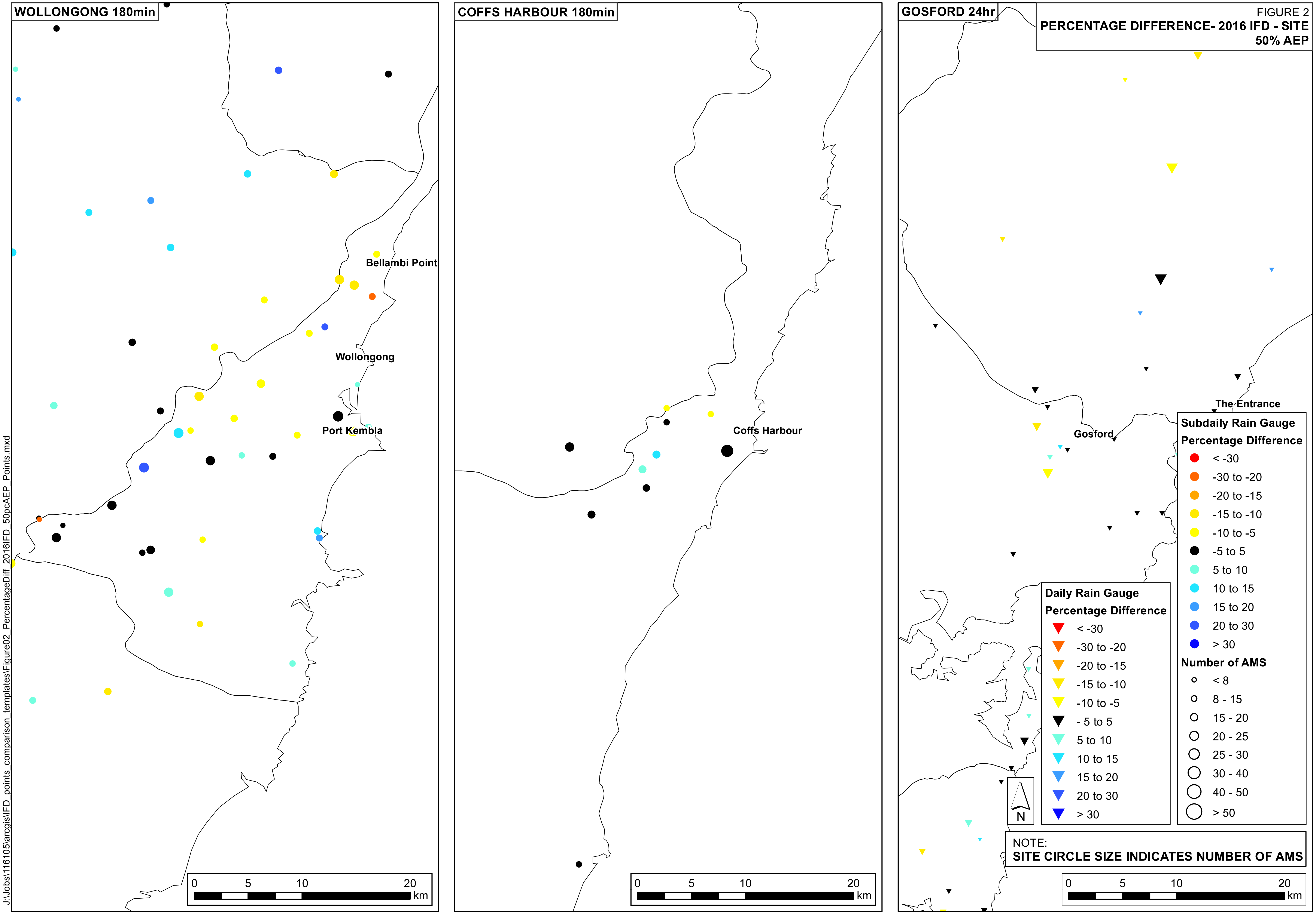
WOLLONGONG 180min
Bellambi Point
Wollongong
Port Kembla
0 5 10 20 km
COFFS HARBOUR 180min
Coffs Harbour
0 5 10 20 km
GOSFORD 24hr
FIGURE 2
PERCENTAGE DIFFERENCE- 2016 IFD - SITE
50% AEP
The Entrance
Gosford
Subdaily Rain Gauge
Percentage Difference
< -30
-30 to -20
-20 to -15
-15 to -10
-10 to -5
-5 to 5
5 to 10
10 to 15
15 to 20
20 to 30
> 30
Number of AMS
< 8
8 - 15
15 - 20
20 - 25
25 - 30
30 - 40
40 - 50
> 50
Daily Rain Gauge
Percentage Difference
< -30
-30 to -20
-20 to -15
-15 to -10
-10 to -5
- 5 to 5
5 to 10
10 to 15
15 to 20
20 to 30
> 30
N
NOTE:
SITE CIRCLE SIZE INDICATES NUMBER OF AMS
0 5 10 20 km
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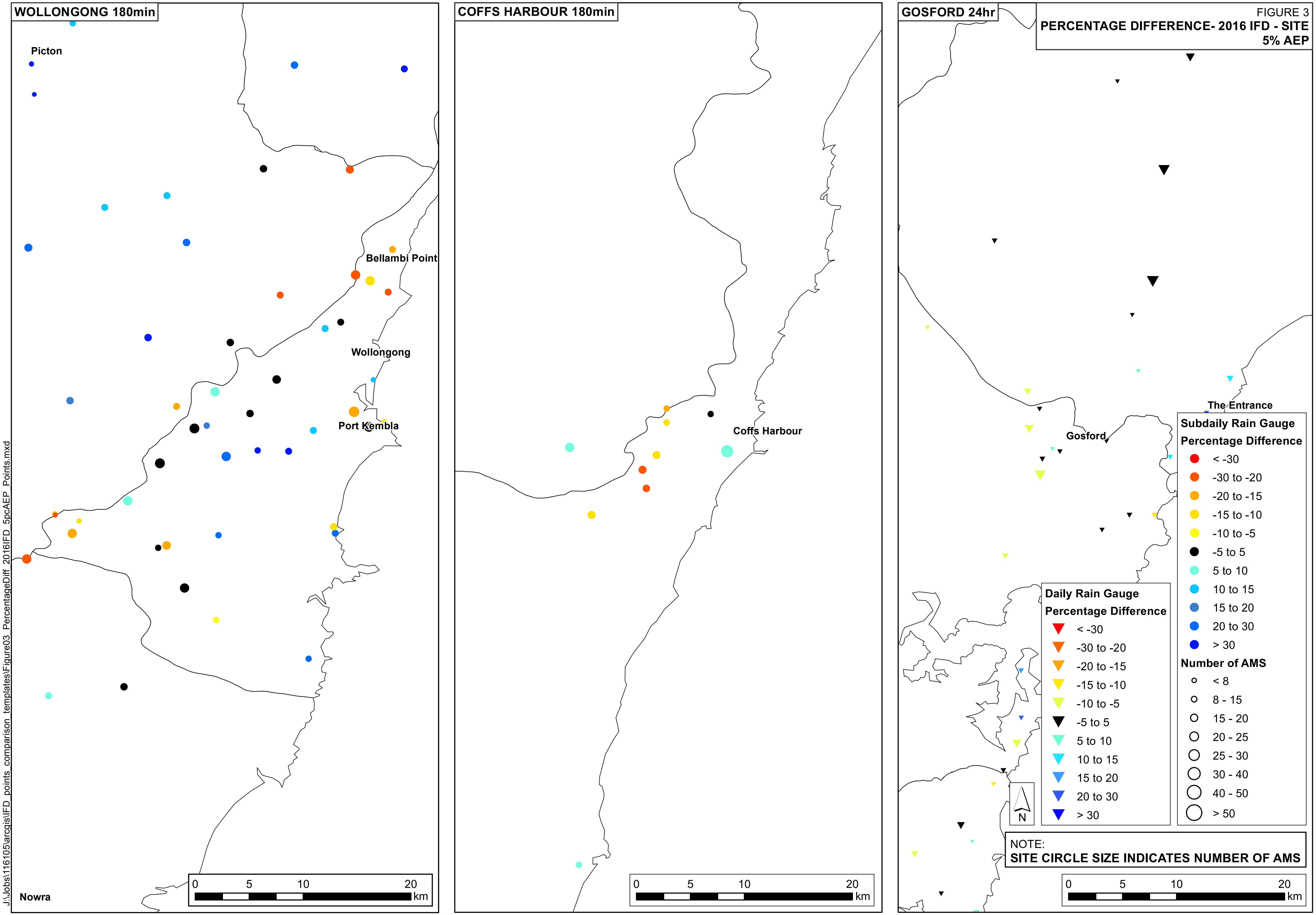

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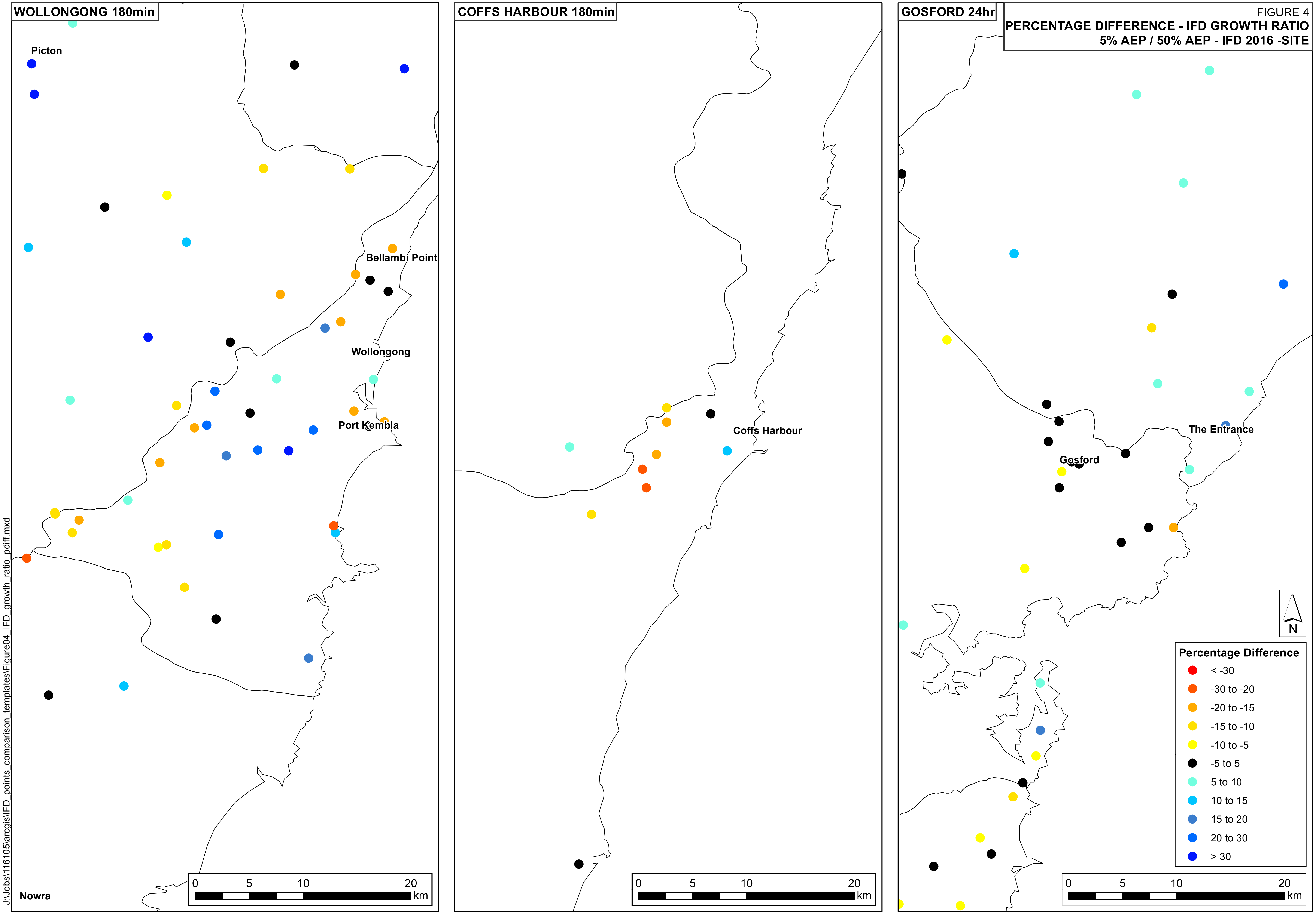

FIGURE 4
PERCENTAGE DIFFERENCE - IFD GROWTH RATIO
5% AEP / 50% AEP - IFD 2016 -SITE
WOLLONGONG 180min
Picton
Bellambi Point
Wollongong
Port Kembla
Nowra
COFFS HARBOUR 180min
Coffs Harbour
GOSFORD 24hr
The Entrance
Gosford
N
Percentage Difference
< -30
-30 to -20
-20 to -15
-15 to -10
-10 to -5
-5 to 5
5 to 10
10 to 15
15 to 20
20 to 30
> 30
0
5
10
20
km
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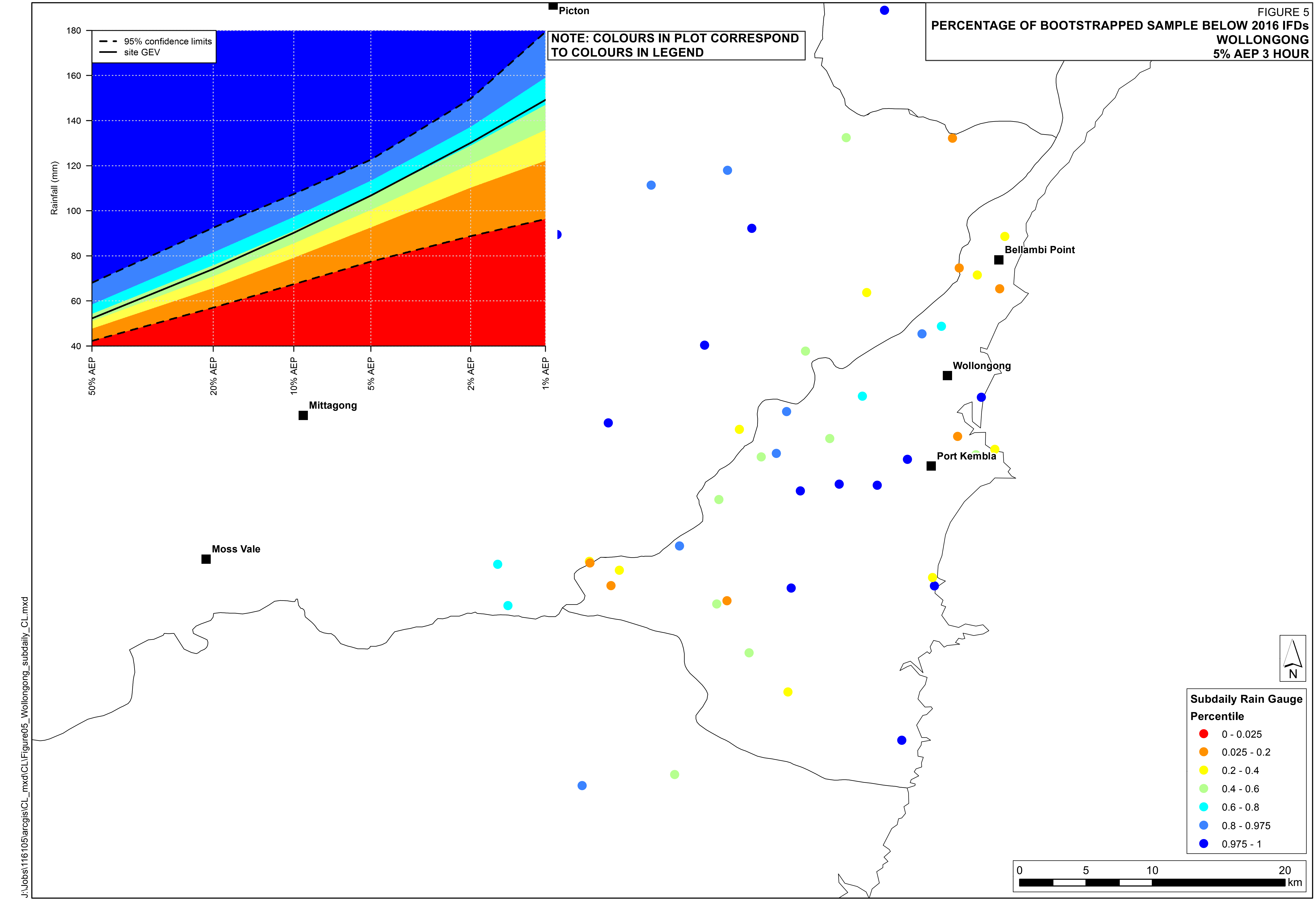
FIGURE 5
PERCENTAGE OF BOOTSTRAPPED SAMPLE BELOW 2016 IFDs
WOLLONGONG
5% AEP 3 HOUR
NOTE: COLOURS IN PLOT CORRESPOND TO COLOURS IN LEGEND
95% confidence limits
site GEV
Rainfall (mm)
180
160
140
120
100
80
60
40
50% AEP
20% AEP
10% AEP
5% AEP
2% AEP
1% AEP
Picton
Bellambi Point
Wollongong
Port Kembla
Mittagong
Moss Vale
N
Subdaily Rain Gauge Percentile
0 - 0.025
0.025 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 0.975
0.975 - 1
0
5
10
20
km
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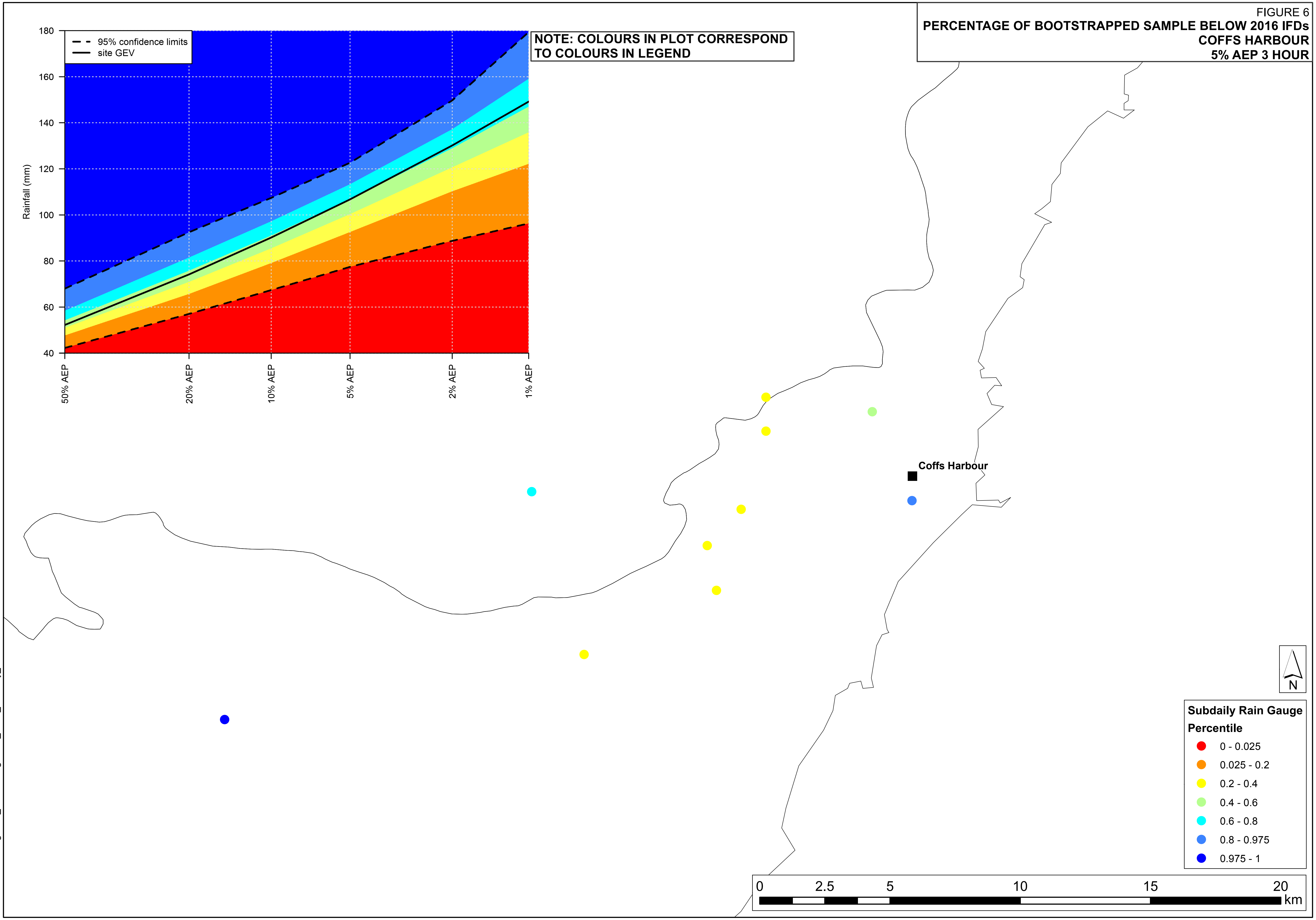

FIGURE 6
PERCENTAGE OF BOOTSTRAPPED SAMPLE BELOW 2016 IFDs
COFFS HARBOUR
5% AEP 3 HOUR
NOTE: COLOURS IN PLOT CORRESPOND TO COLOURS IN LEGEND
95% confidence limits
site GEV
Rainfall (mm)
180
160
140
120
100
80
60
40
50% AEP
20% AEP
10% AEP
5% AEP
2% AEP
1% AEP
Coffs Harbour
Subdaily Rain Gauge
Percentile
0 - 0.025
0.025 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 0.975
0.975 - 1
0
2.5
5
10
15
20
km
N
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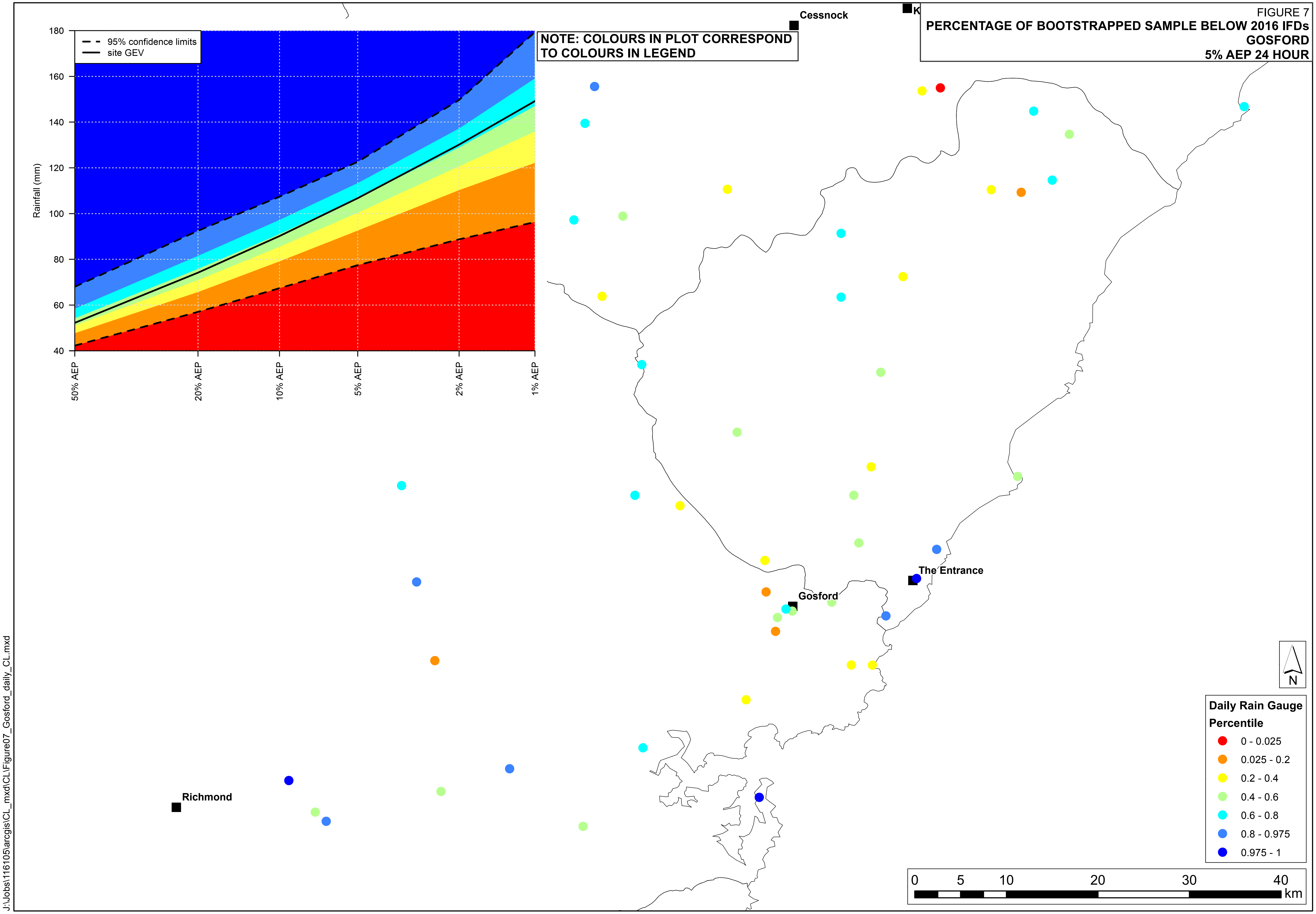
FIGURE 7
PERCENTAGE OF BOOTSTRAPPED SAMPLE BELOW 2016 IFDs
GOSFORD
5% AEP 24 HOUR
NOTE: COLOURS IN PLOT CORRESPOND
TO COLOURS IN LEGEND
95% confidence limits
site GEV
Rainfall (mm)
180
160
140
120
100
80
60
40
50% AEP
20% AEP
10% AEP
5% AEP
2% AEP
1% AEP
Cessnock
Gosford
The Entrance
Richmond
N
Daily Rain Gauge
Percentile
0 - 0.025
0.025 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 0.975
0.975 - 1
0
5
10
20
30
40
km
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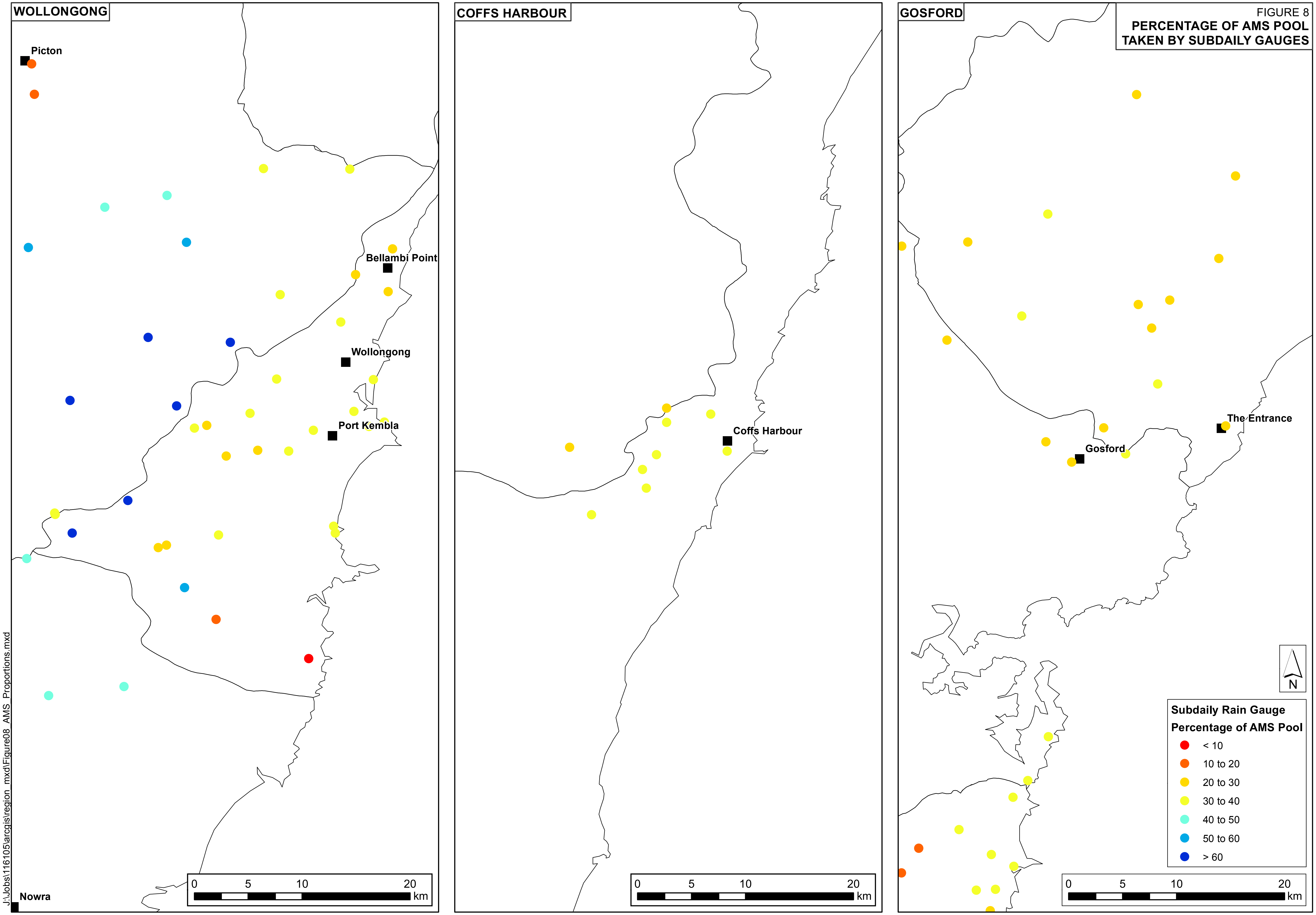


FIGURE 8
PERCENTAGE OF AMS POOL TAKEN BY SUBDAILY GAUGES
WOLLONGONG
Picton
Bellambi Point
Wollongong
Port Kembla
Nowra
COFFS HARBOUR
Coffs Harbour
GOSFORD
Gosford
The Entrance
N
Subdaily Rain Gauge Percentage of AMS Pool
< 10
10 to 20
20 to 30
30 to 40
40 to 50
50 to 60
> 60
0 5 10 20 km
J:\Jobs\116105\arcgis\region_mxd\Figure08_AMS_Proportions.mxd

FIGURE 9

COEFFECIENT OF DETERMINATION
L-CV REGRESSION COMPARISONS

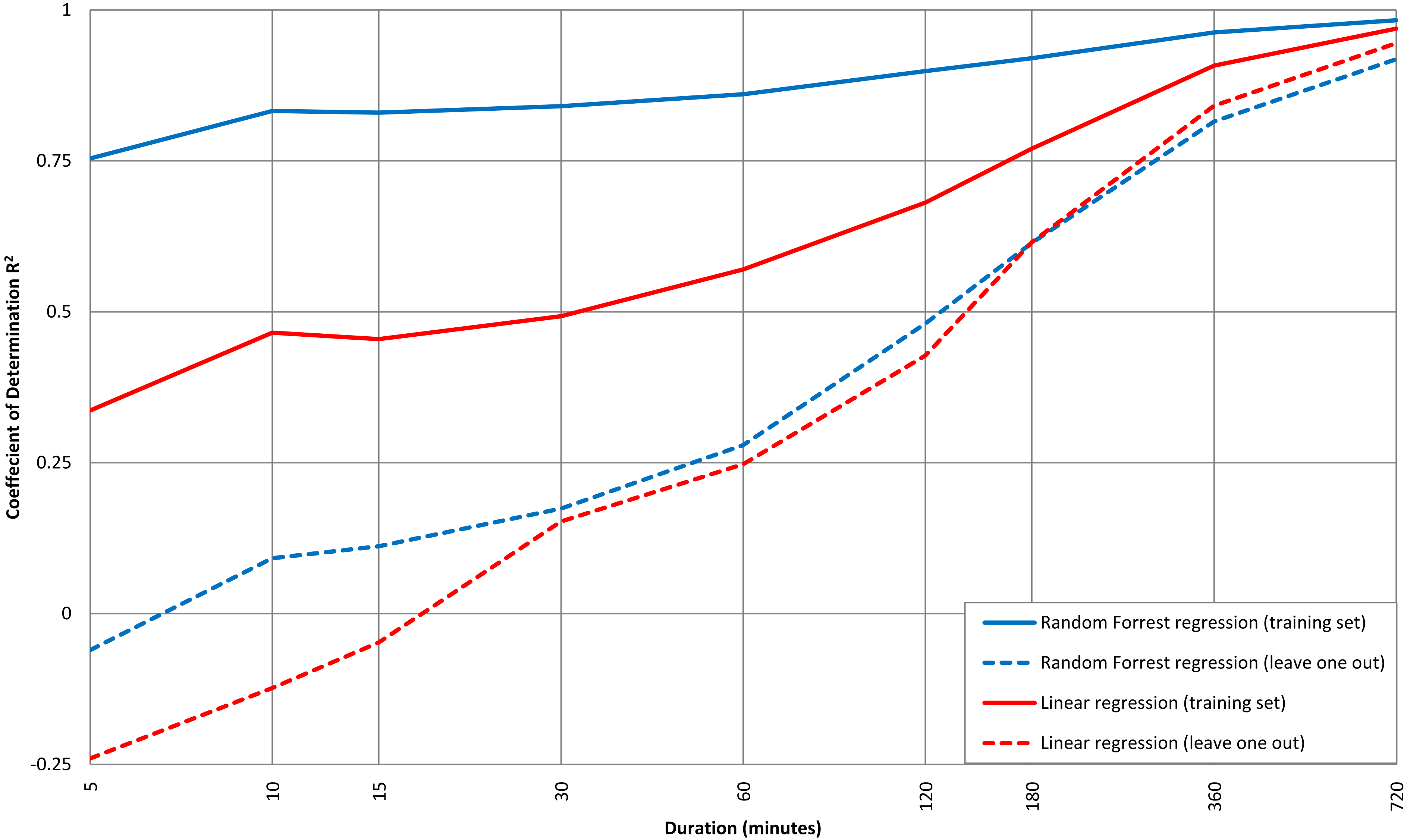
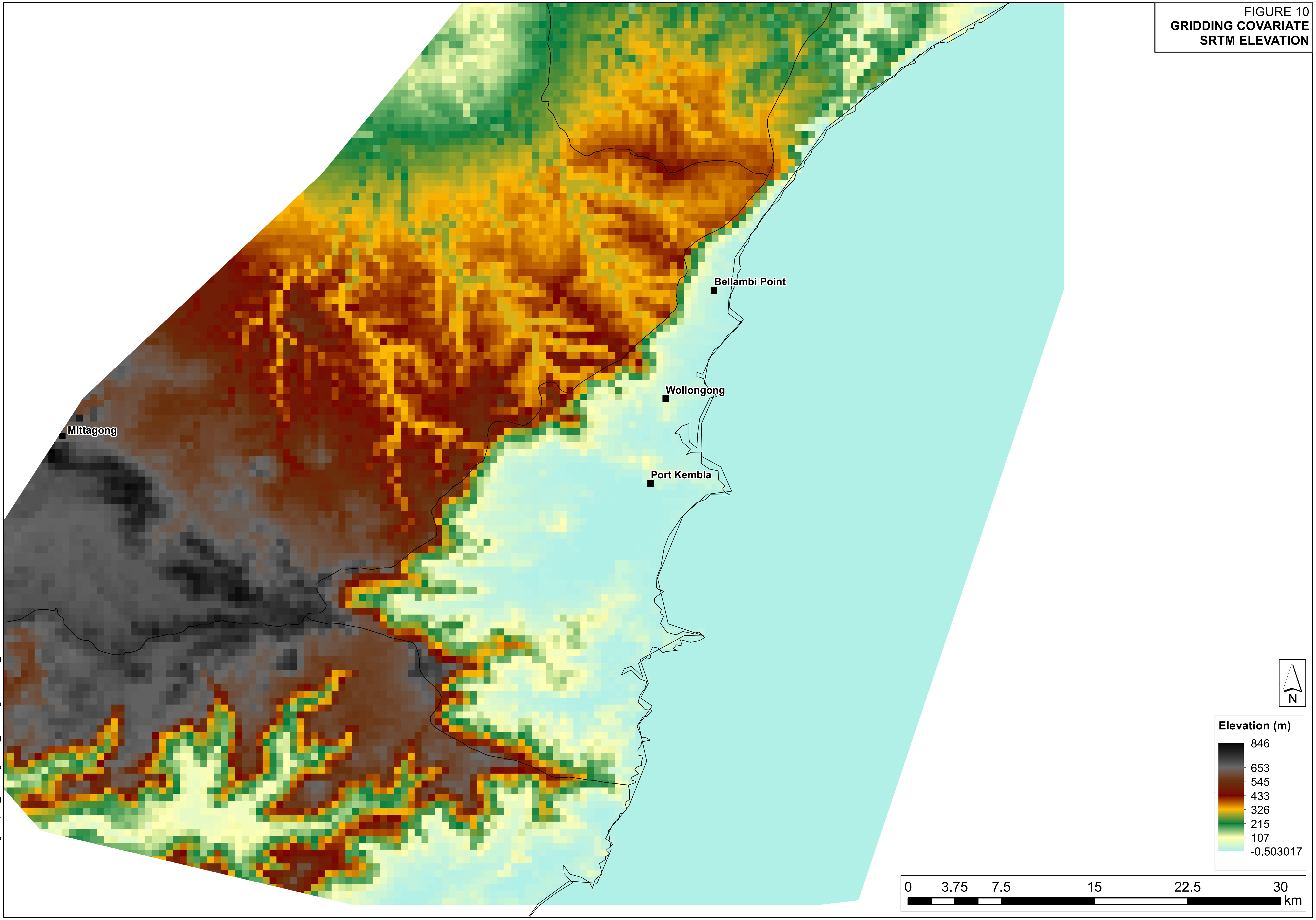
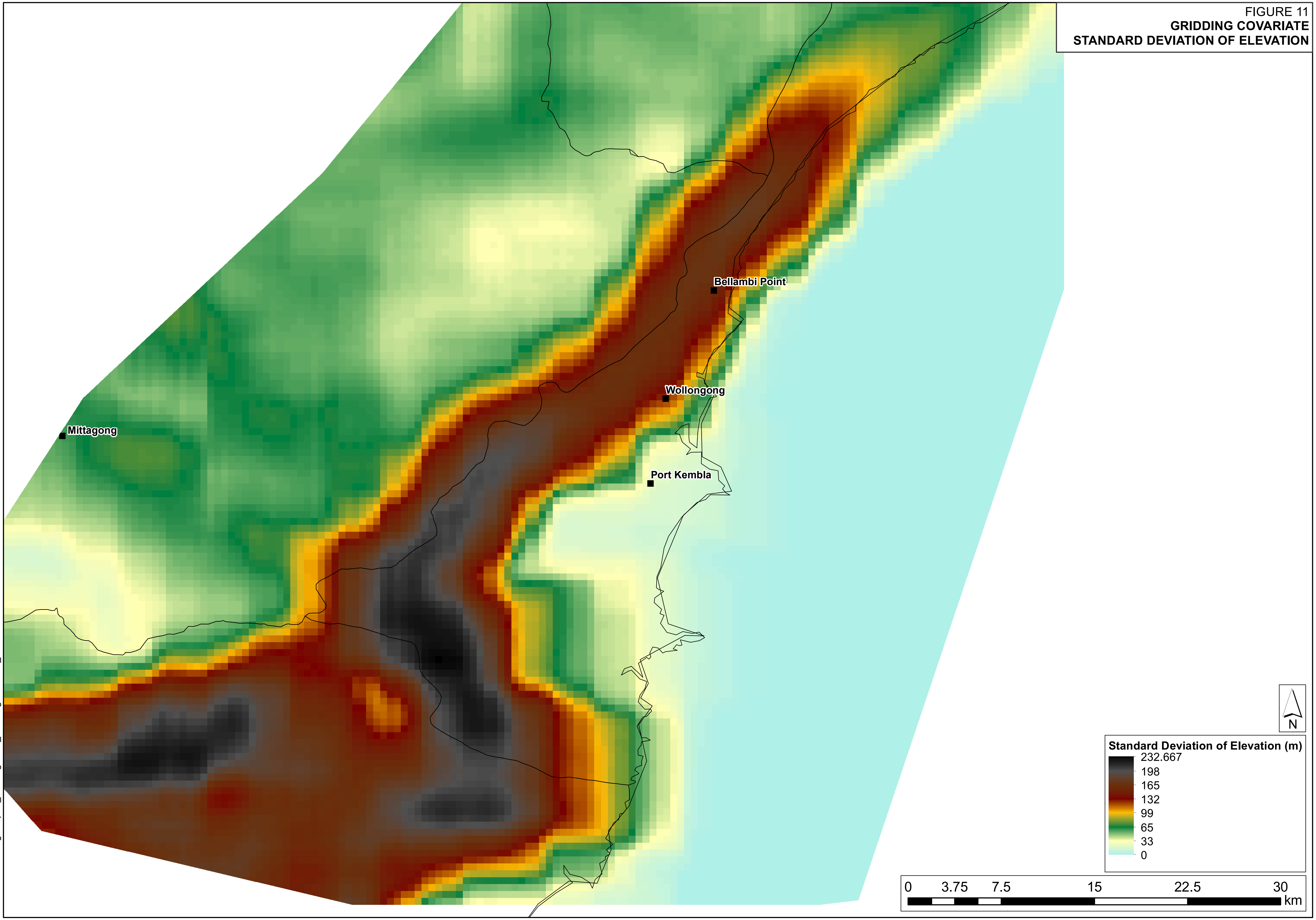


FIGURE 10
GRIDDING COVARIATE
SRTM ELEVATION



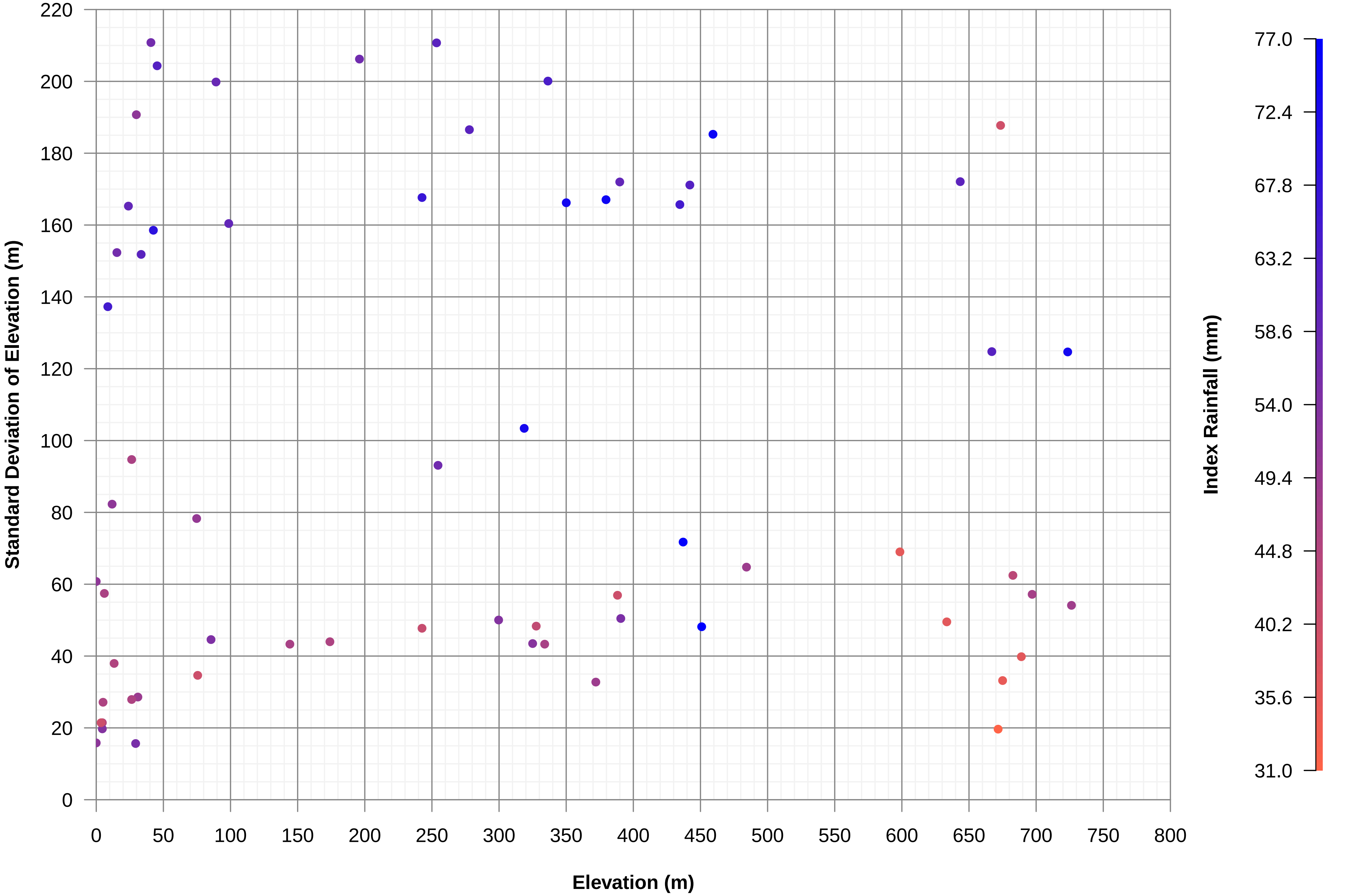
J:\Jobs\116105\arcgis\report_mxd\Figure10_GriddingCovariate_SRTMelevation.mxd

FIGURE 11
GRIDDING COVARIATE
STANDARD DEVIATION OF ELEVATION



J:\Jobs\116105\arcgis\report_mxd\Figure11_GriddingCovariate_StandardDeviationofElevation.mxd

FIGURE 12
INDEX RAINFALL IN COVARIATE SPACE
3 HOUR DURATION



J:\Jobs\116105\excel\Gridding\[Wollongong_errors_graphs]Graph_Index_Gridding_Covariate

FIGURE 13

COEFFECIENT OF DETERMINATION

INDEX GRIDDING COVARIATE COMPARISONS

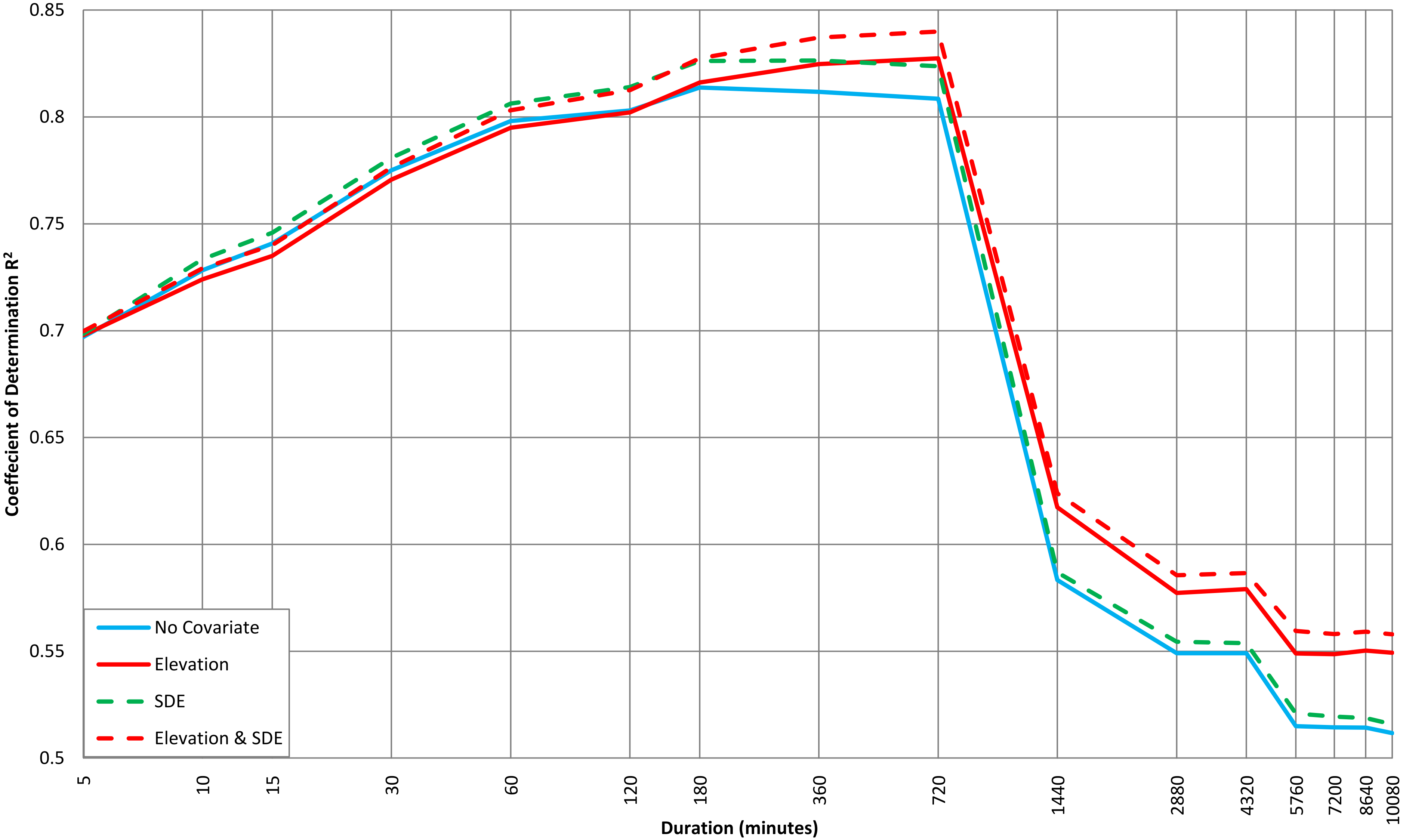
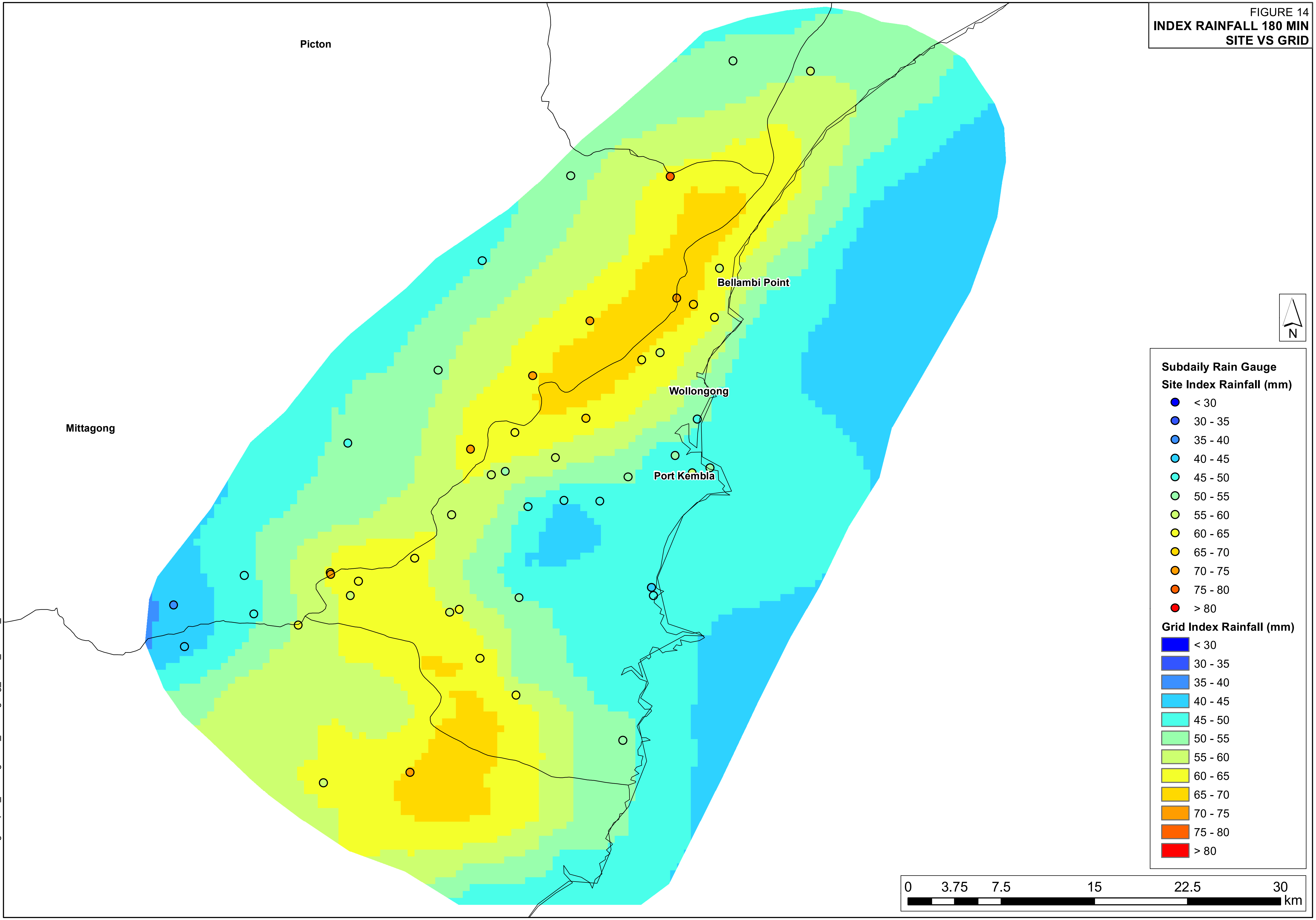


FIGURE 14
INDEX RAINFALL 180 MIN SITE VS GRID



J:\Jobs\116105\arcgis\report_mxd\Figure14_Wollongong_Index_Rainfall_00180min.mxd

FIGURE 15
SITE IFD VS SUM OF SCALED COVARIATES
3 HOUR DURATION 50% AEP

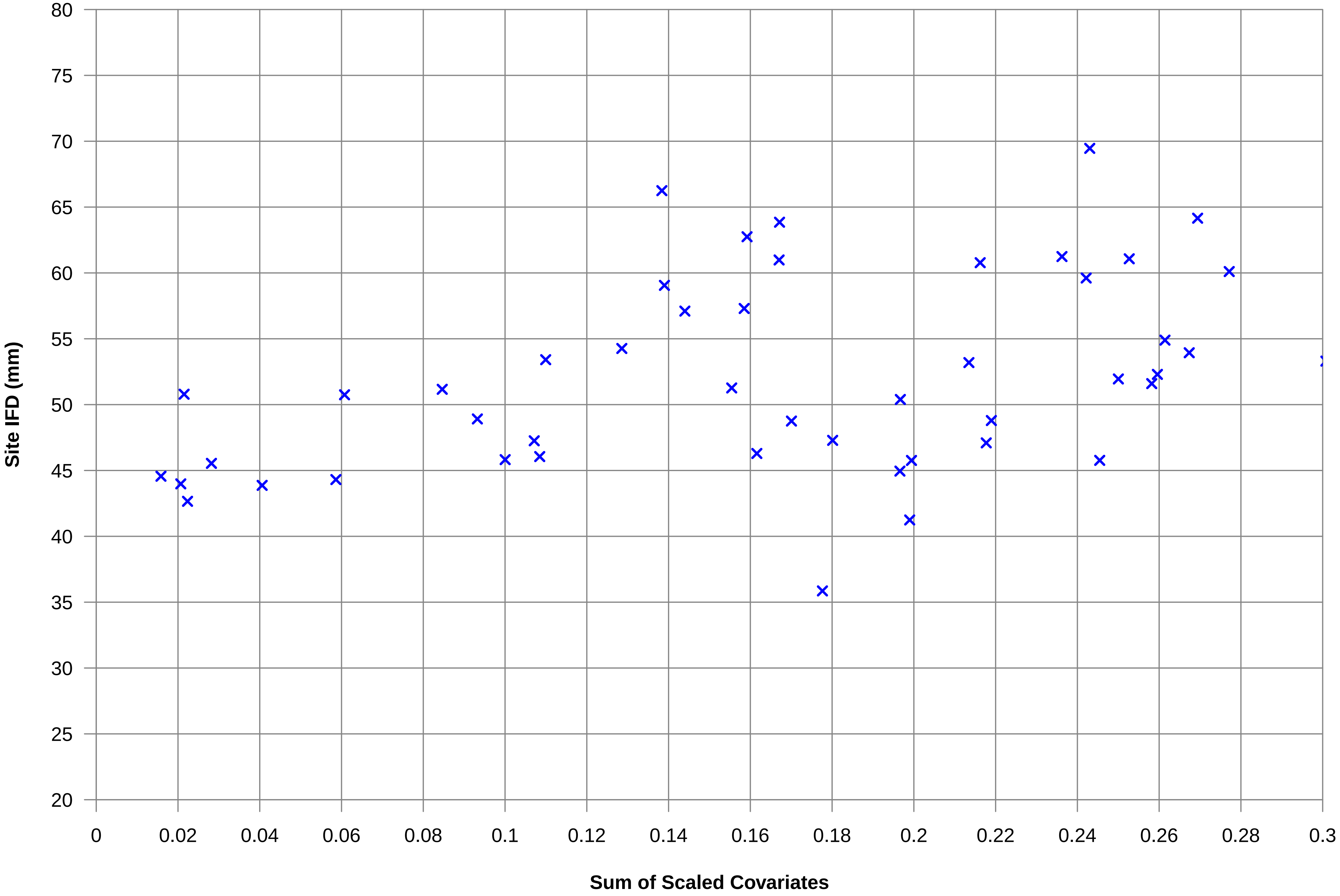


FIGURE 16

SITE IFD VS SUM OF SCALED COVARIATES

3 HOUR DURATION 5% AEP

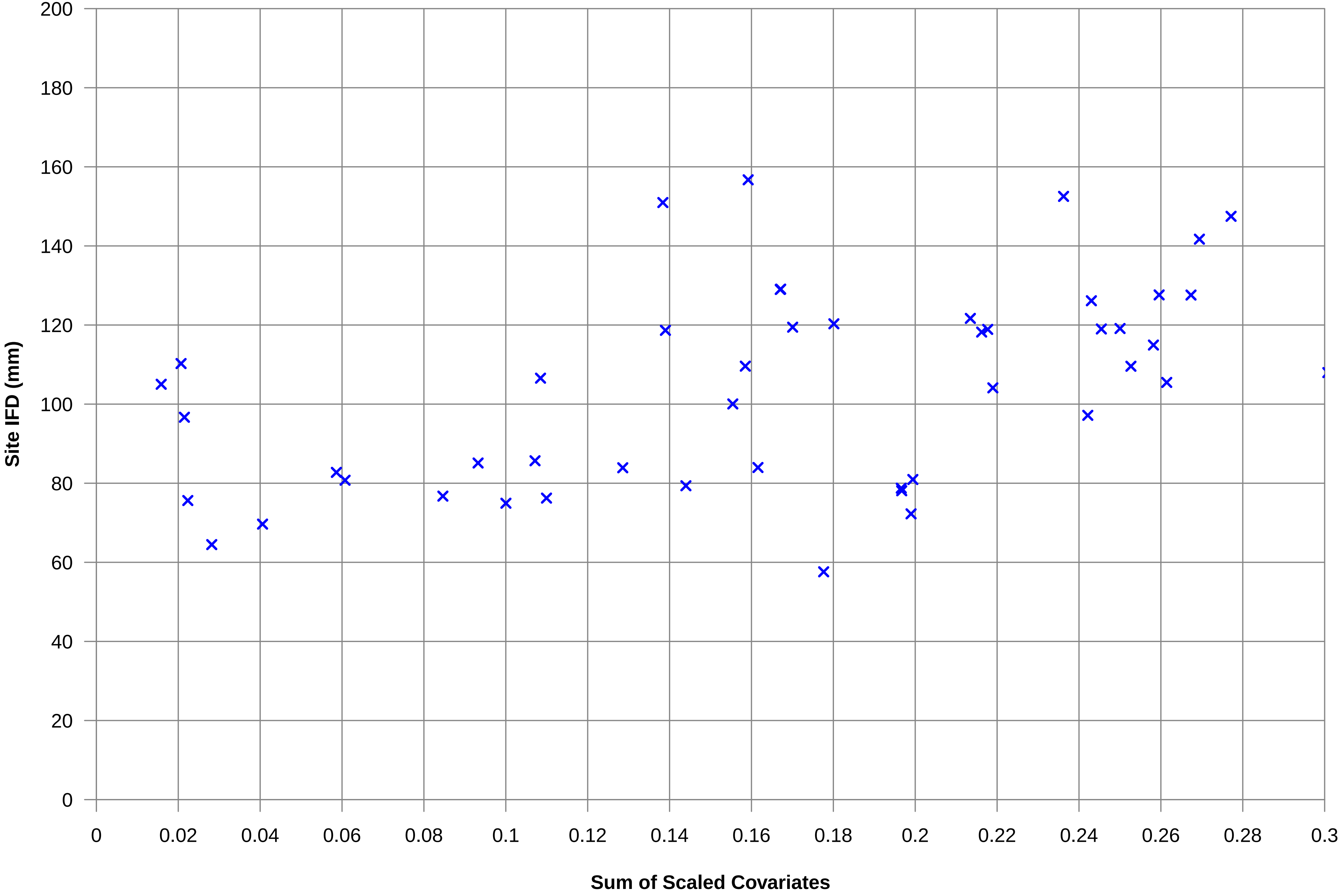


FIGURE 17

SITE IFD VS SUM OF SCALED COVARIATES

3 HOUR DURATION 1% AEP

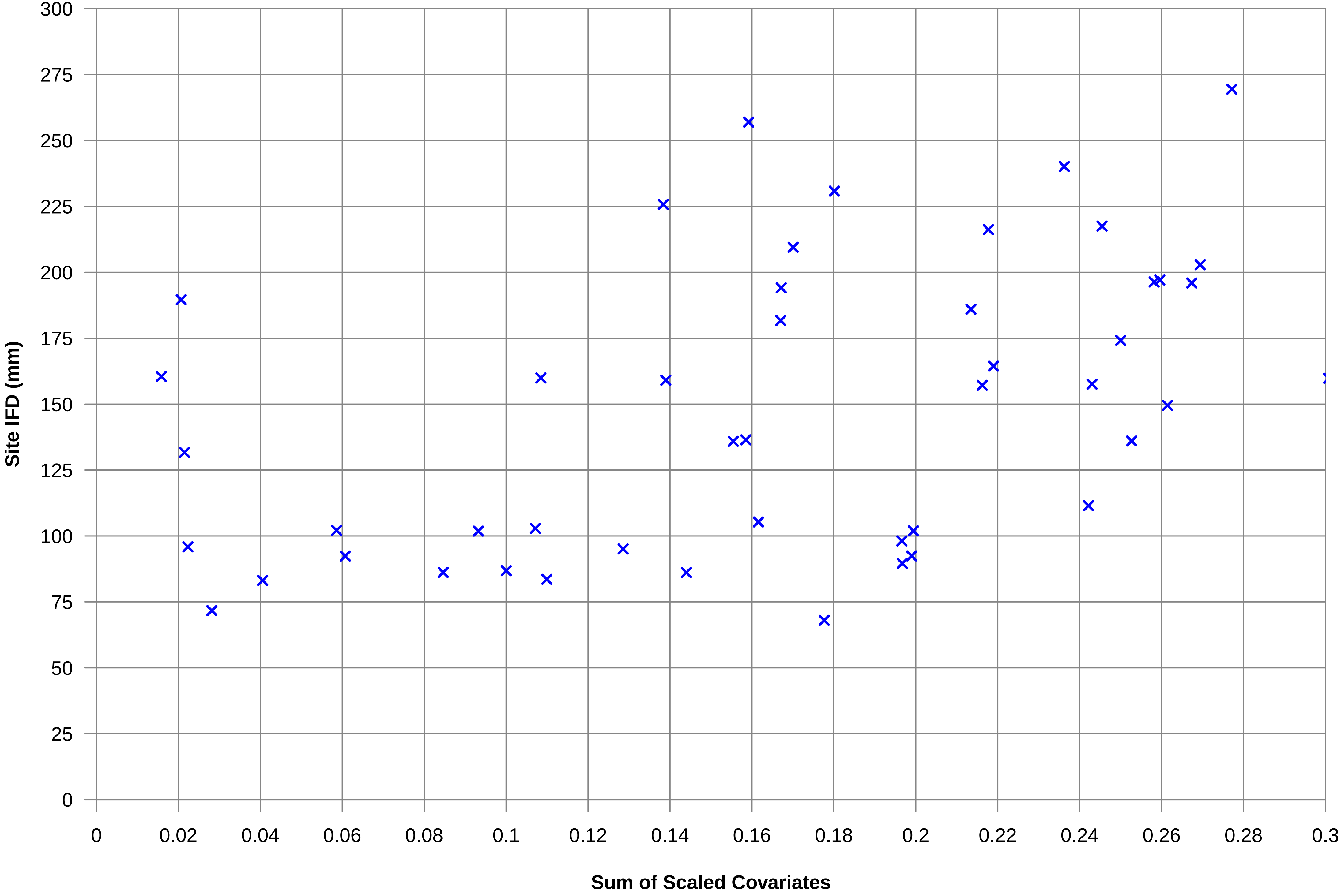


FIGURE 18

COEFFICIENT OF DETERMINATION 180 MINUTES
SDE AND ELEVATION WEIGHTINGS FOR L−CV AND L−SKEW

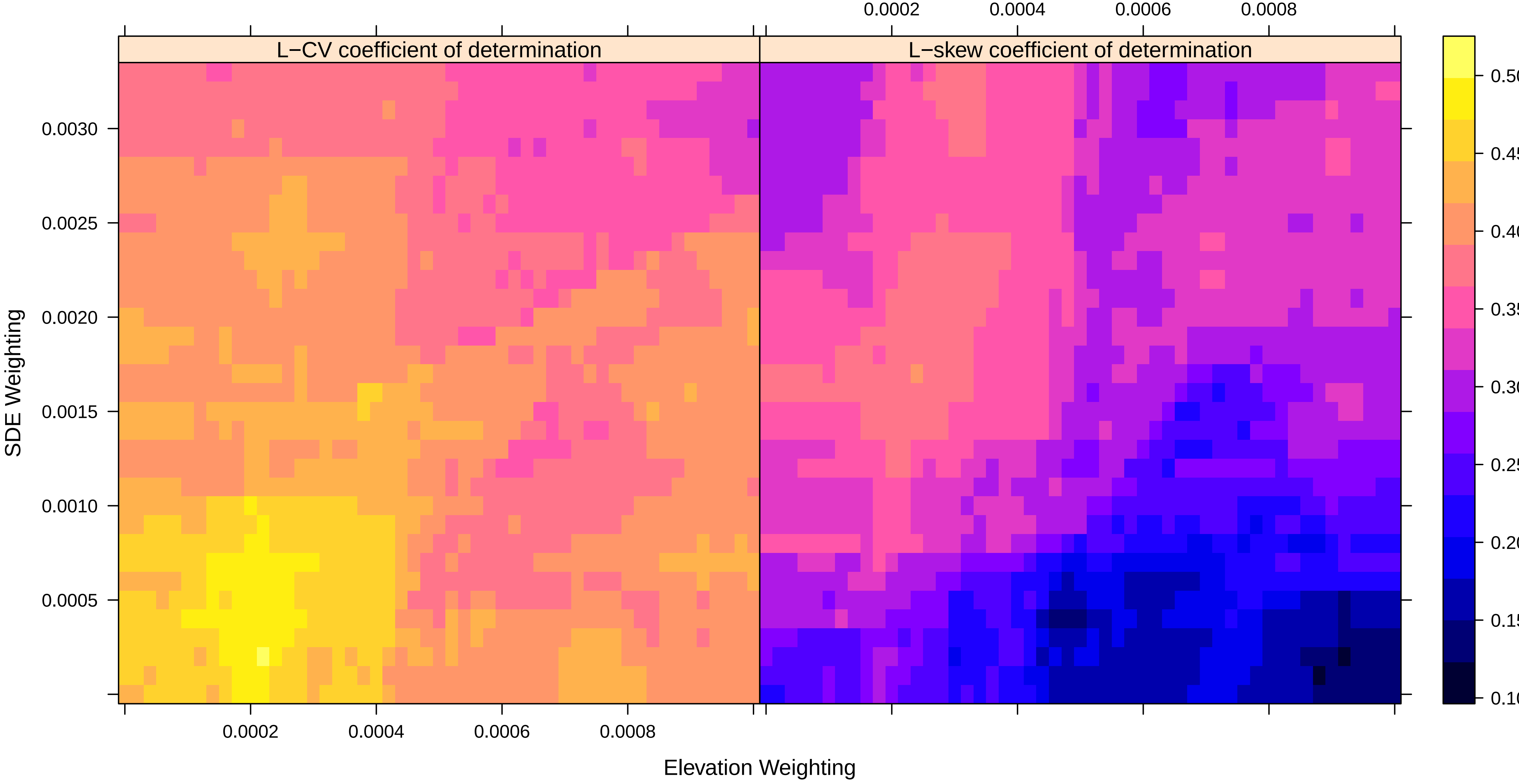


FIGURE 19

COEFFICIENT OF DETERMINATION SUM FOR DURATIONS FROM 30−720 MIN
SDE AND ELEVATION WEIGHTINGS FOR L−CV AND L−SK

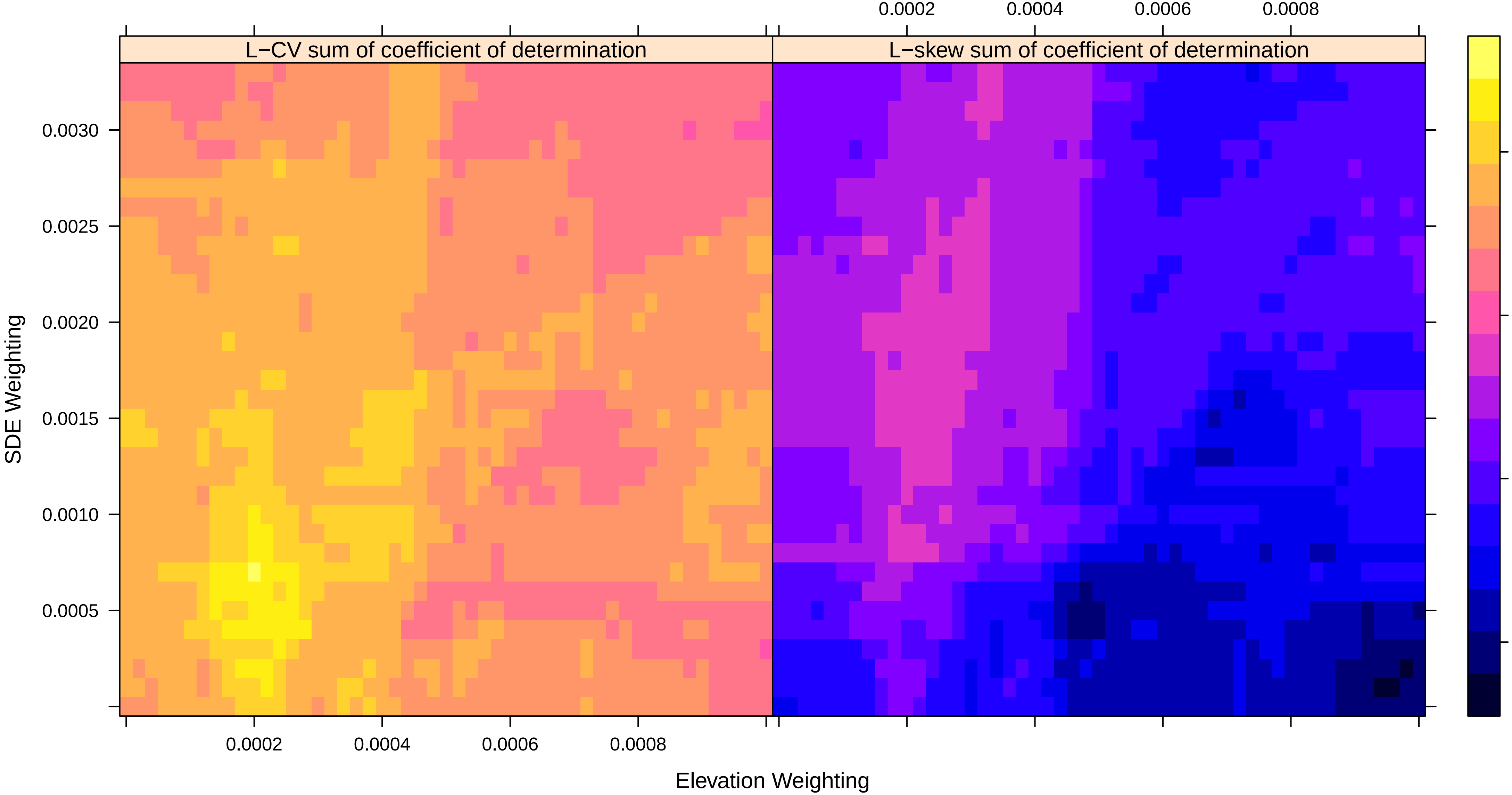
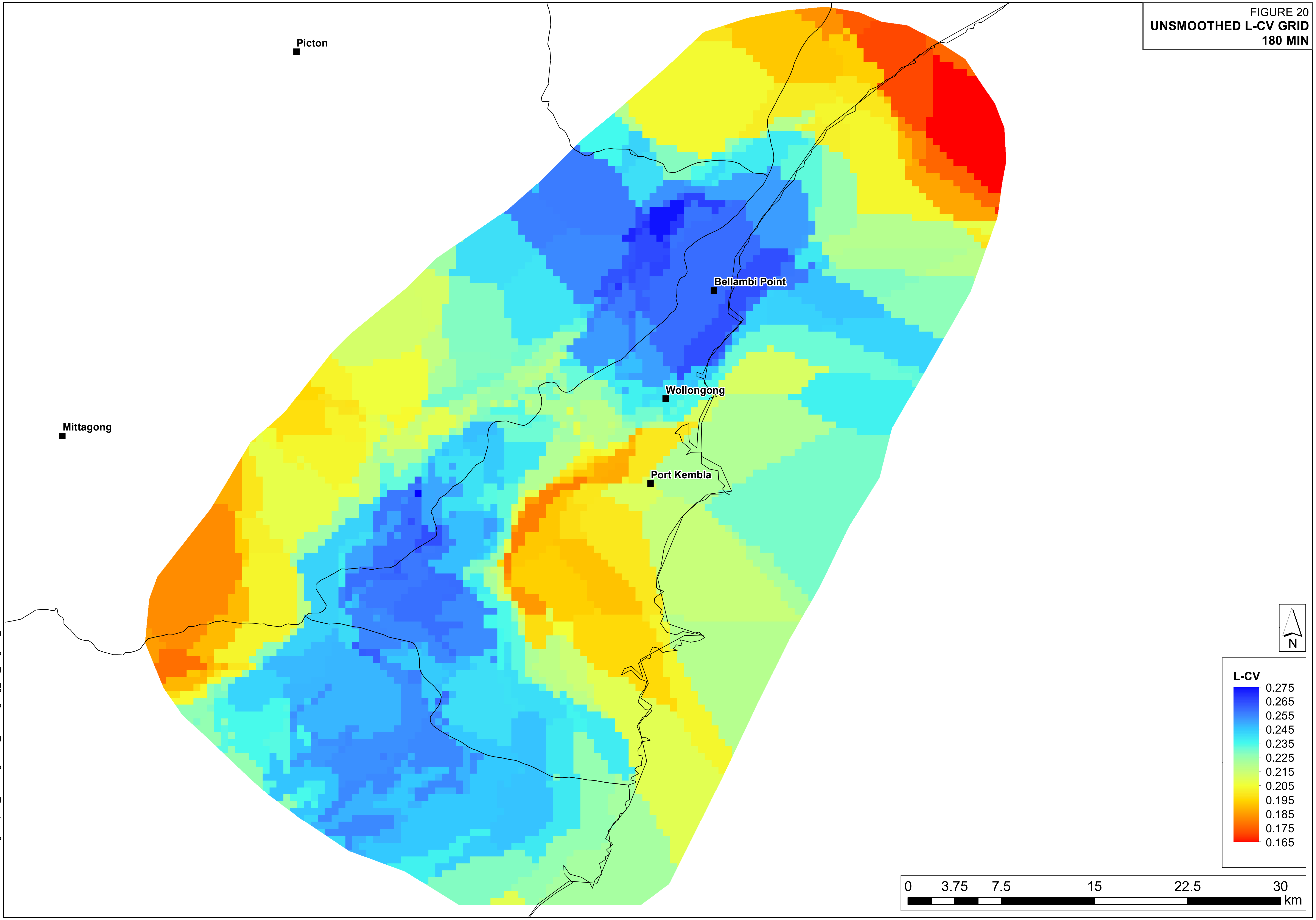


FIGURE 20
UNSMOOTHED L-CV GRID
180 MIN



J:\Jobs\116105\arcgis\report_mxd\Figure20_Wollongong_All_lcvgrids_180min.mxd

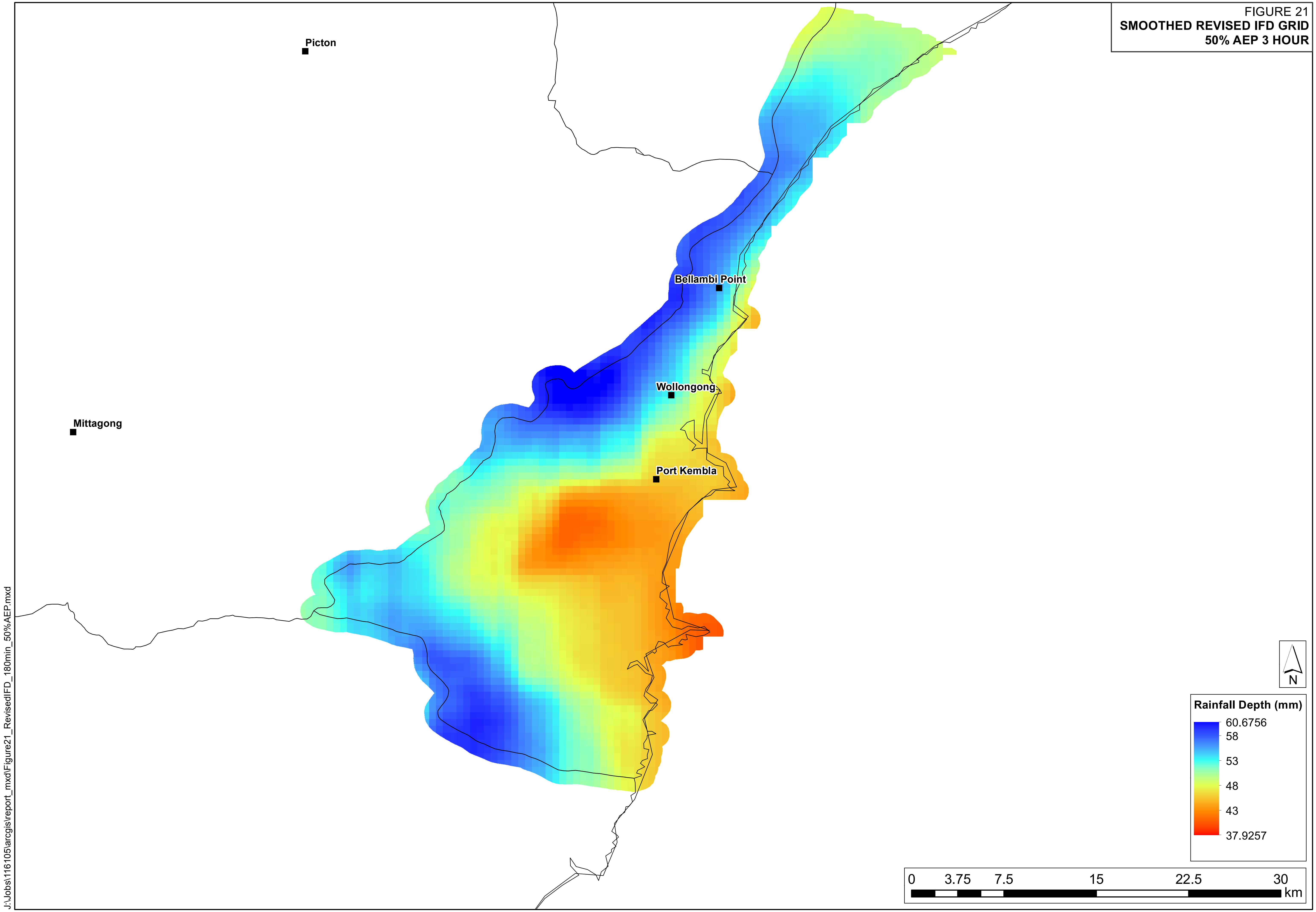
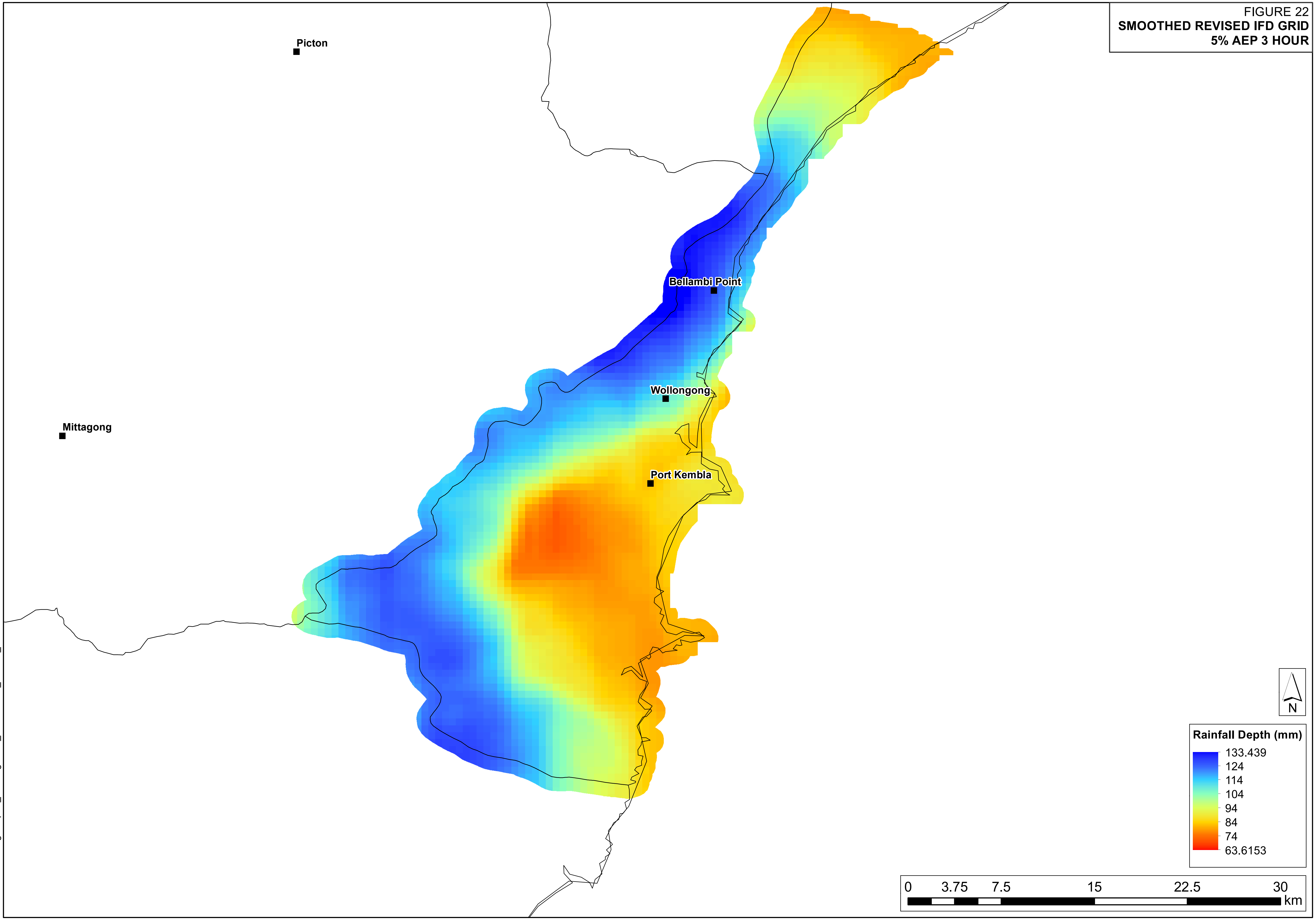


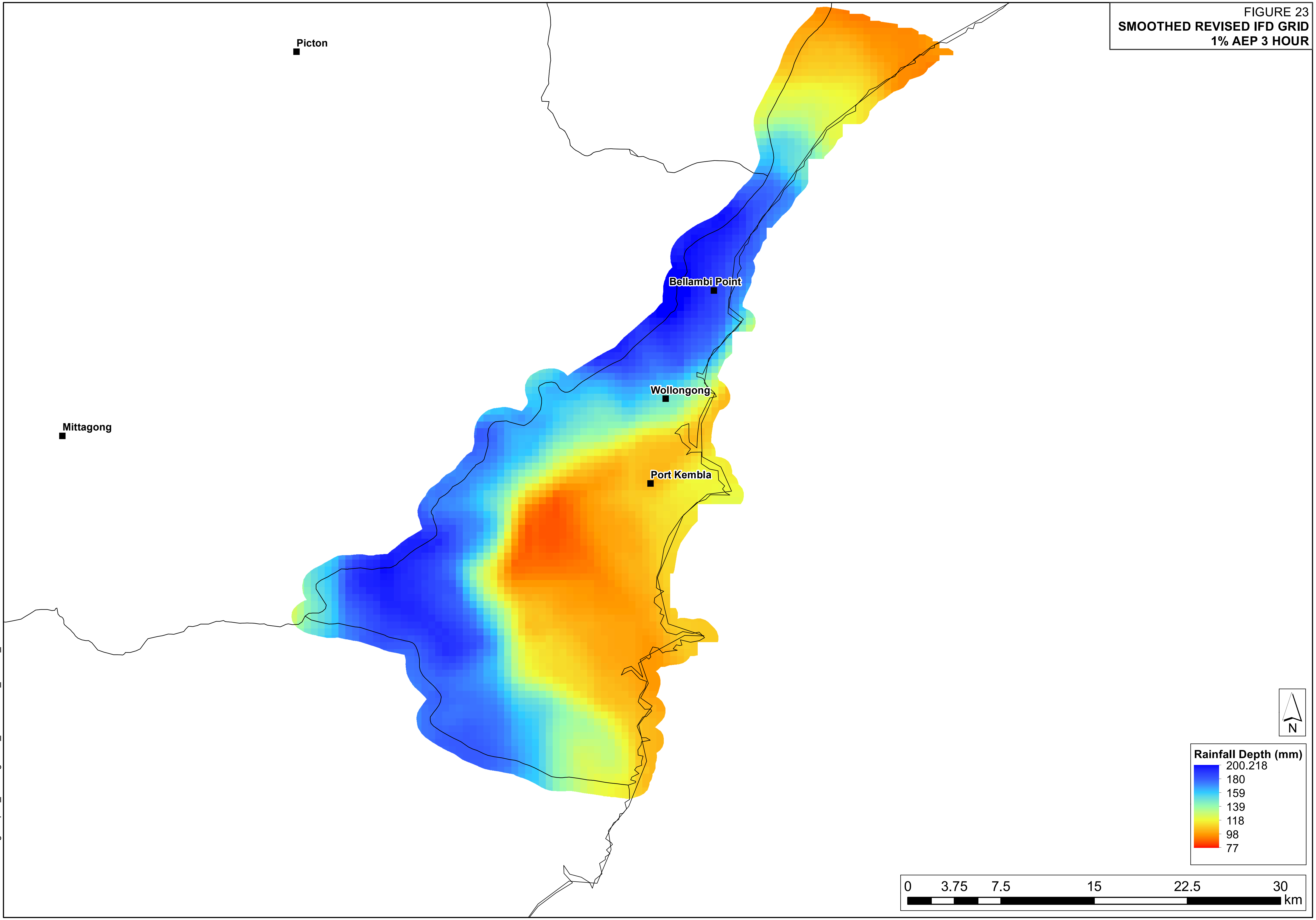
FIGURE 21
SMOOTHED REVISED IFD GRID
50% AEP 3 HOUR
Picton
Mittagong
Bellambi Point
Wollongong
Port Kembla
N
Rainfall Depth (mm)
60.6756
58
53
48
43
37.9257
0
3.75
7.5
15
22.5
30
km
J:\Jobs\116105\arcgis\report_mxd\Figure21_RevisedIFD_180min_50%AEP.mxd

FIGURE 22
SMOOTHED REVISED IFD GRID
5% AEP 3 HOUR



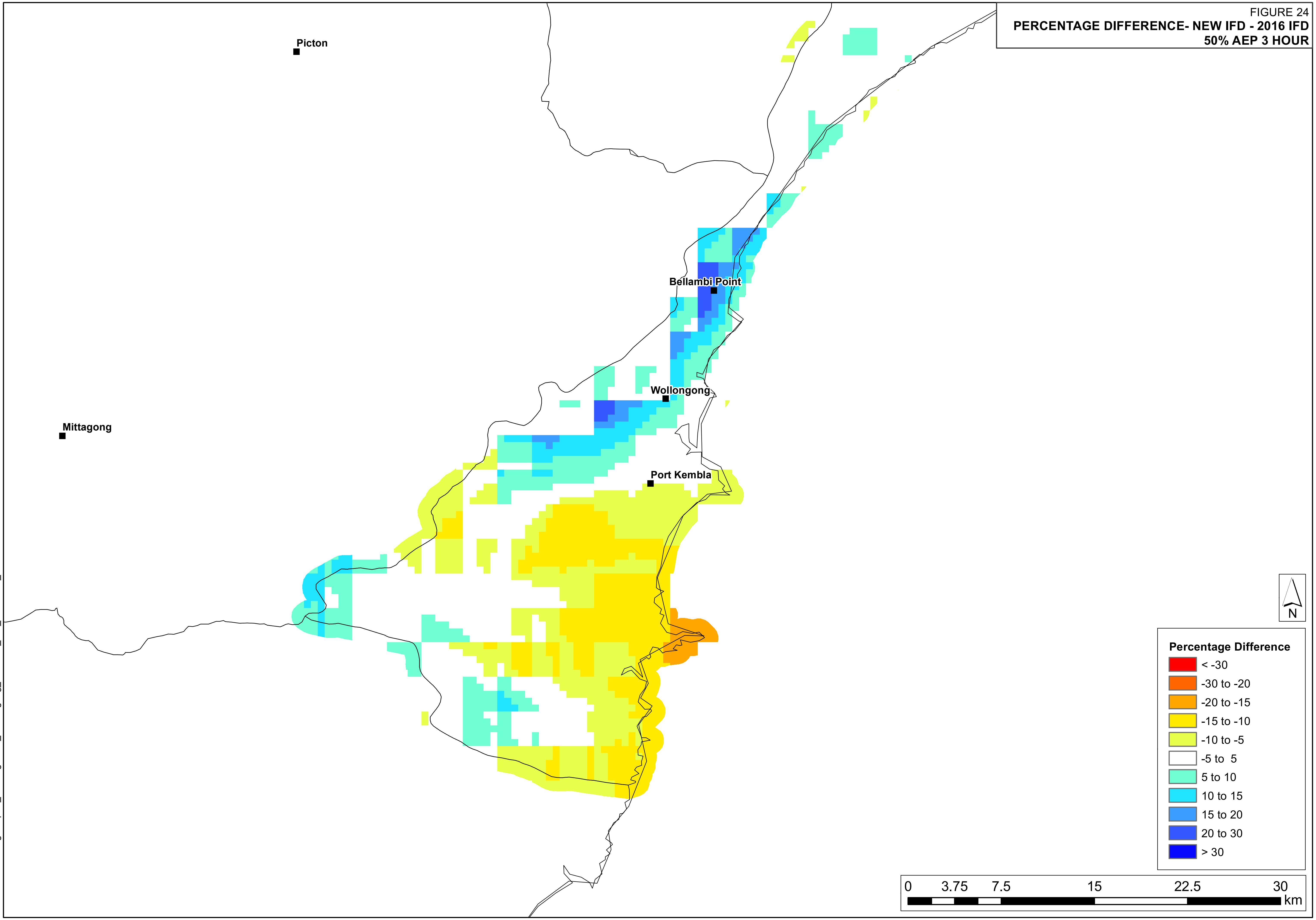
J:\Jobs\116105\arcgis\report_mxd\Figure22_RevisedIFD_180min_5%AEP.mxd

FIGURE 23
SMOOTHED REVISED IFD GRID
1% AEP 3 HOUR



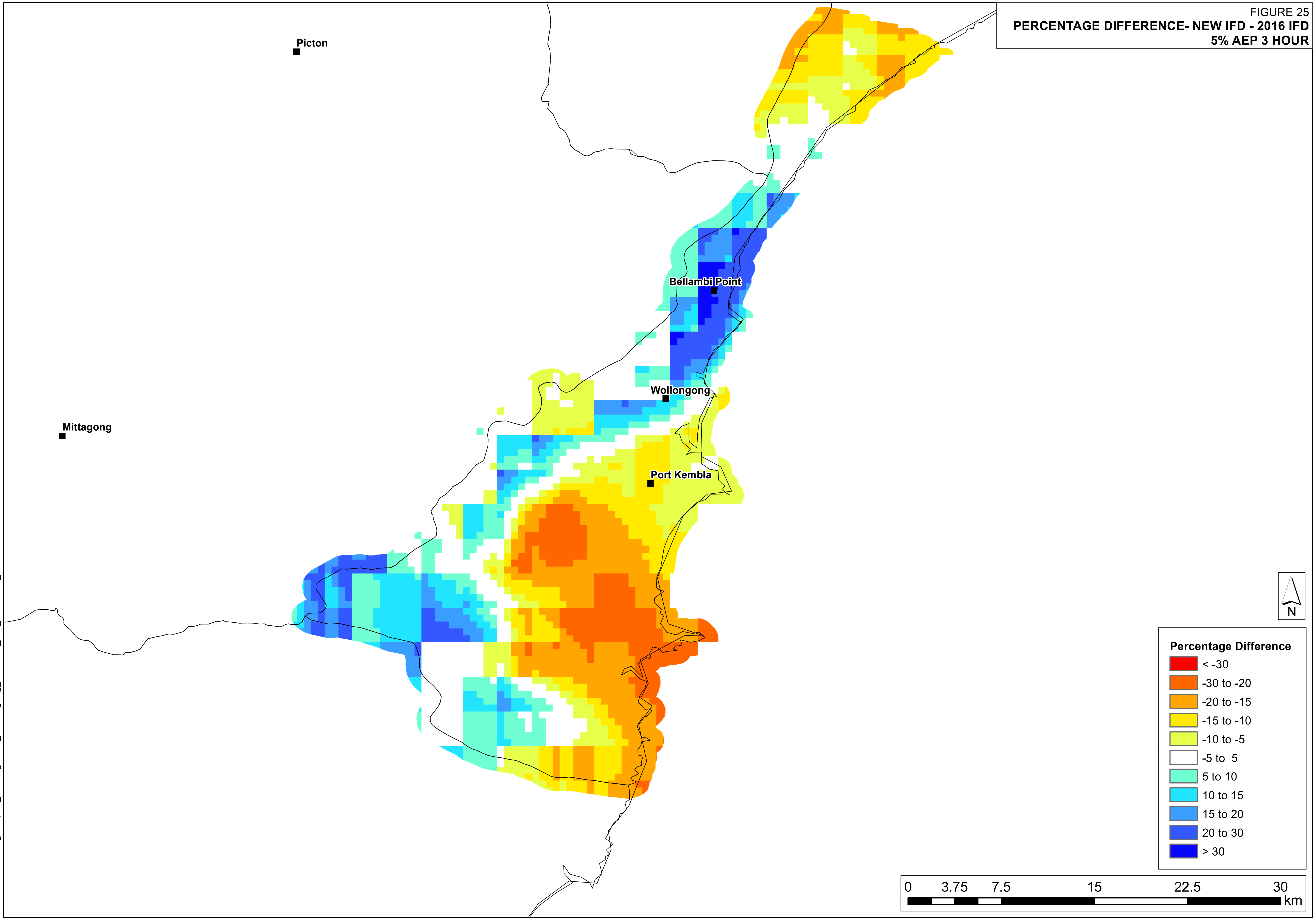
J:\Jobs\116105\arcgis\report_mxd\Figure23_RevisedIFD_180min_1%AEP.mxd

FIGURE 24
PERCENTAGE DIFFERENCE- NEW IFD - 2016 IFD
50% AEP 3 HOUR



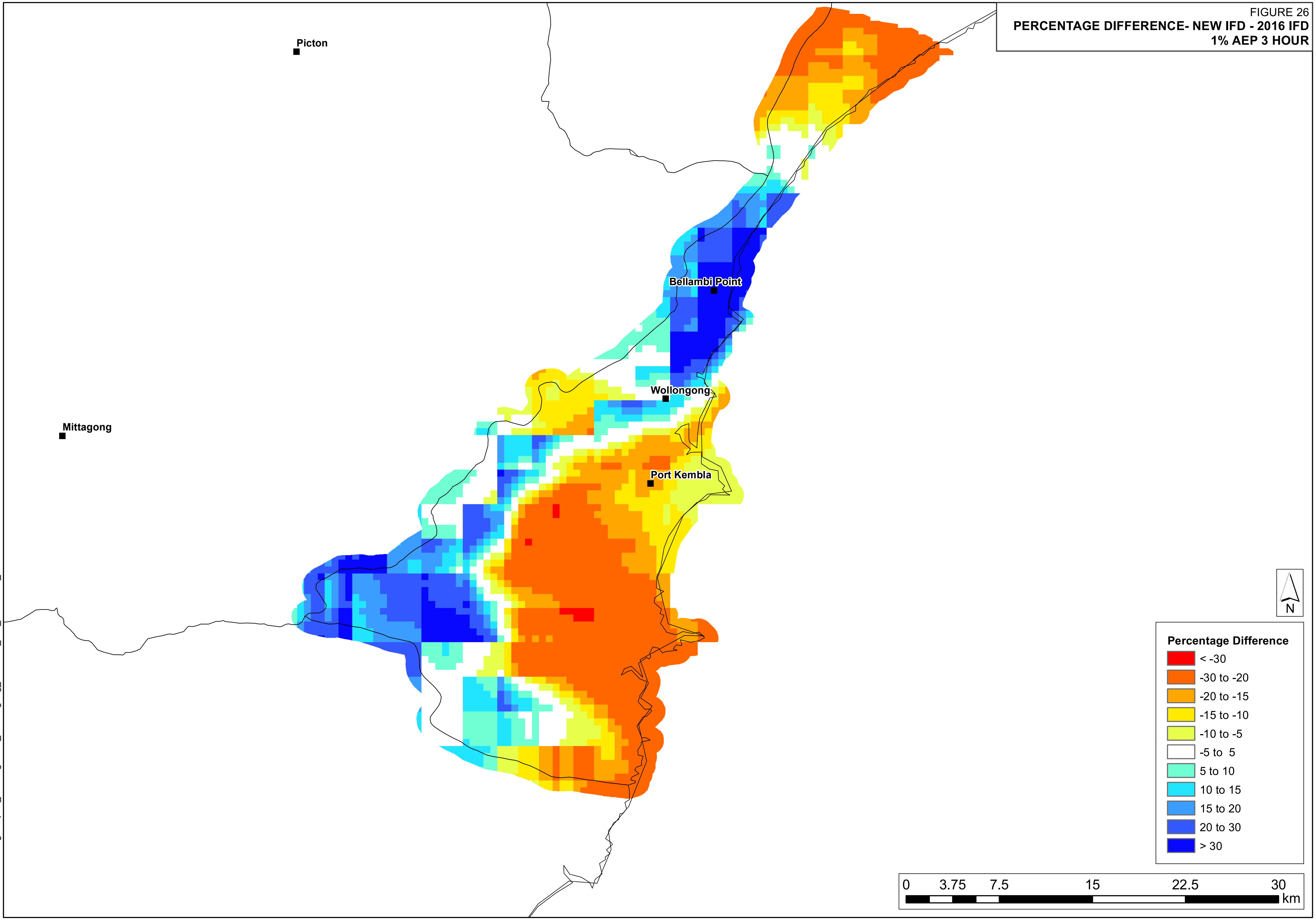
J:\Jobs\116105\arcgis\report_mxd\Figure24_Wollongong_NEWIFD_IFD_00180min_50%AEP.mxd

FIGURE 25
PERCENTAGE DIFFERENCE- NEW IFD - 2016 IFD
5% AEP 3 HOUR



J:\Jobs\116105\arcgis\report_mxd\Figure25_Wollongong_NEWIFD_IFD_00180min_5%AEP.mxd

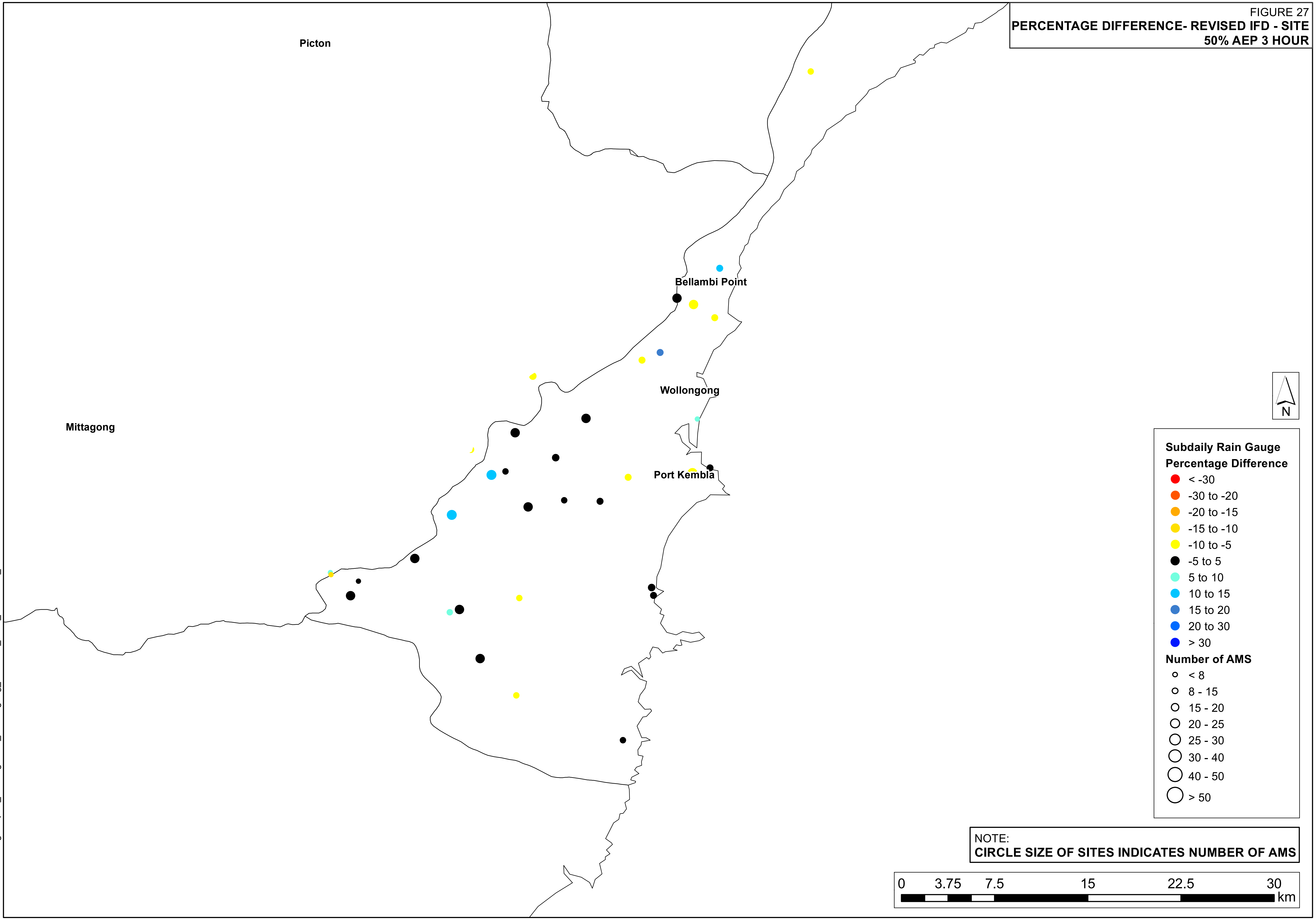
FIGURE 26
PERCENTAGE DIFFERENCE- NEW IFD - 2016 IFD
1% AEP 3 HOUR



J:\Jobs\116105\arcgis\report_mxd\Figure26_Wollongong_NEWIFD_IFD_00180min_1%AEP.mxd

FIGURE 27

PERCENTAGE DIFFERENCE- REVISED IFD - SITE 50% AEP 3 HOUR



NOTE:
CIRCLE SIZE OF SITES INDICATES NUMBER OF AMS

J:\Jobs\116105\arcgis\report_mxd\Figure27_Wollongong_NEWIFD_SITE_00180min_50%AEP.mxd

FIGURE 28
PERCENTAGE DIFFERENCE- REVISED IFD - SITE
5% AEP 3 HOUR

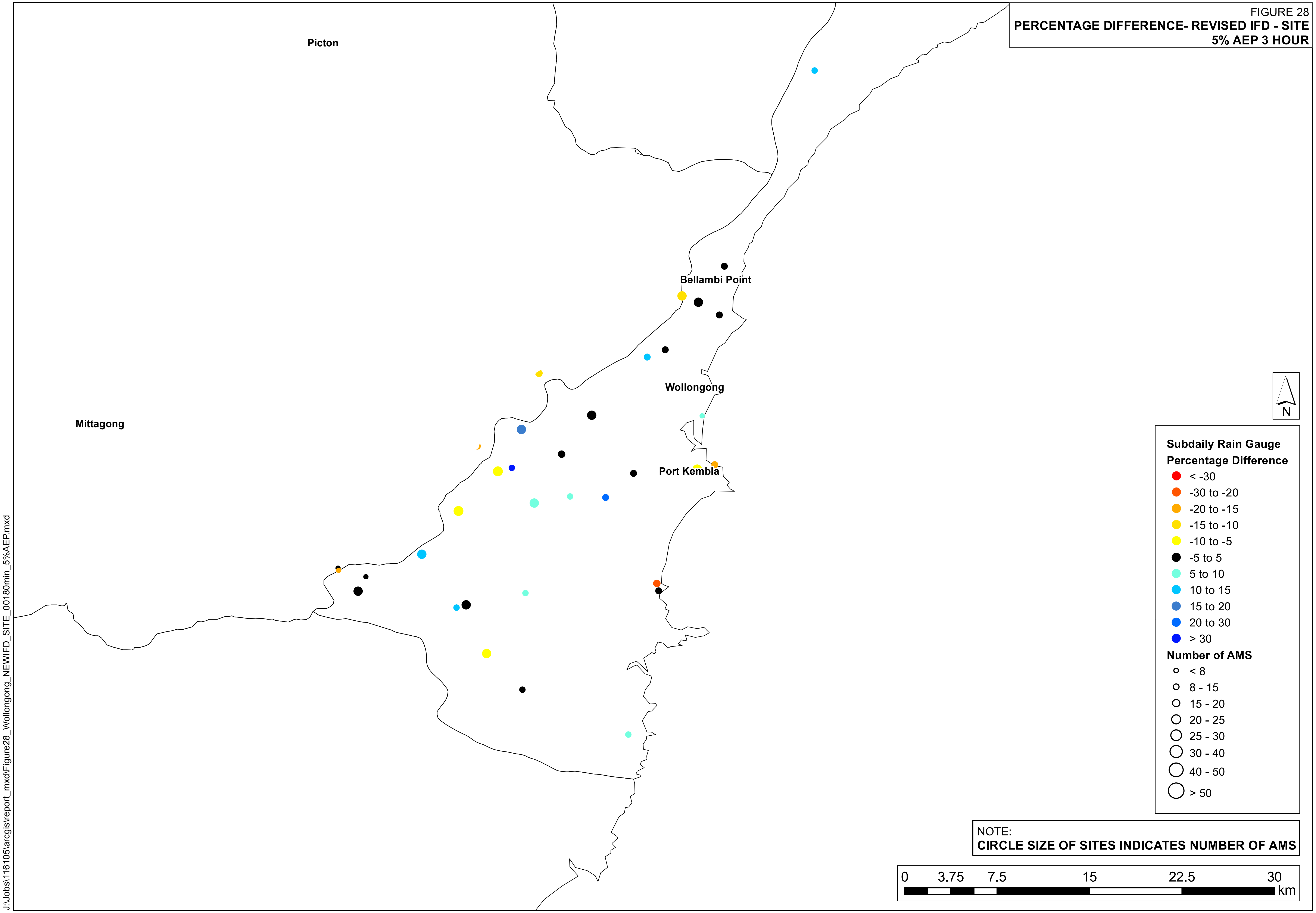
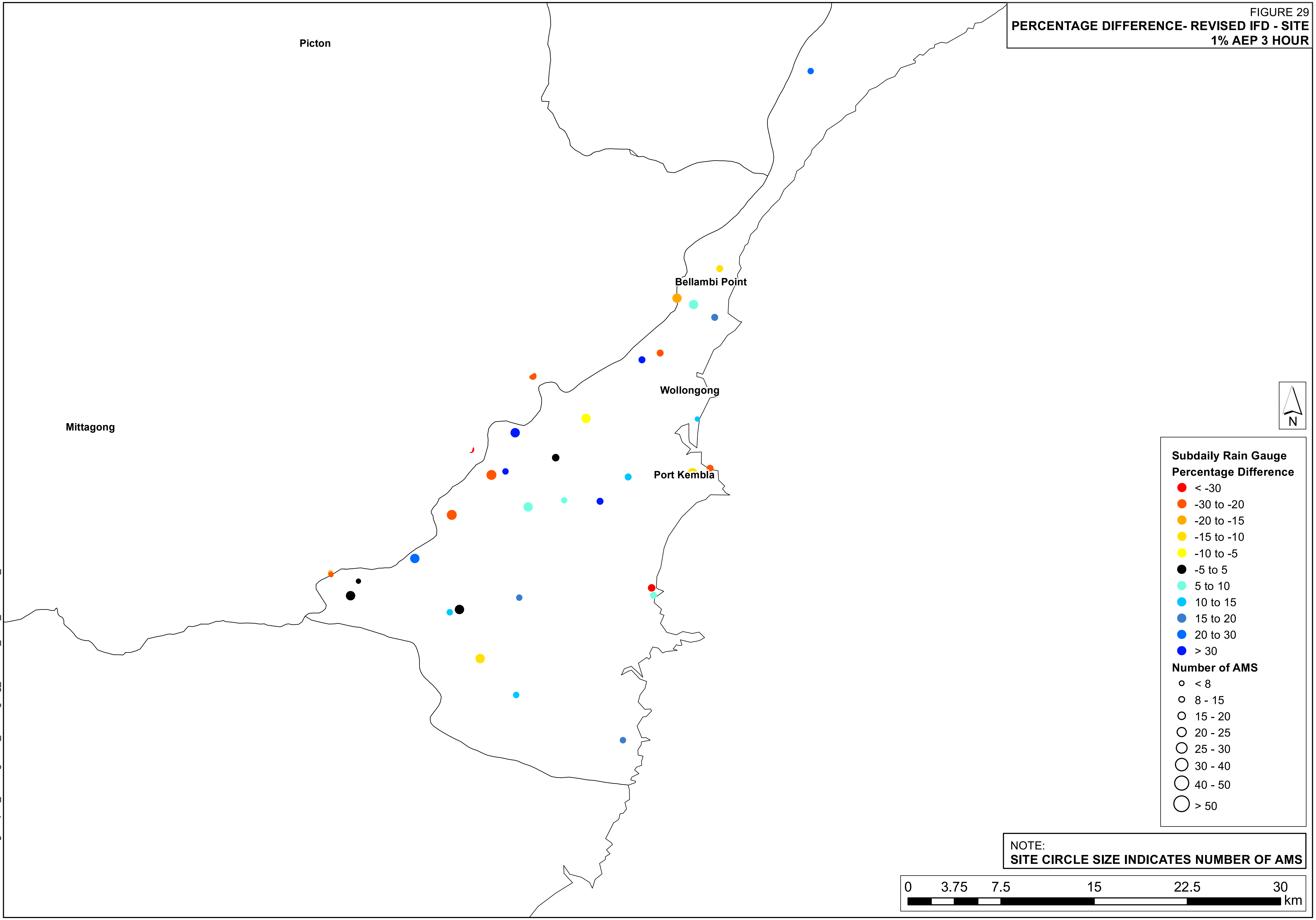


FIGURE 29
PERCENTAGE DIFFERENCE- REVISED IFD - SITE
1% AEP 3 HOUR



NOTE:
SITE CIRCLE SIZE INDICATES NUMBER OF AMS

J:\Jobs\116105\arcgis\report_mxd\Figure29_Wollongong_NEWIFD_SITE_00180min_1%AEP.mxd

FIGURE 30

QUANTILES OF PERCENTAGE DIFFERENCES − REVISED IFD − SITE 50% AEP

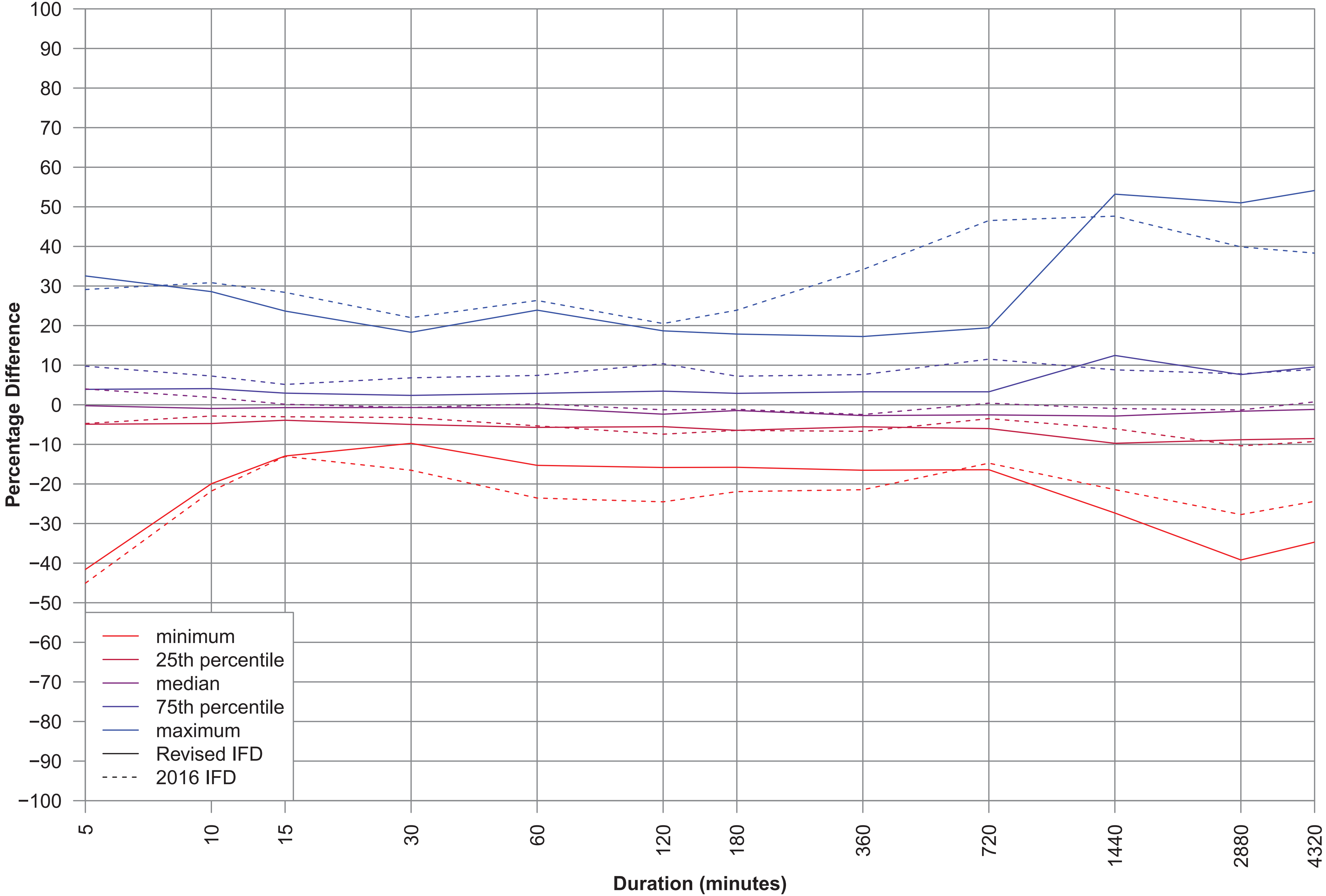


FIGURE 31

QUANTILES OF PERCENTAGE DIFFERENCES − REVISED IFD − SITE 5% AEP

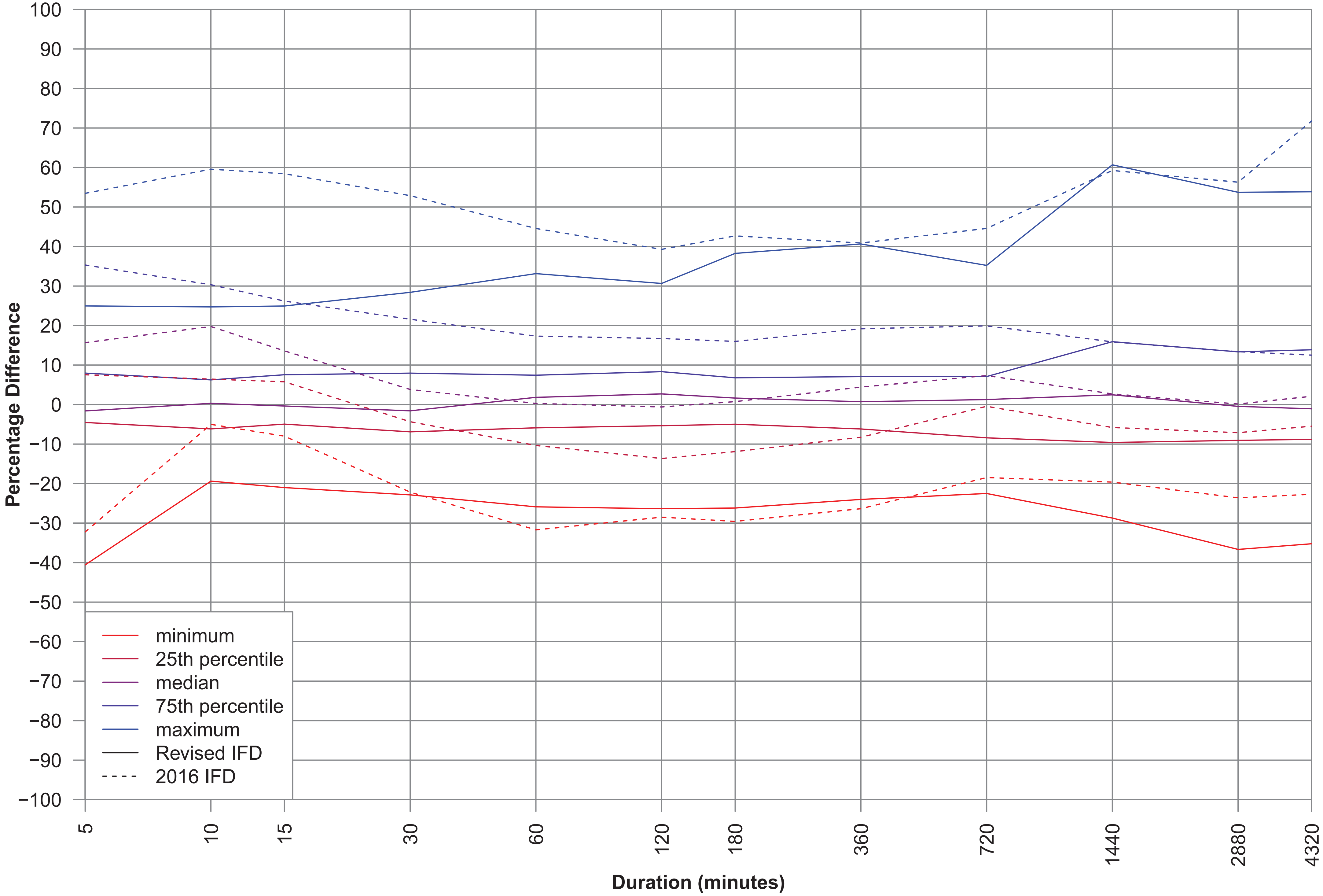


FIGURE 32

QUANTILES OF PERCENTAGE DIFFERENCES – REVISED IFD – SITE 1% AEP

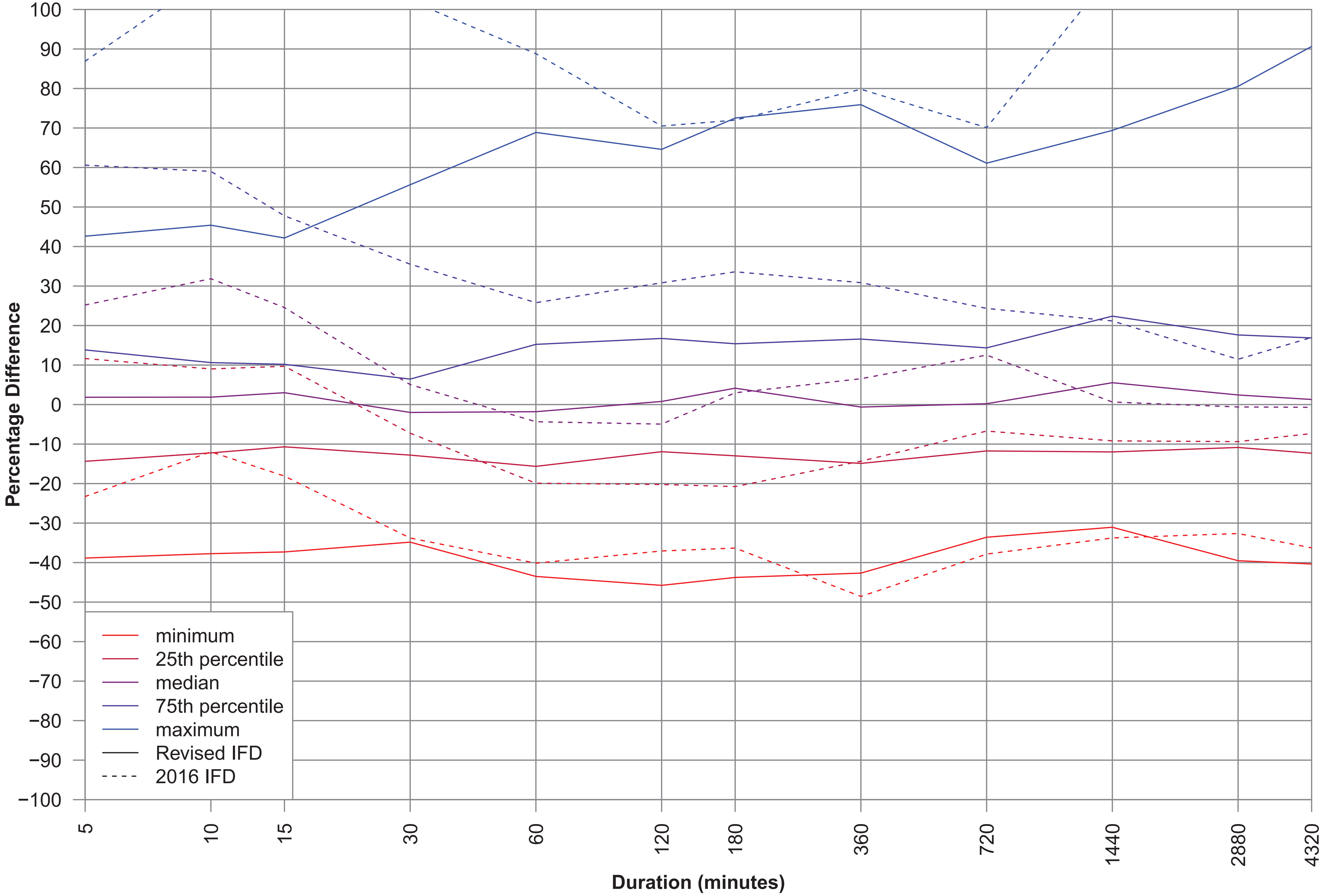


FIGURE 33
MEAN ABSOLUTE ERROR
REVISED IFD VS 2016 IFD

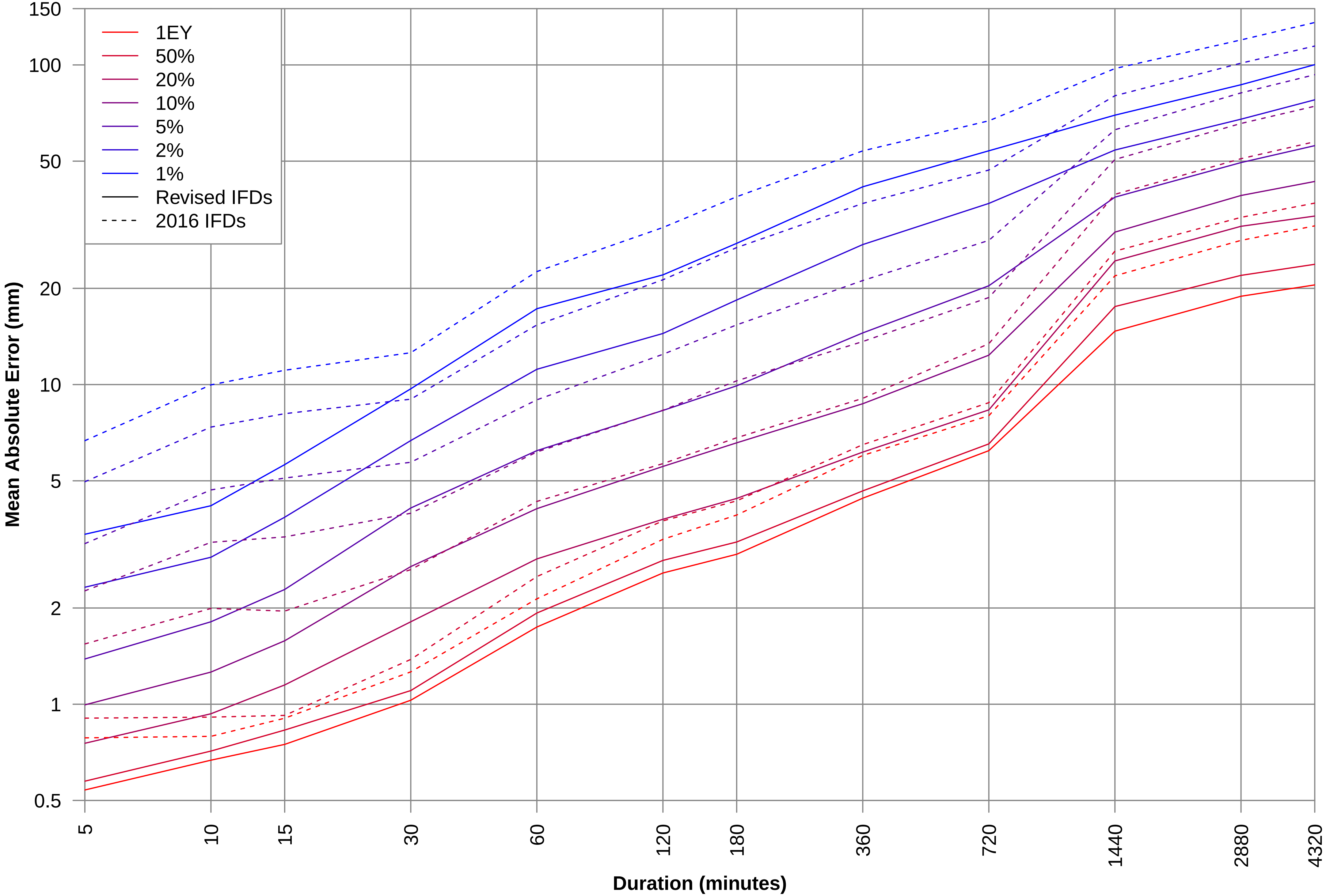


FIGURE 34
ROOT MEAN SQUARED ERROR
REVISED IFD VS 2016 IFD

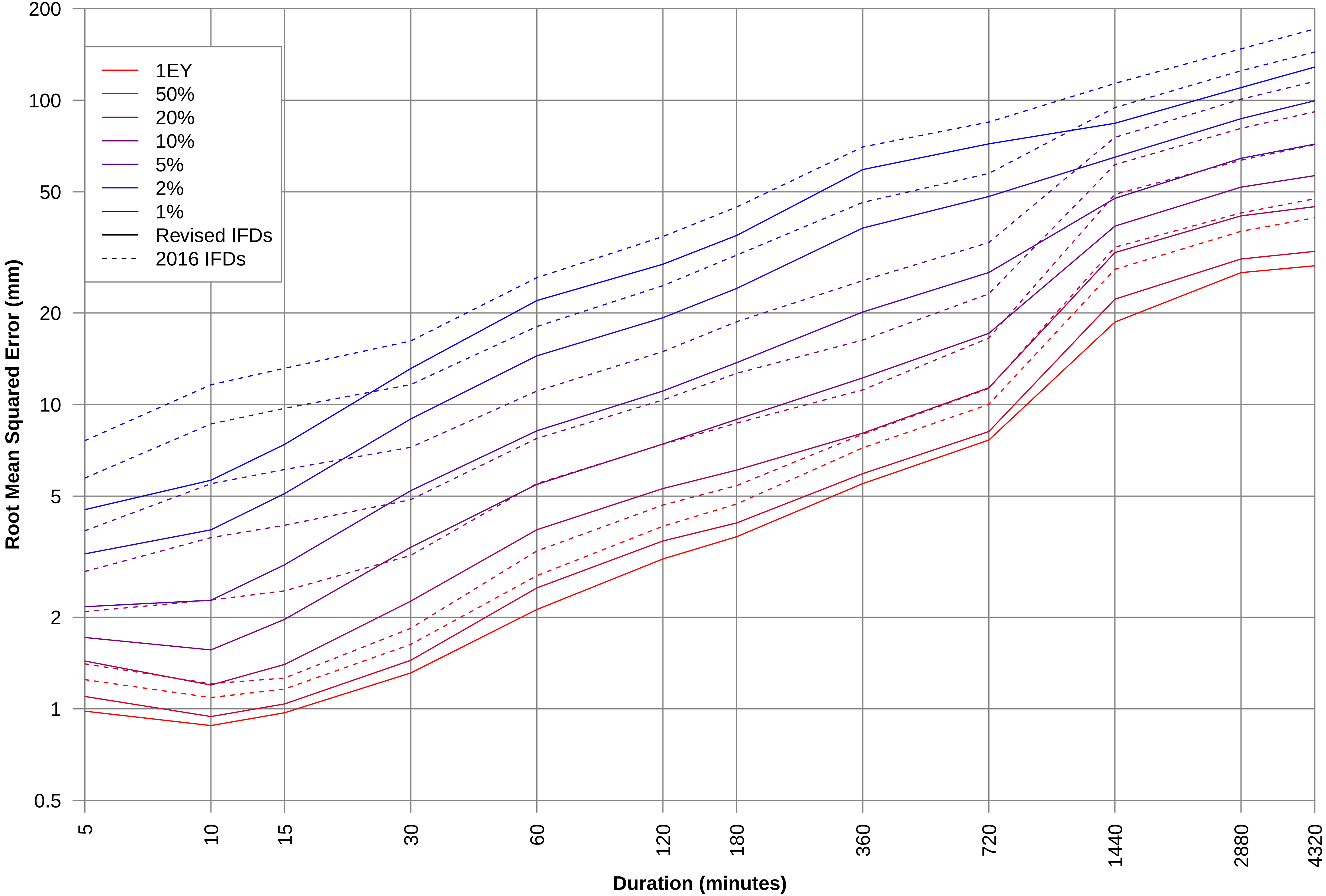


FIGURE 35

COEFFICIENT OF DETERMINATION
REVISED IFD VS 2016 IFD

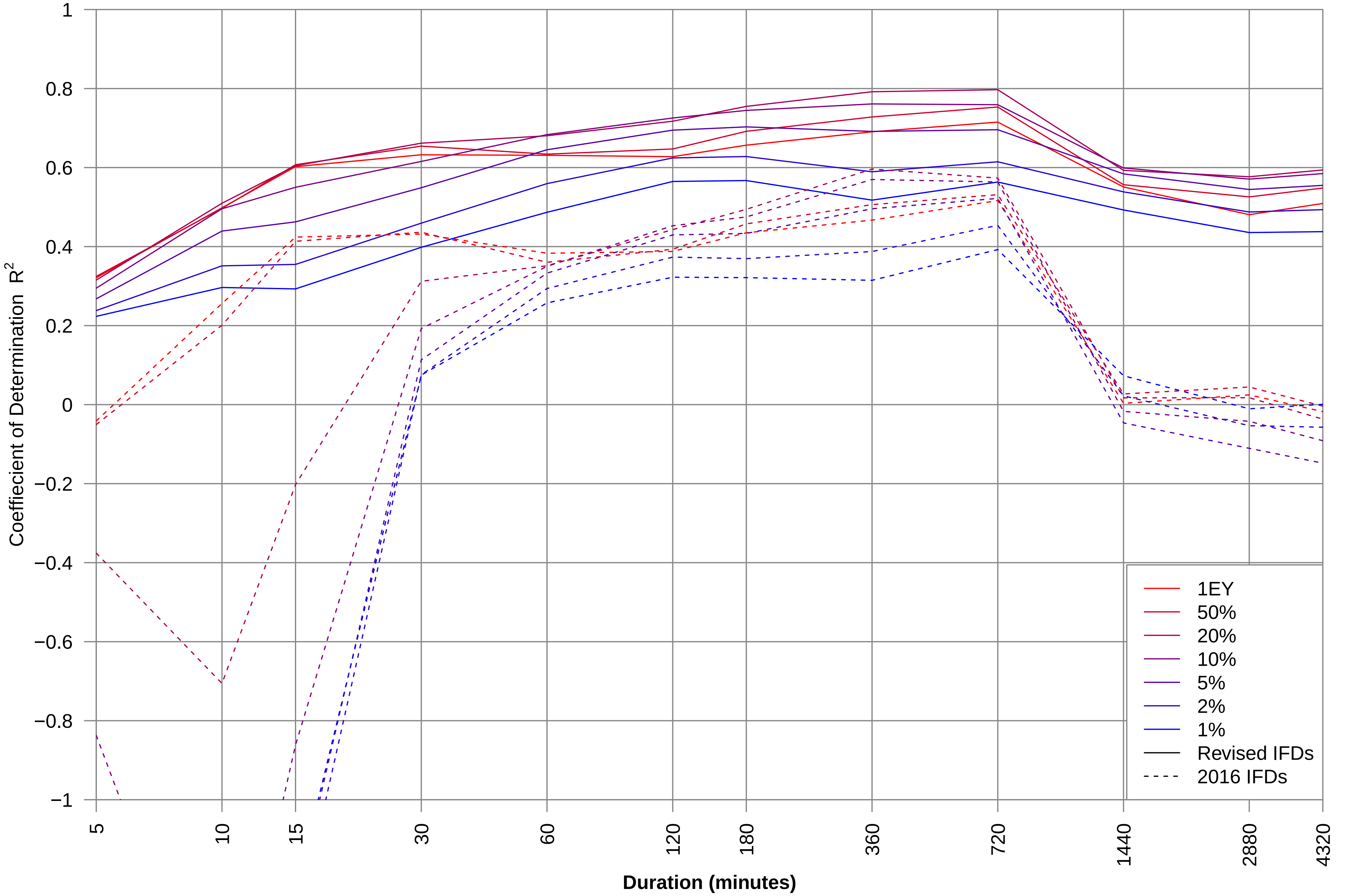
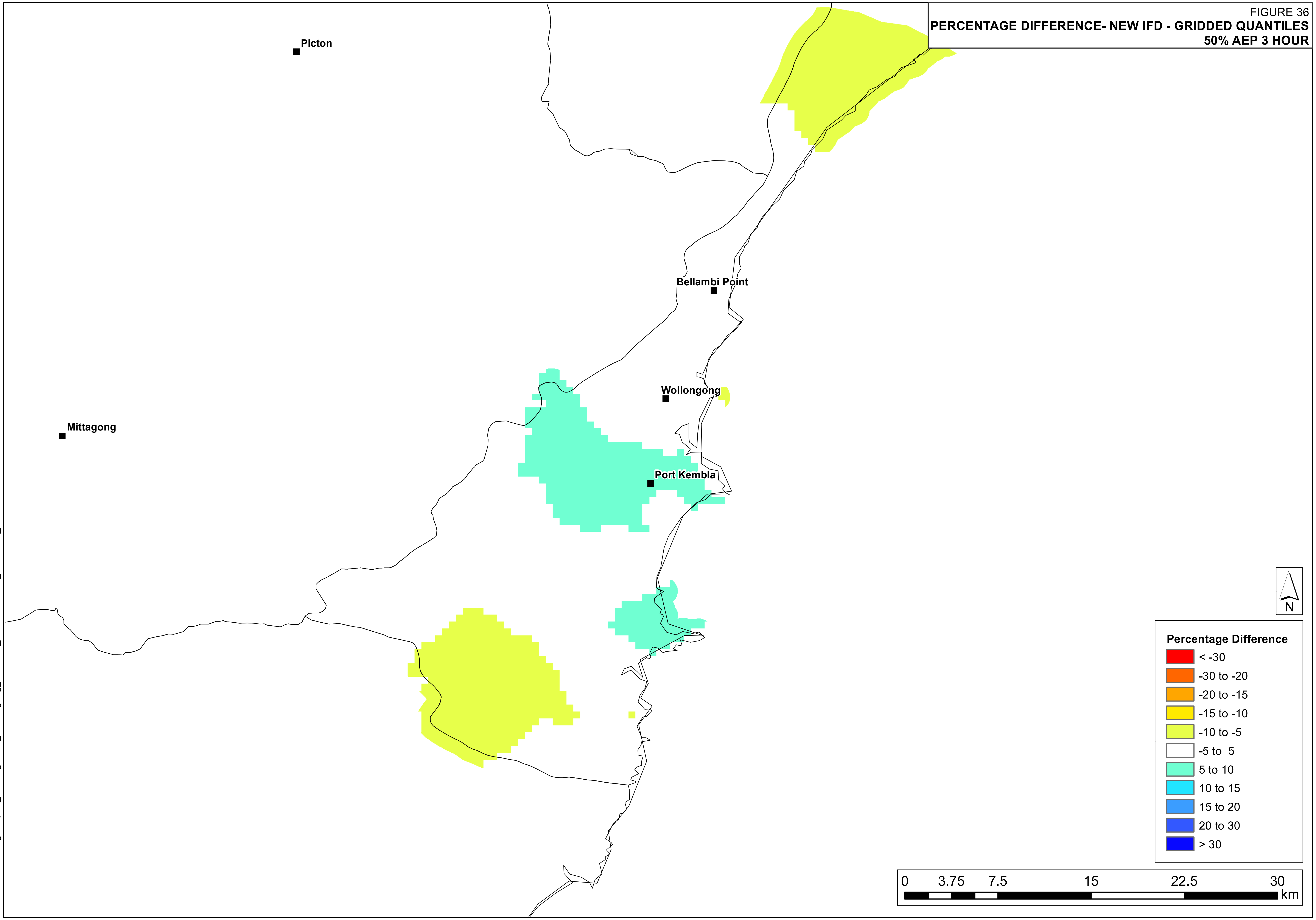


FIGURE 36

PERCENTAGE DIFFERENCE- NEW IFD - GRIDDED QUANTILES

50% AEP 3 HOUR

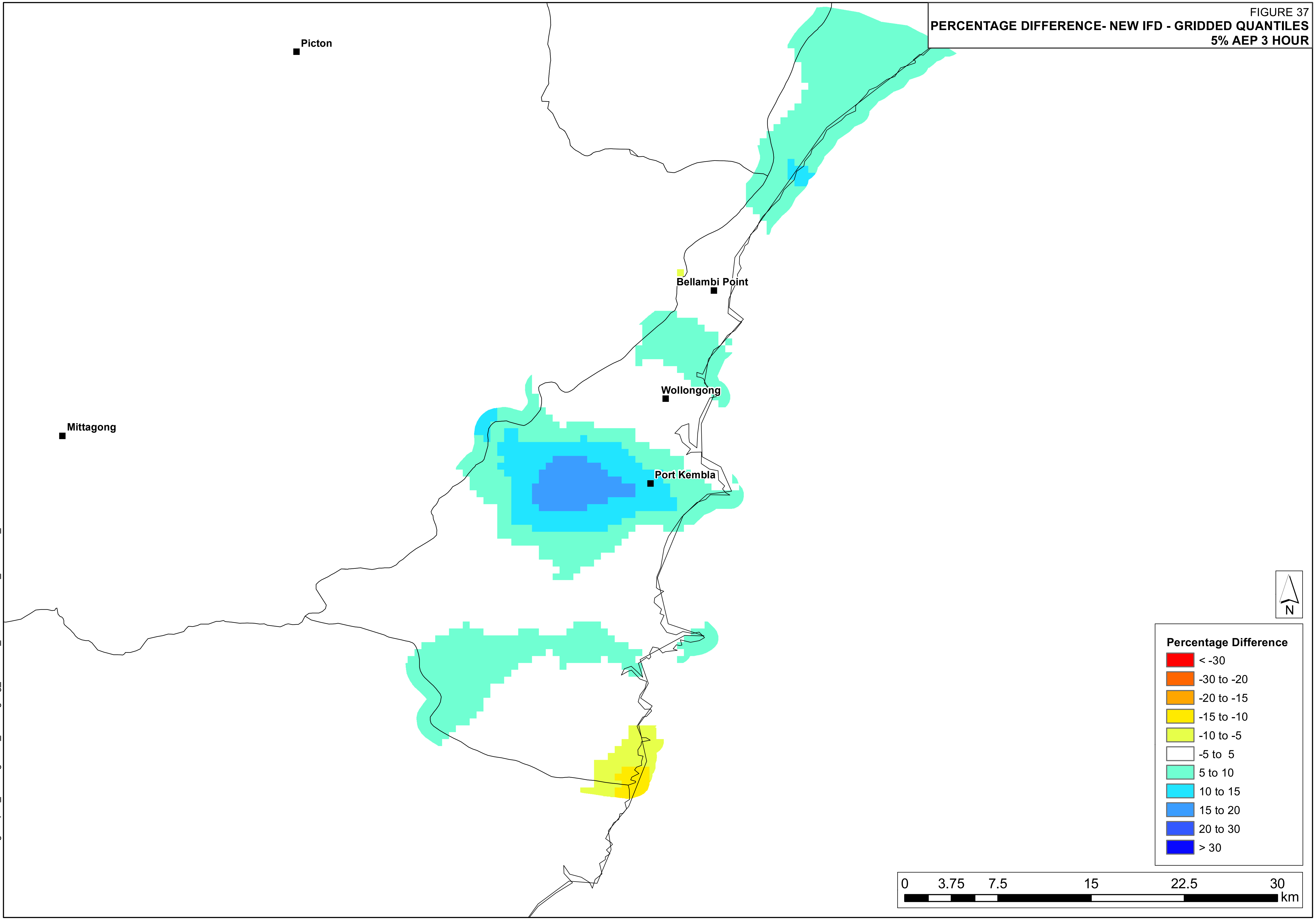


J:\Jobs\116105\arcgis\report_mxd\Figure36_Wollongong_NEWIFD_GRIDDEDQRT_00180min_50%AEP.mxd

FIGURE 37

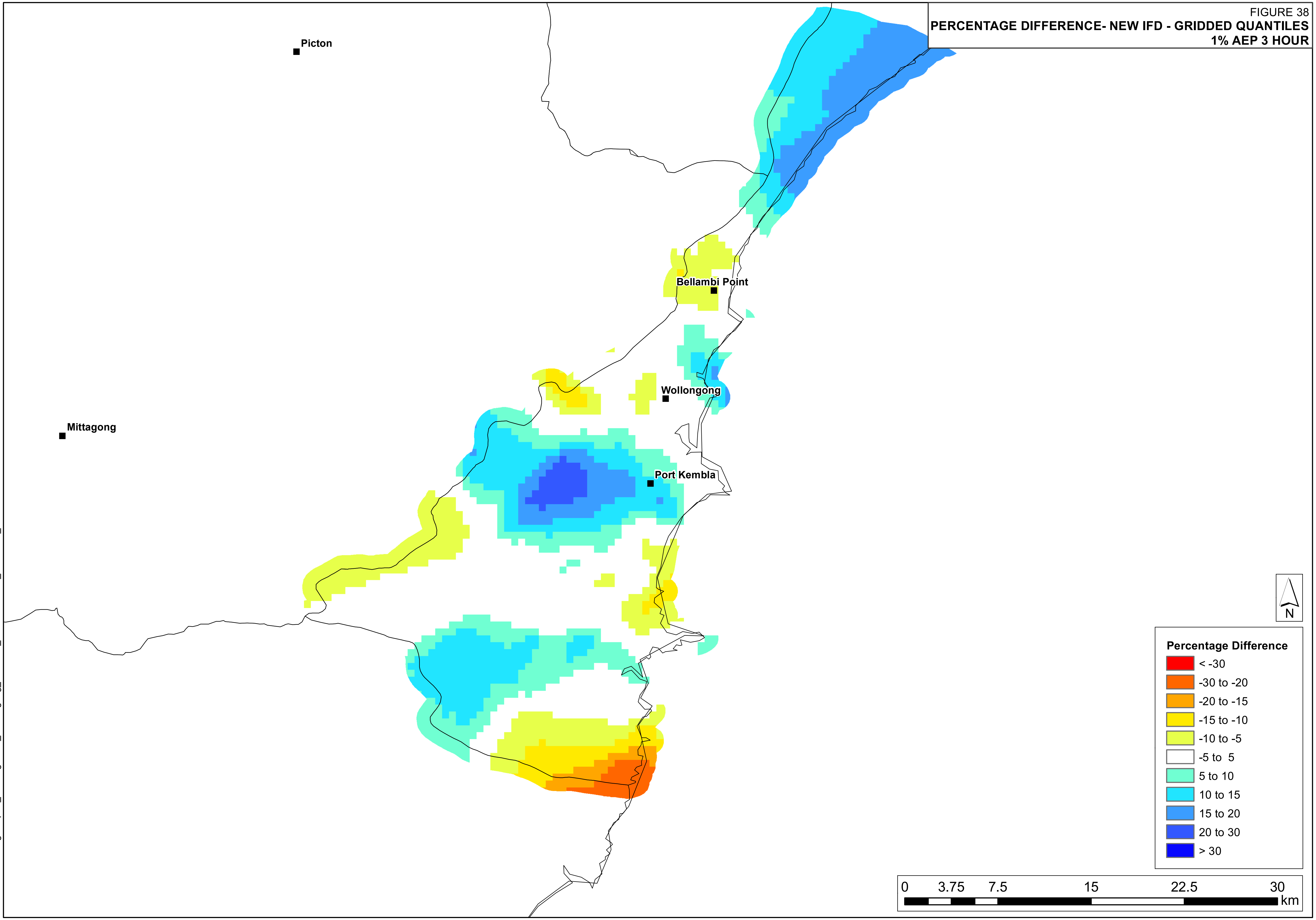
PERCENTAGE DIFFERENCE- NEW IFD - GRIDDED QUANTILES

5% AEP 3 HOUR



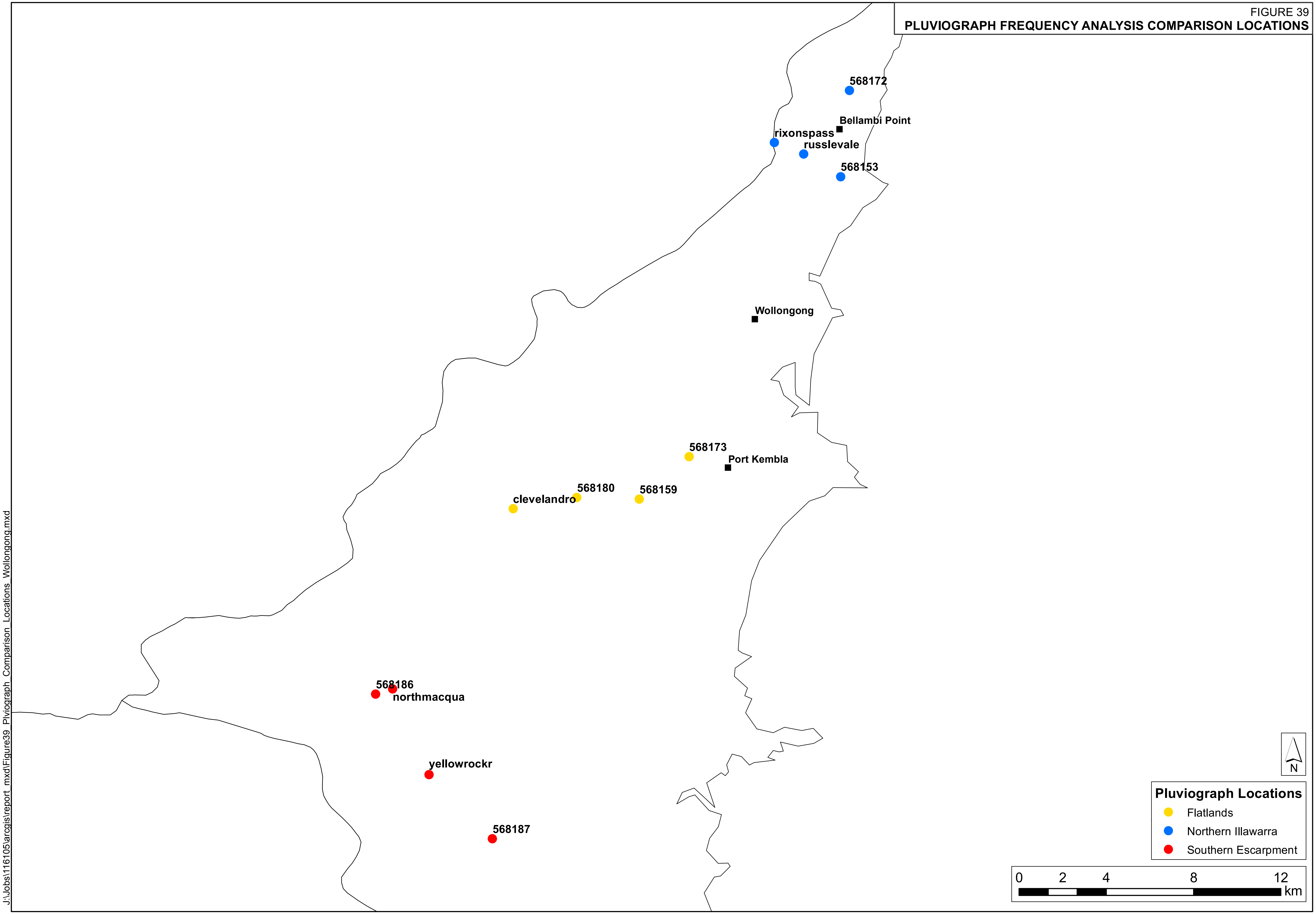
J:\Jobs\116105\arcgis\report_mxd\Figure37_Wollongong_NEWIFD_GRIDDEDQRT_00180min_5%AEP.mxd

FIGURE 38
PERCENTAGE DIFFERENCE- NEW IFD - GRIDDED QUANTILES
1% AEP 3 HOUR

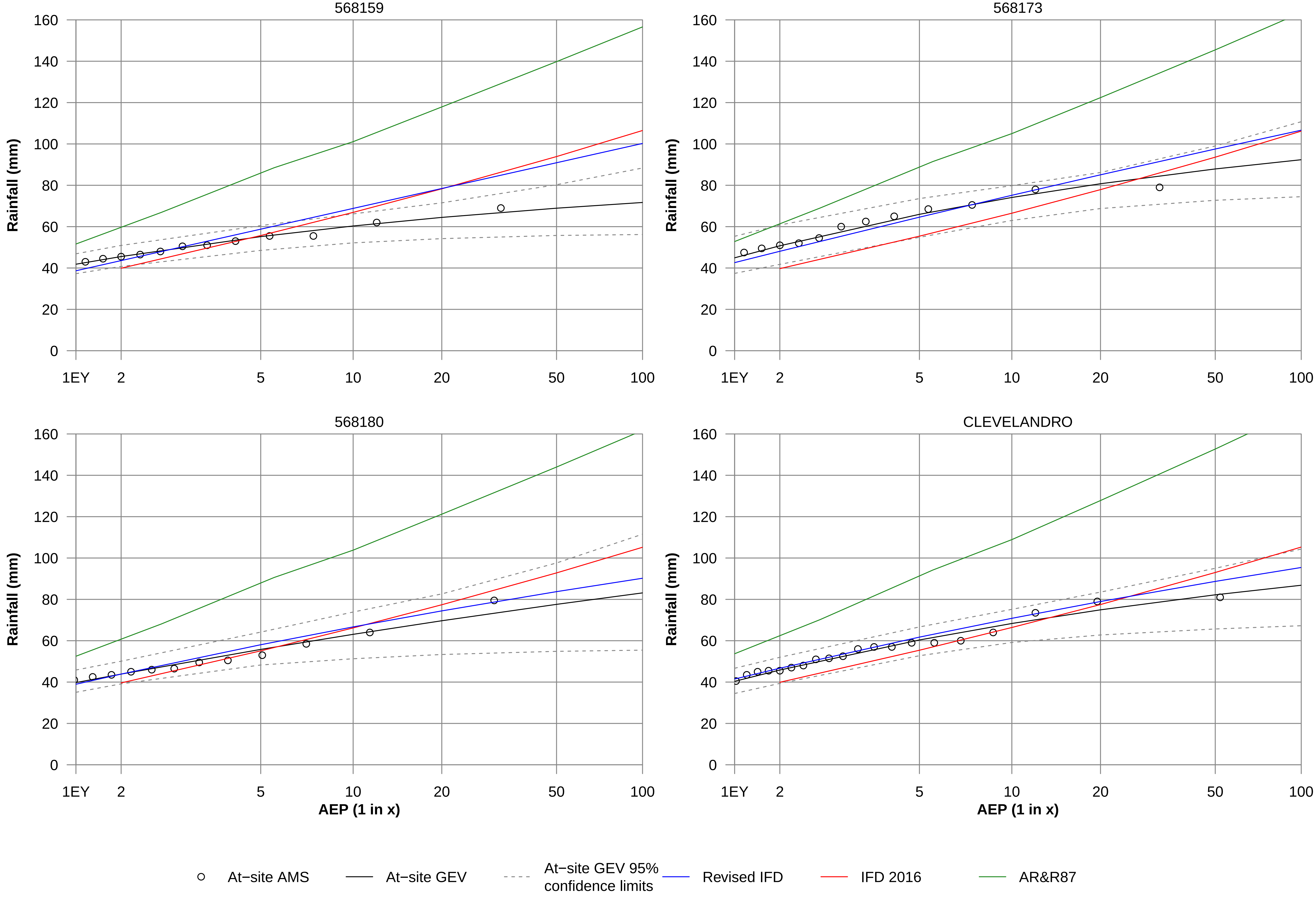


J:\Jobs\116105\arcgis\report_mxd\Figure38_Wollongong_NEWIFD_GRIDDEDQRT_00180min_1%AEP.mxd

FIGURE 39
PLUVIOGRAPH FREQUENCY ANALYSIS COMPARISON LOCATIONS



J:\Jobs\116105\arcgis\report_mxd\Figure39_Plviograph_Comparison_Locations_Wollongong.mxd


568159
568173
568180
CLEVELANDRO
Rainfall (mm)
0
20
40
60
80
100
120
140
160
1EY
2
5
10
20
50
100
AEP (1 in x)
At−site AMS
At−site GEV
At−site GEV 95% confidence limits
Revised IFD
IFD 2016
AR&R87

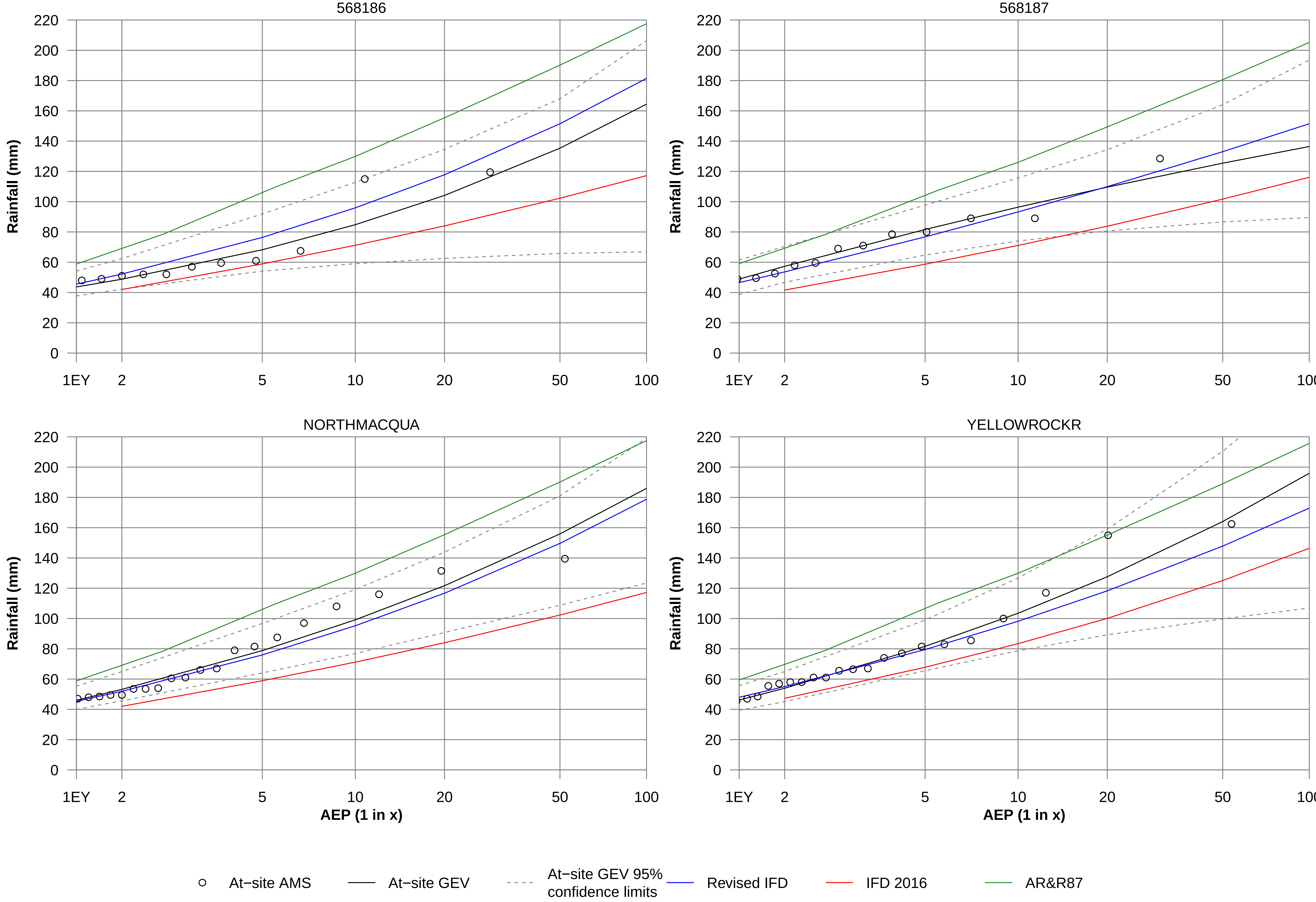

568186
568187
NORTHMACQUA
YELLOWROCKR
Rainfall (mm)
220
200
180
160
140
120
100
80
60
40
20
0
1EY
2
5
10
20
50
100
AEP (1 in x)
At−site AMS
At−site GEV
At−site GEV 95% confidence limits
Revised IFD
IFD 2016
AR&R87

FIGURE 42

NORTHERN ILLAWARRA STATIONS

3 HOUR IFD COMPARISON

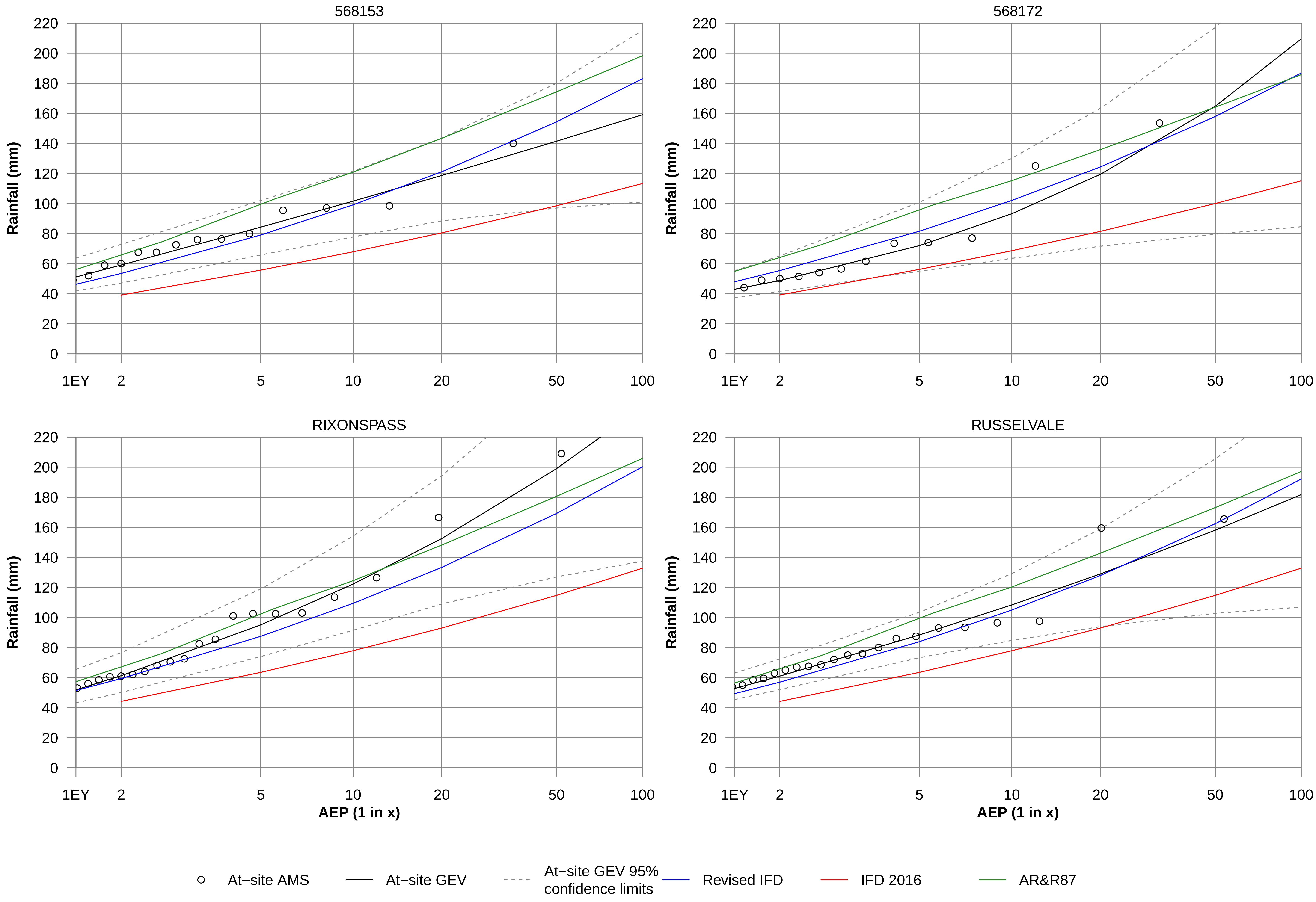


FIGURE 43
COFFS HARBOUR AREA
3 HOUR GEVS

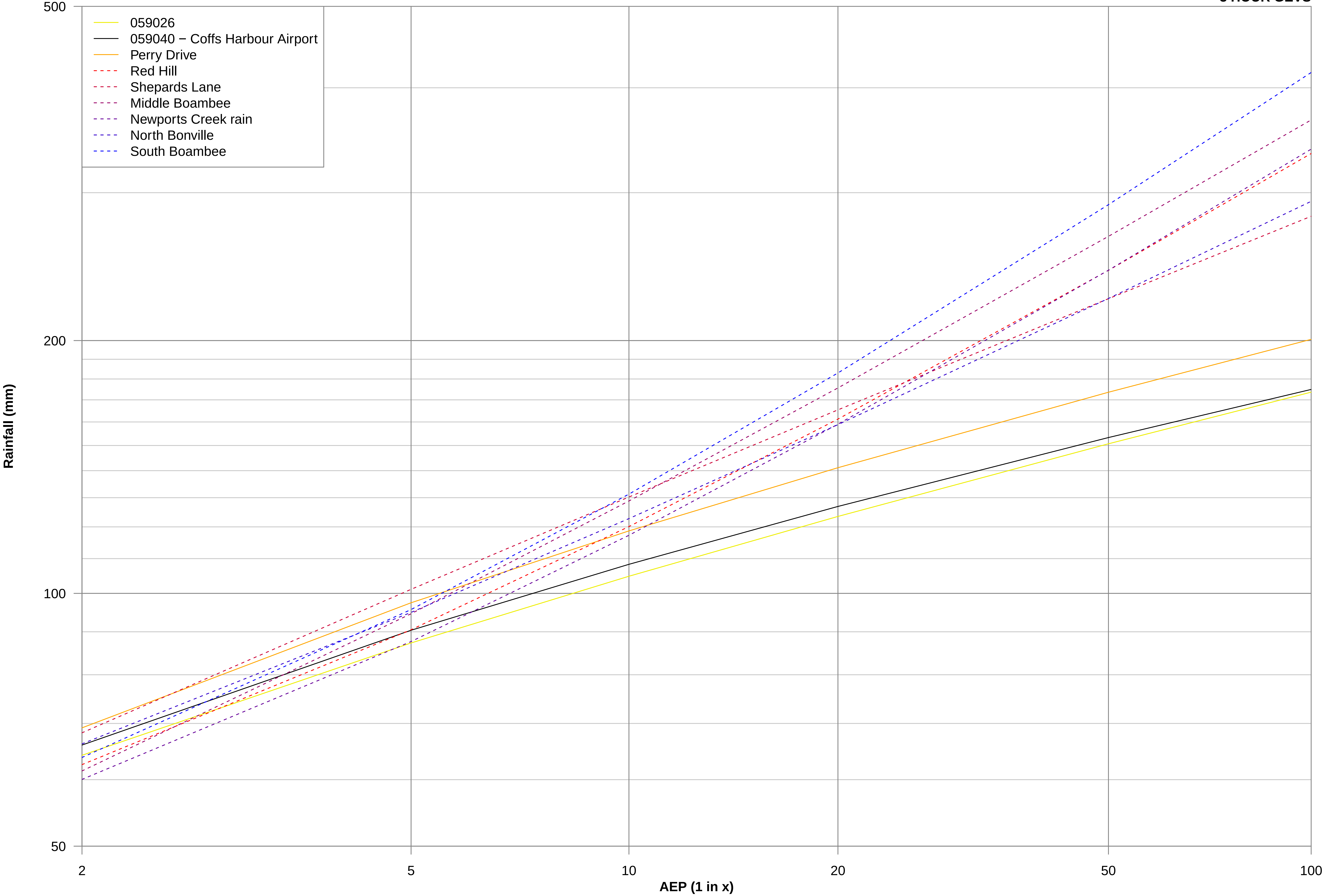
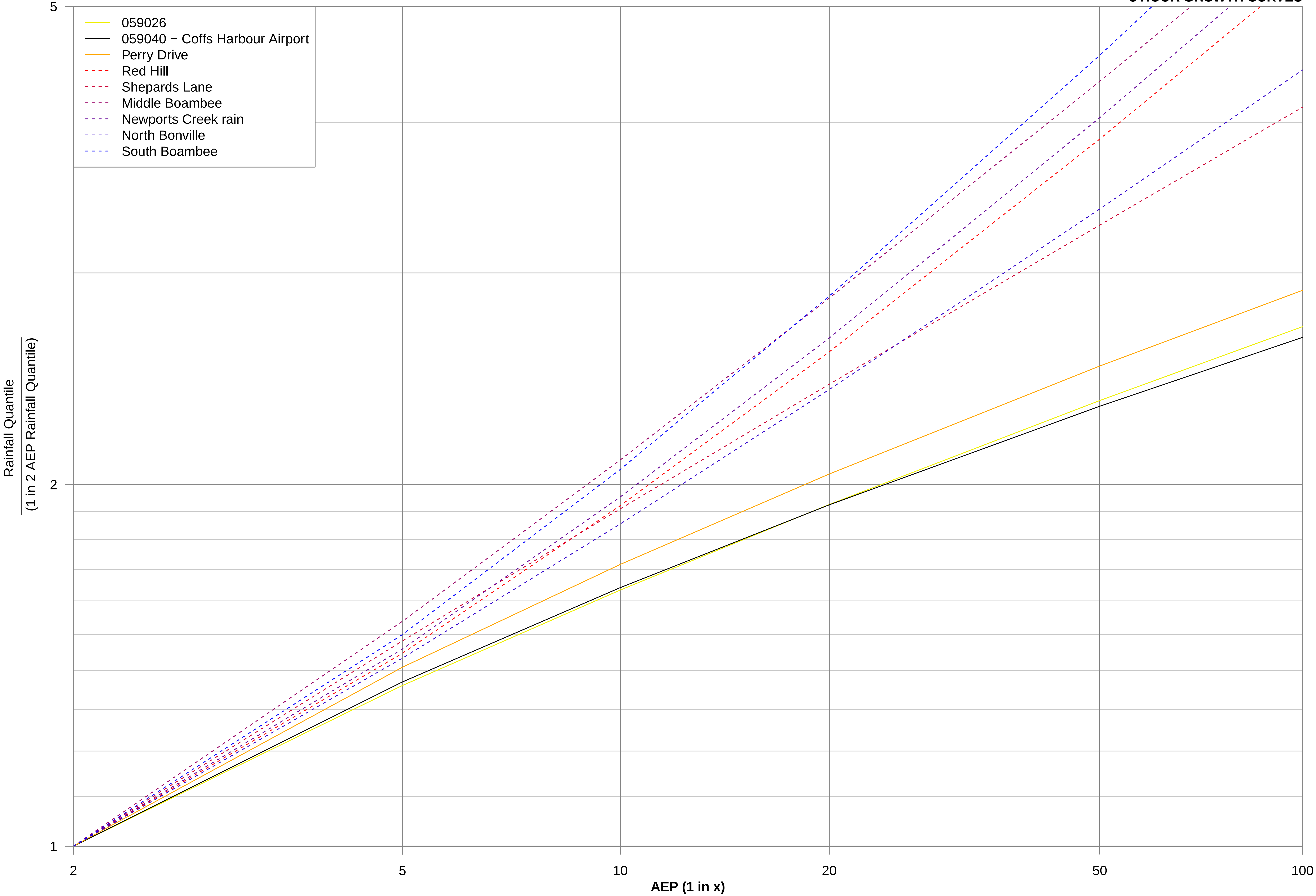


FIGURE 44
COFFS HARBOUR AREA
3 HOUR GROWTH CURVES



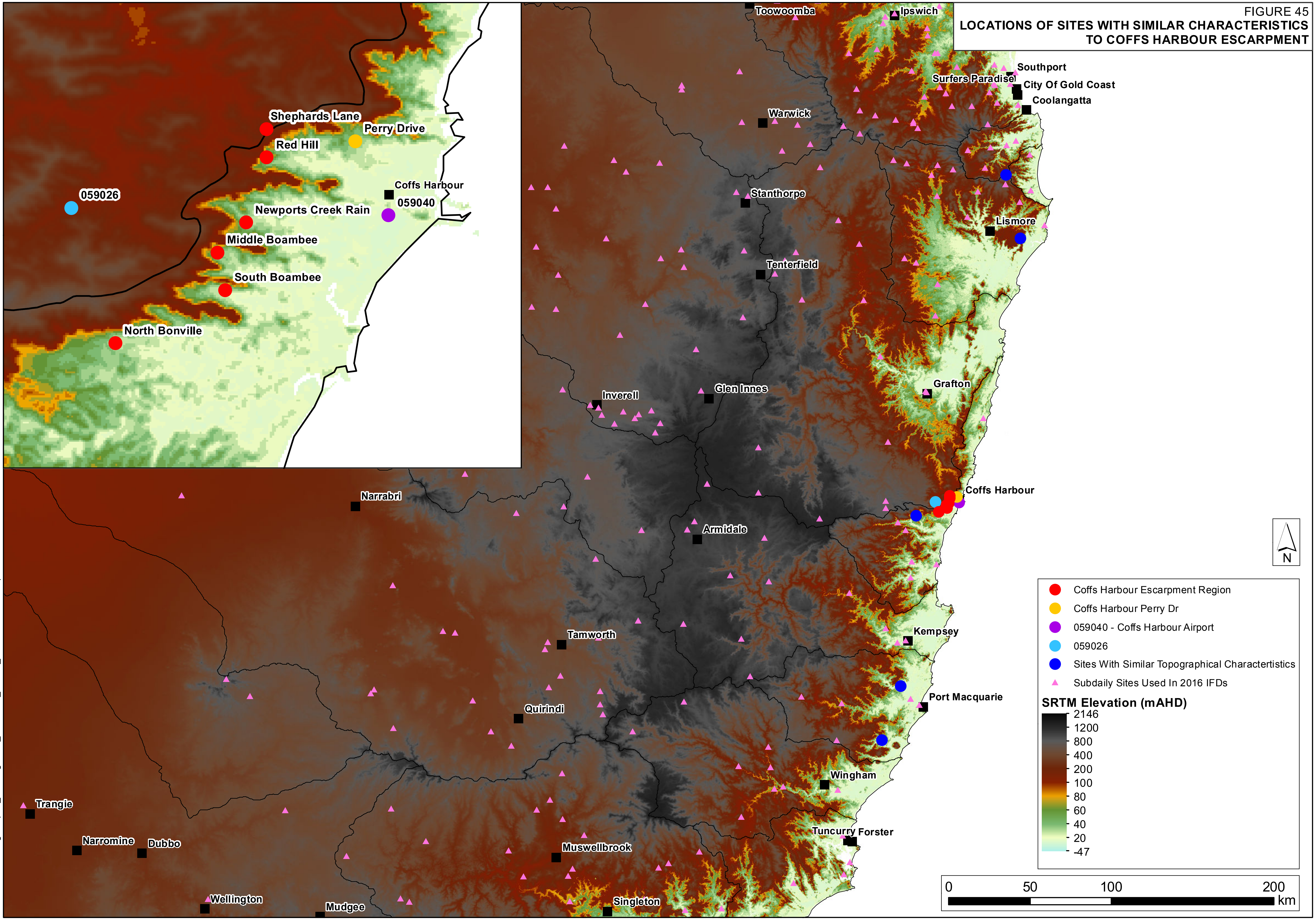
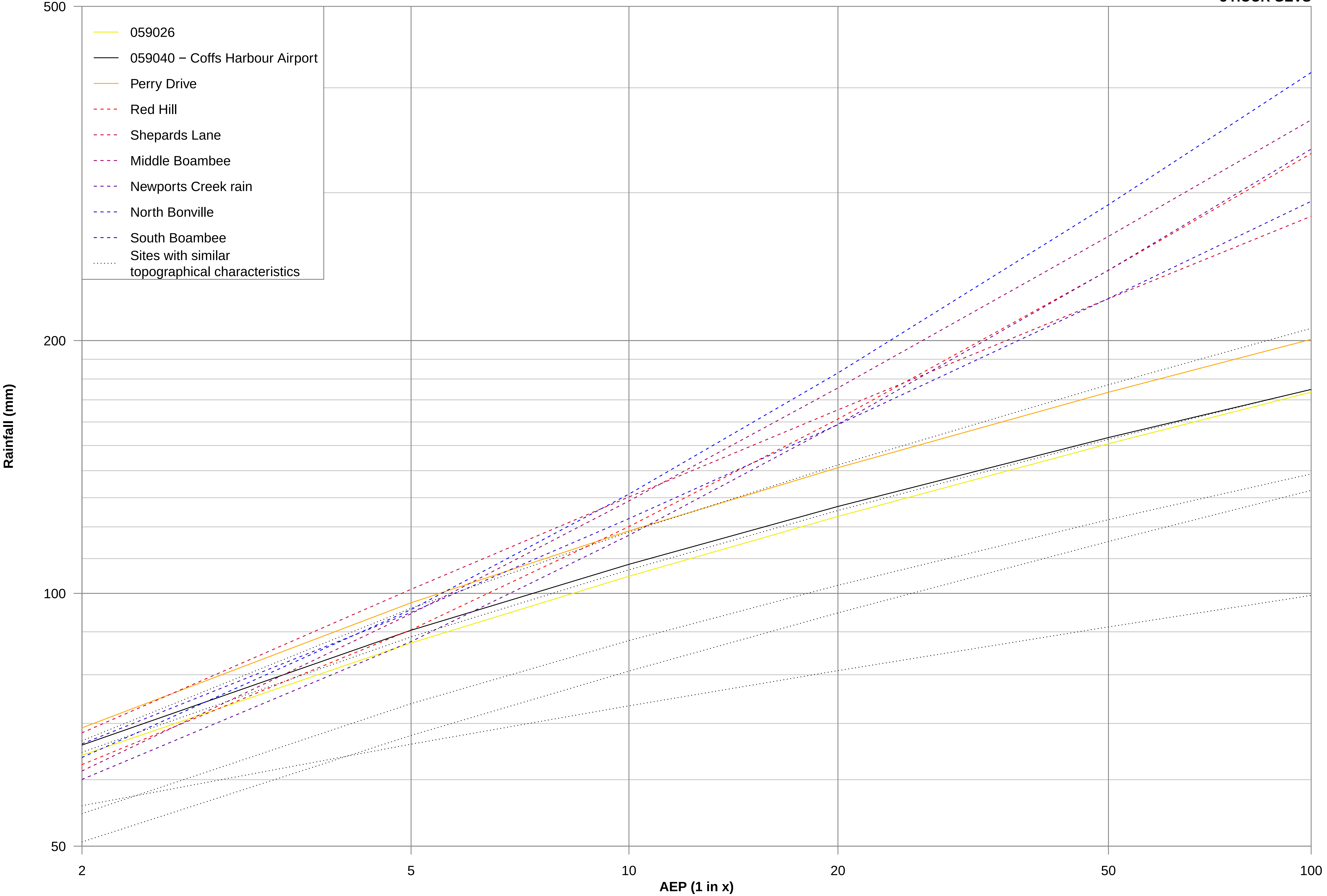


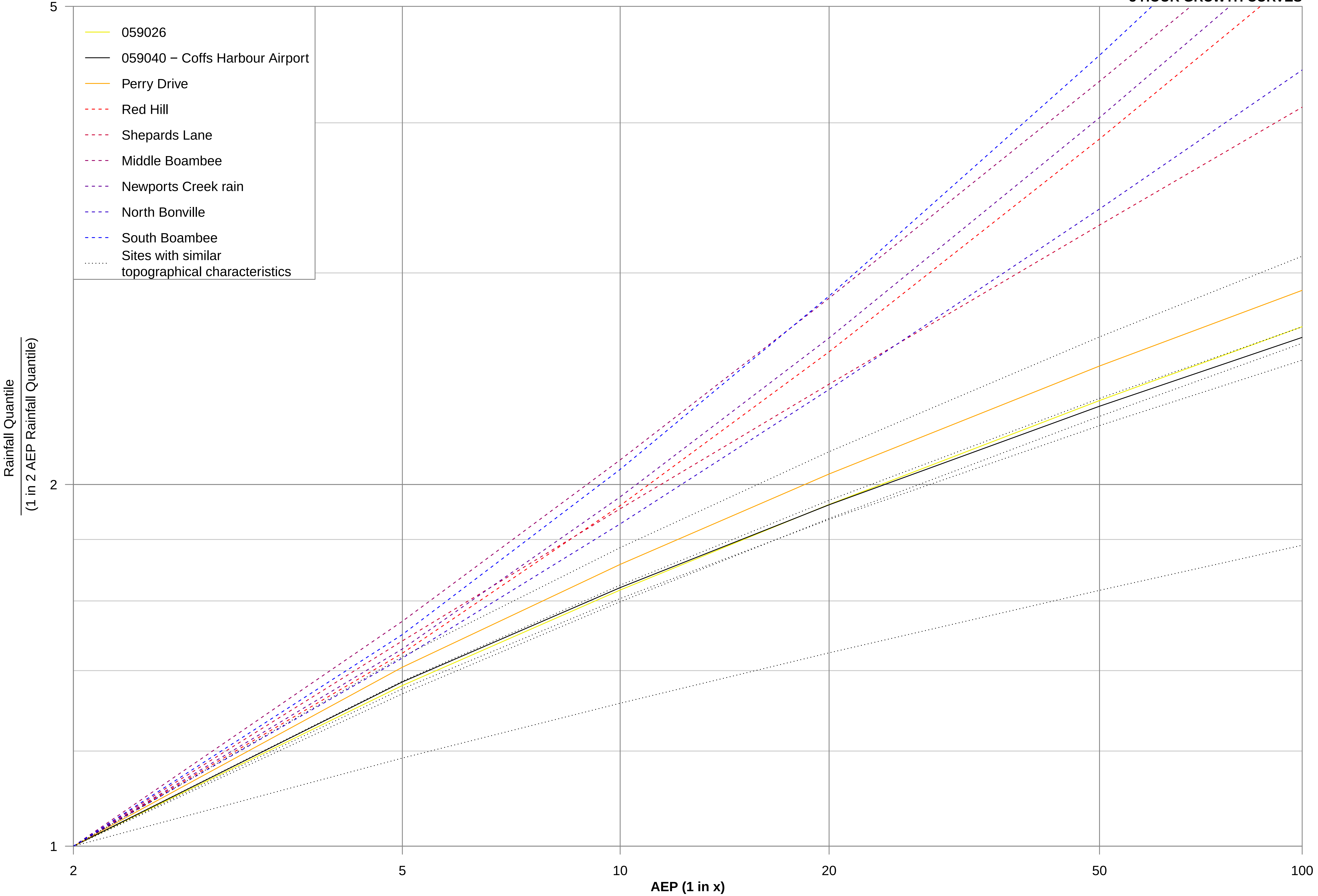
FIGURE 45
LOCATIONS OF SITES WITH SIMILAR CHARACTERISTICS TO COFFS HARBOUR ESCARPMENT

J:\Jobs\116105\arcgis\report_mxd\Figure45_Locations_Similar_CoffsHarbourEscarpment.mxd

COFFS HARBOUR AREA AND SIMILAR GAUGES
3 HOUR GEVS



COFFS HARBOUR AREA AND SIMILAR GAUGES
3 HOUR GROWTH CURVES



COFFS ESCARPMENT REGIONAL ESTIMATE CONPARISON
3 HOUR

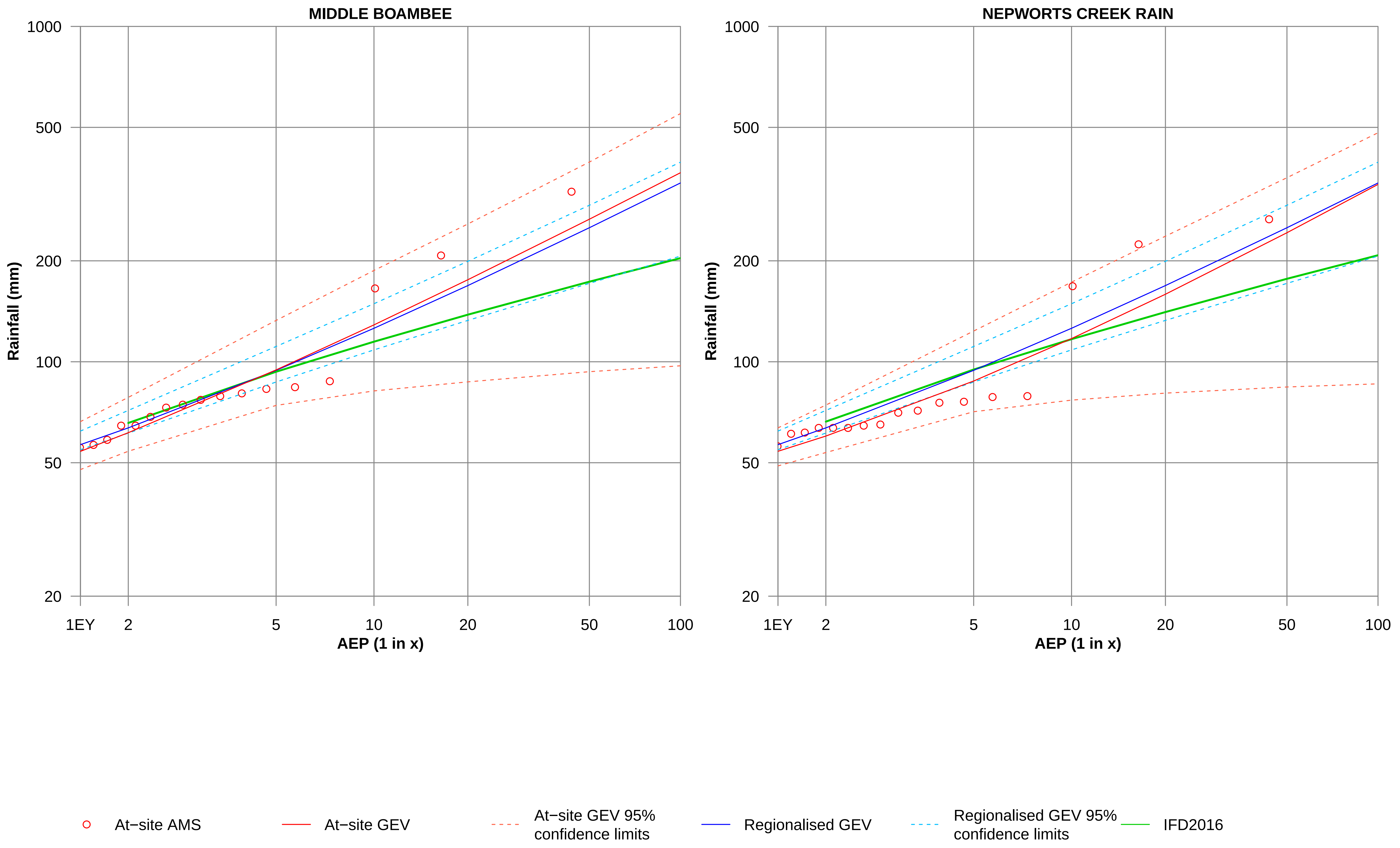


FIGURE 49
COFFS ESCARPMENT REGIONAL ESTIMATE CONPARISON
3 HOUR

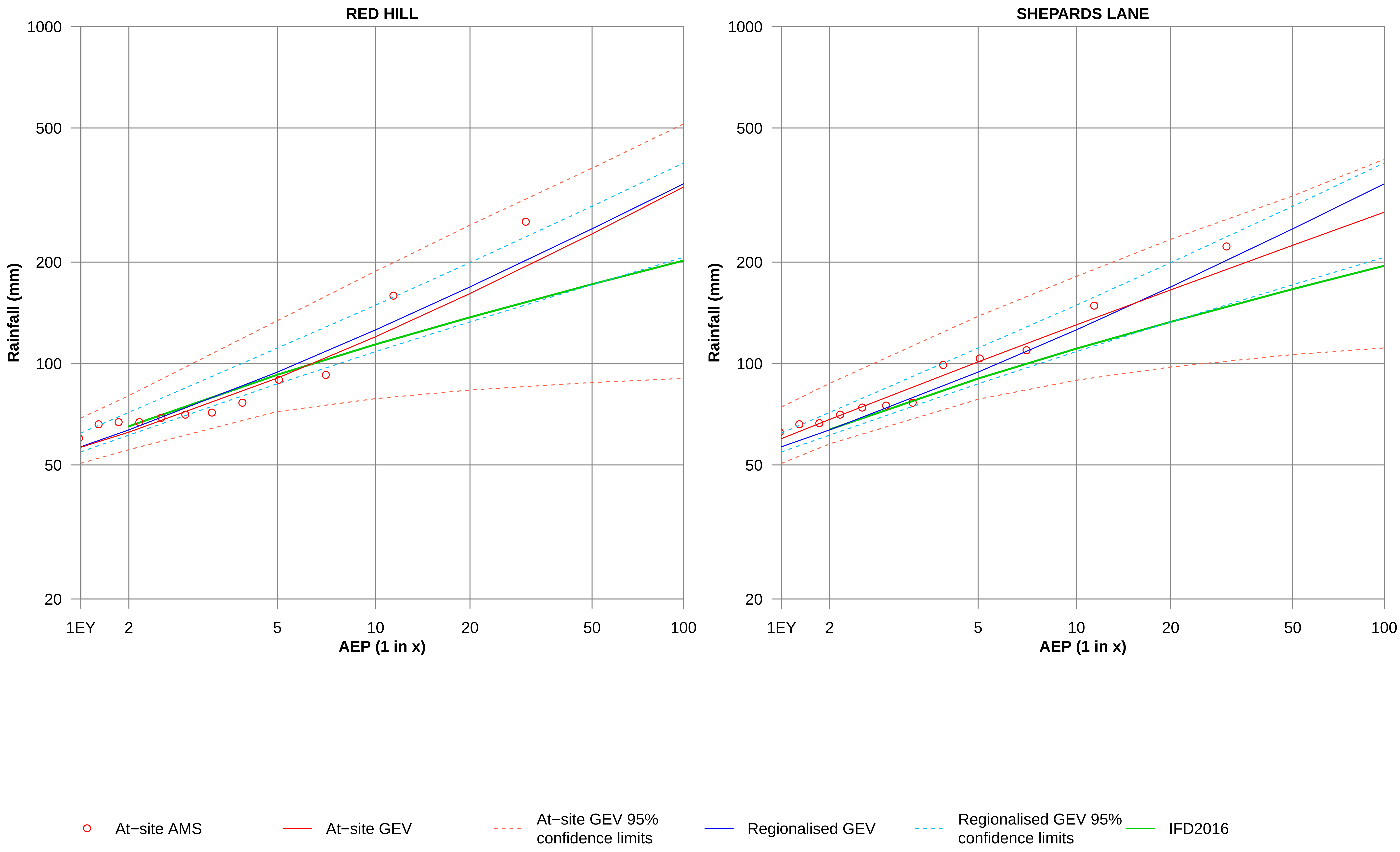


FIGURE 50
COFFS ESCARPMENT REGIONAL ESTIMATE CONPARISON
3 HOUR

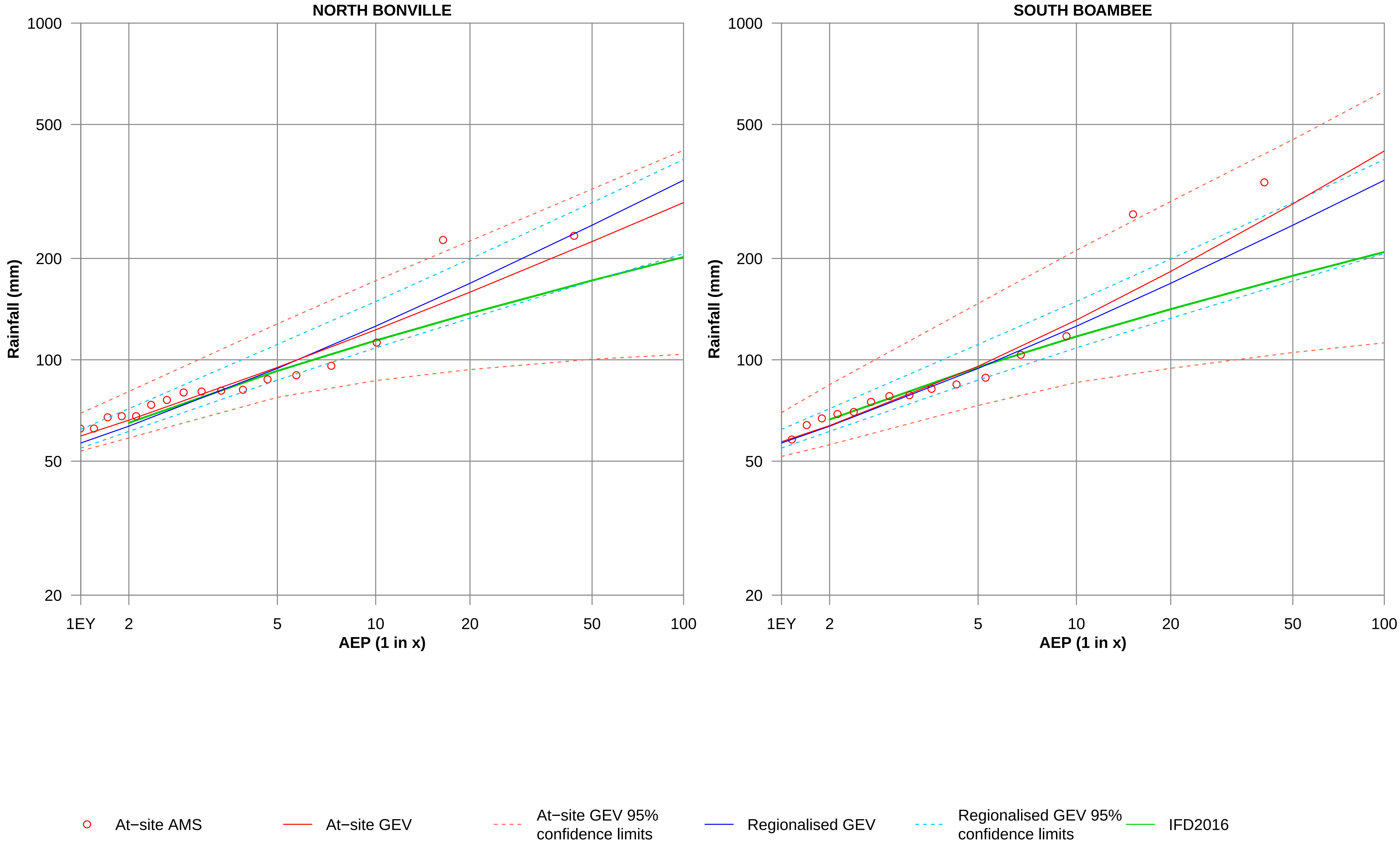


FIGURE 51

COFFS HARBOUR AIRPORT REGION

1 DAY MEAN AMS ESTIMATES

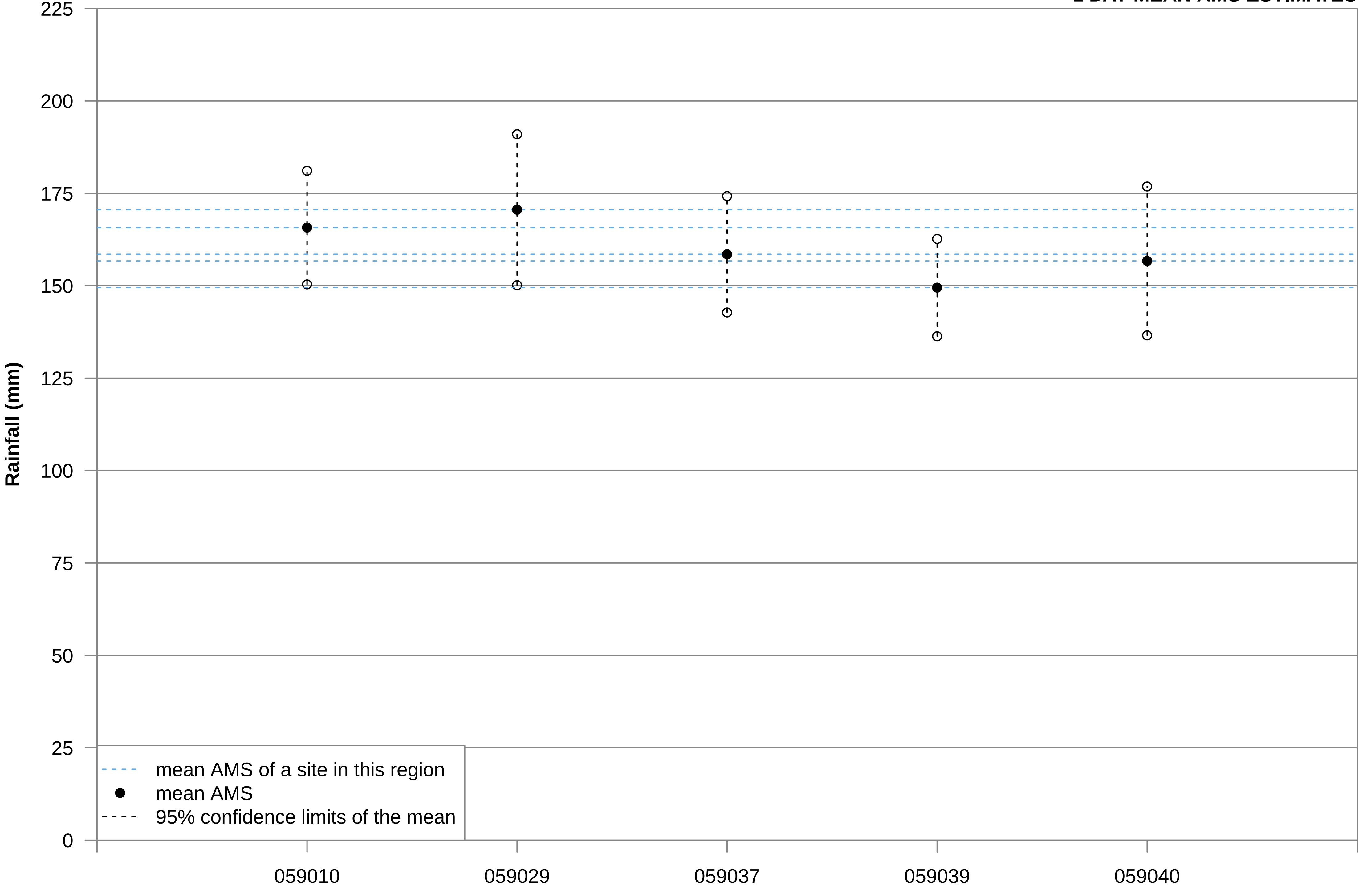


FIGURE 52
COFFS AIRPORT REGIONAL ESTIMATE COMPARISON
1 DAY

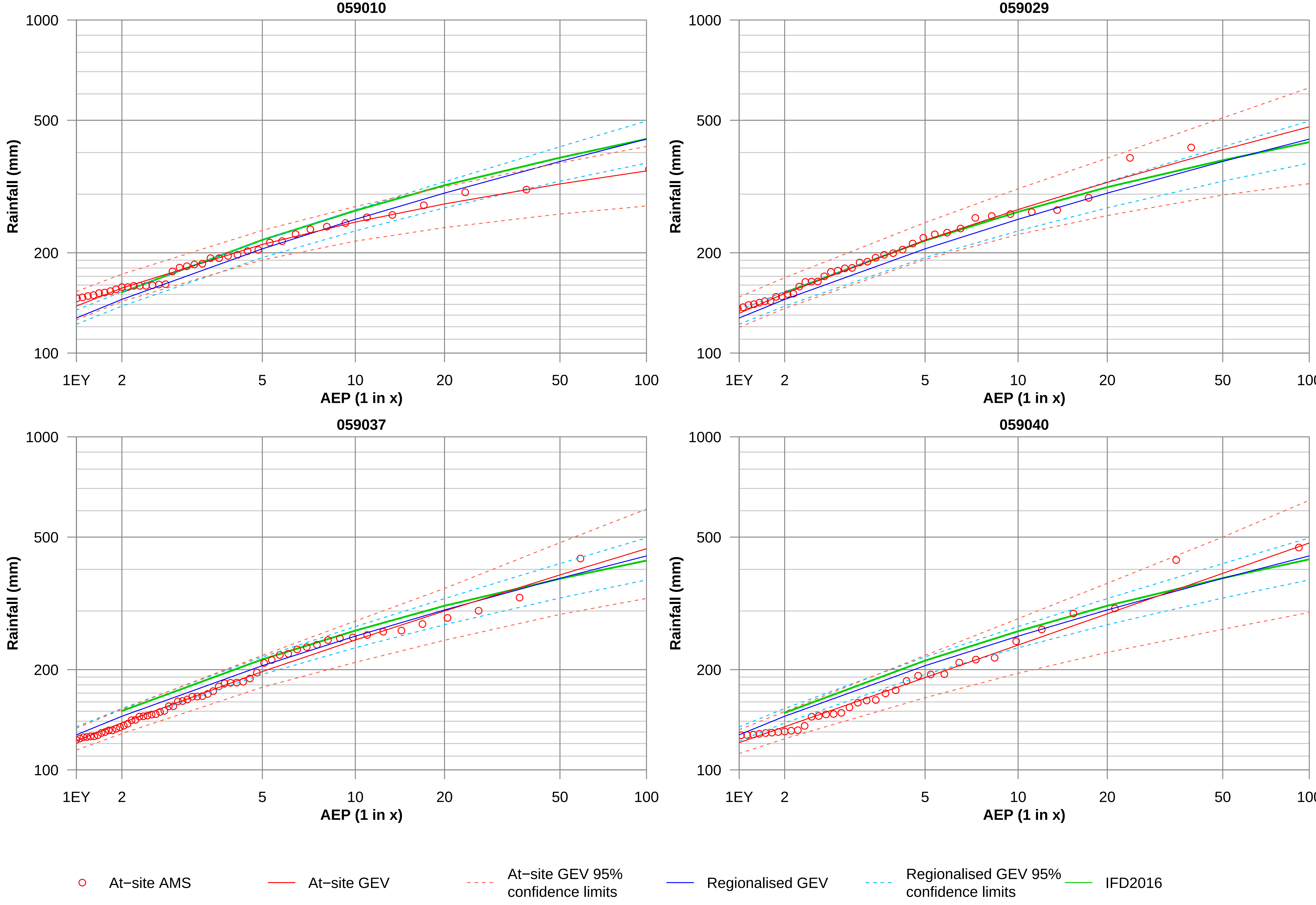
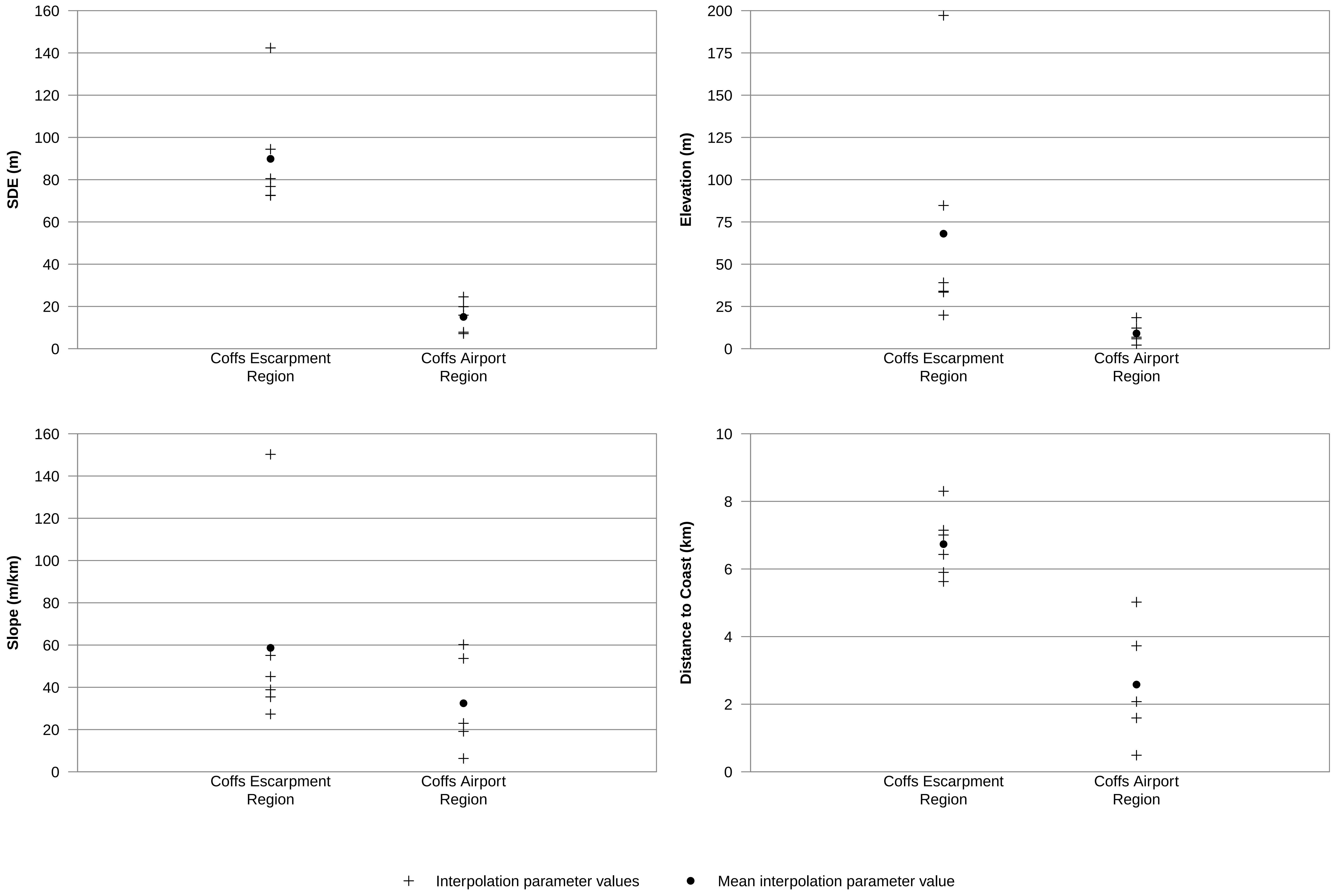


FIGURE 53
COFFS HARBOUR AREA REGIONS
POTENTIAL INTERPOLATION PARAMATER SITE VALUES



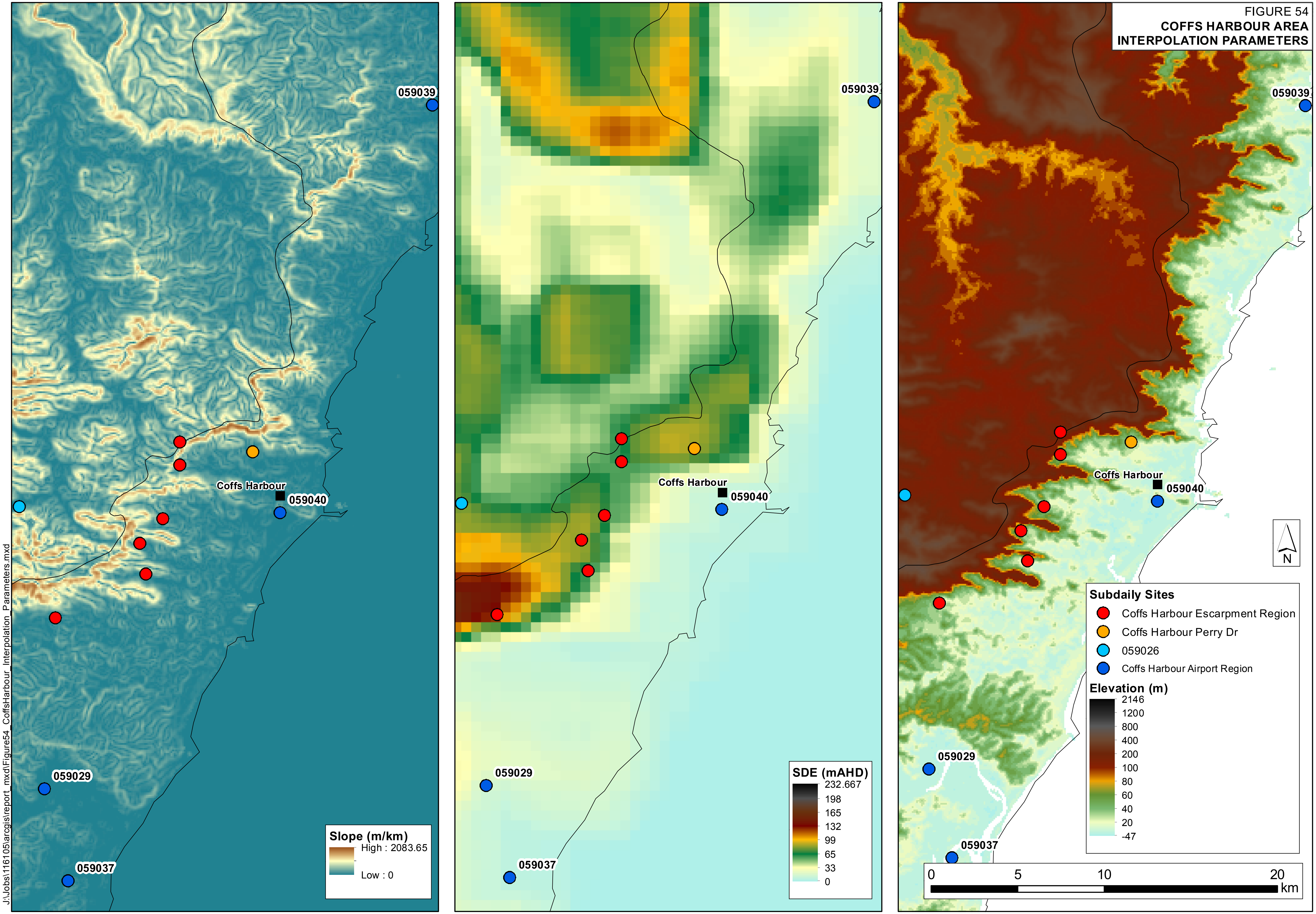
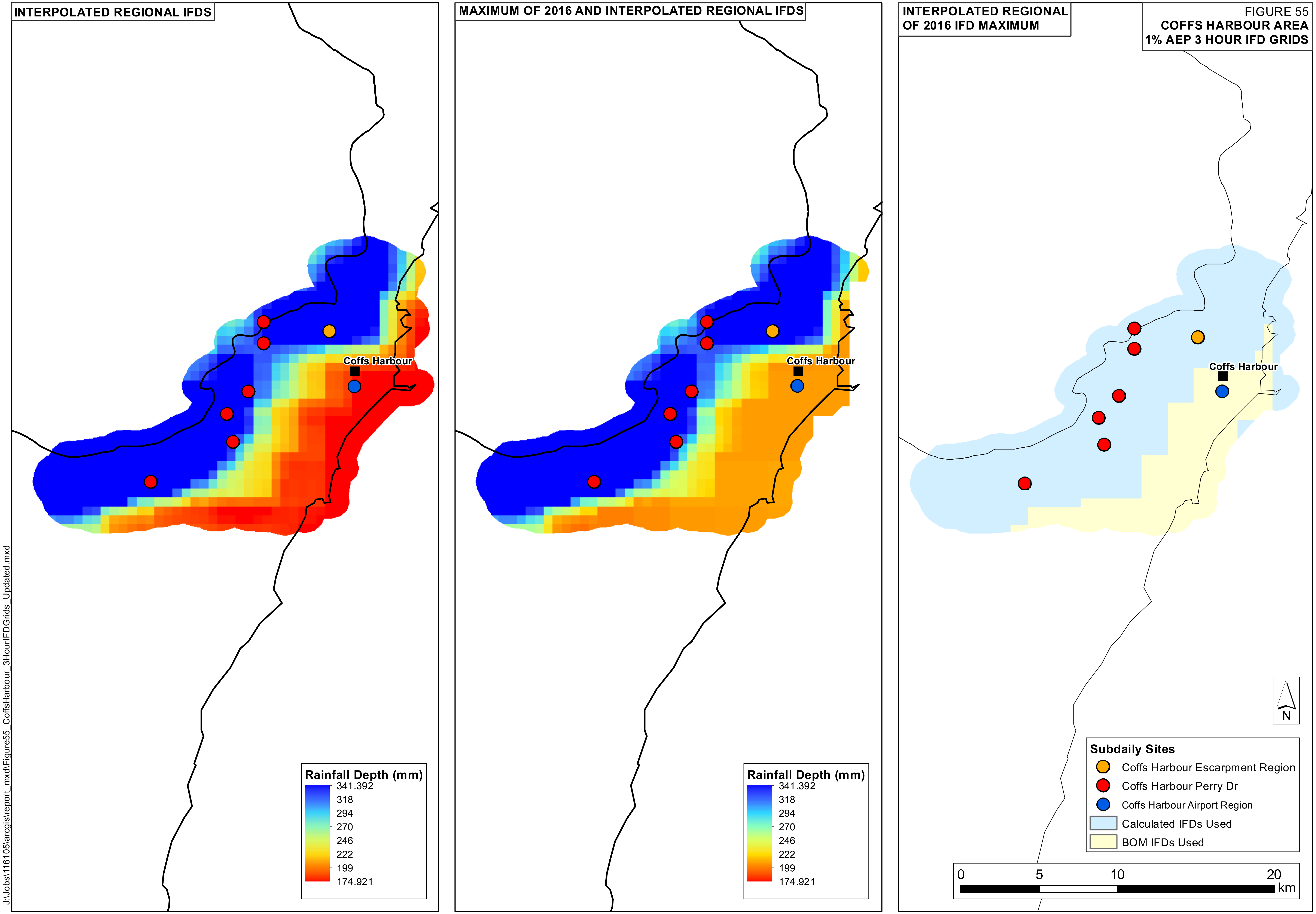
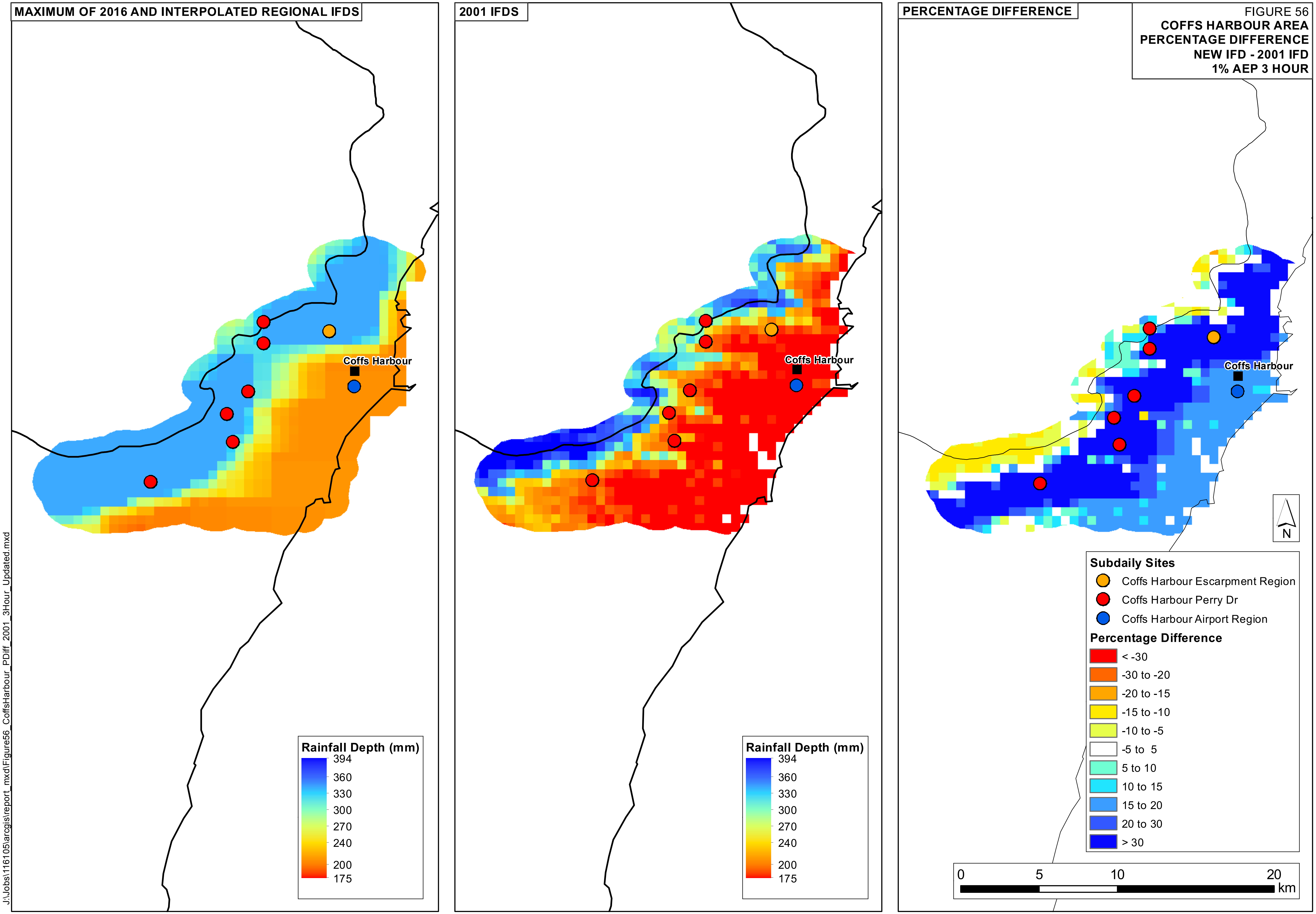


FIGURE 54
COFFS HARBOUR AREA INTERPOLATION PARAMETERS

J:\Jobs\116105\arcgis\report_mxd\Figure54_CoffsHarbour_Interpolation_Parameters.mxd

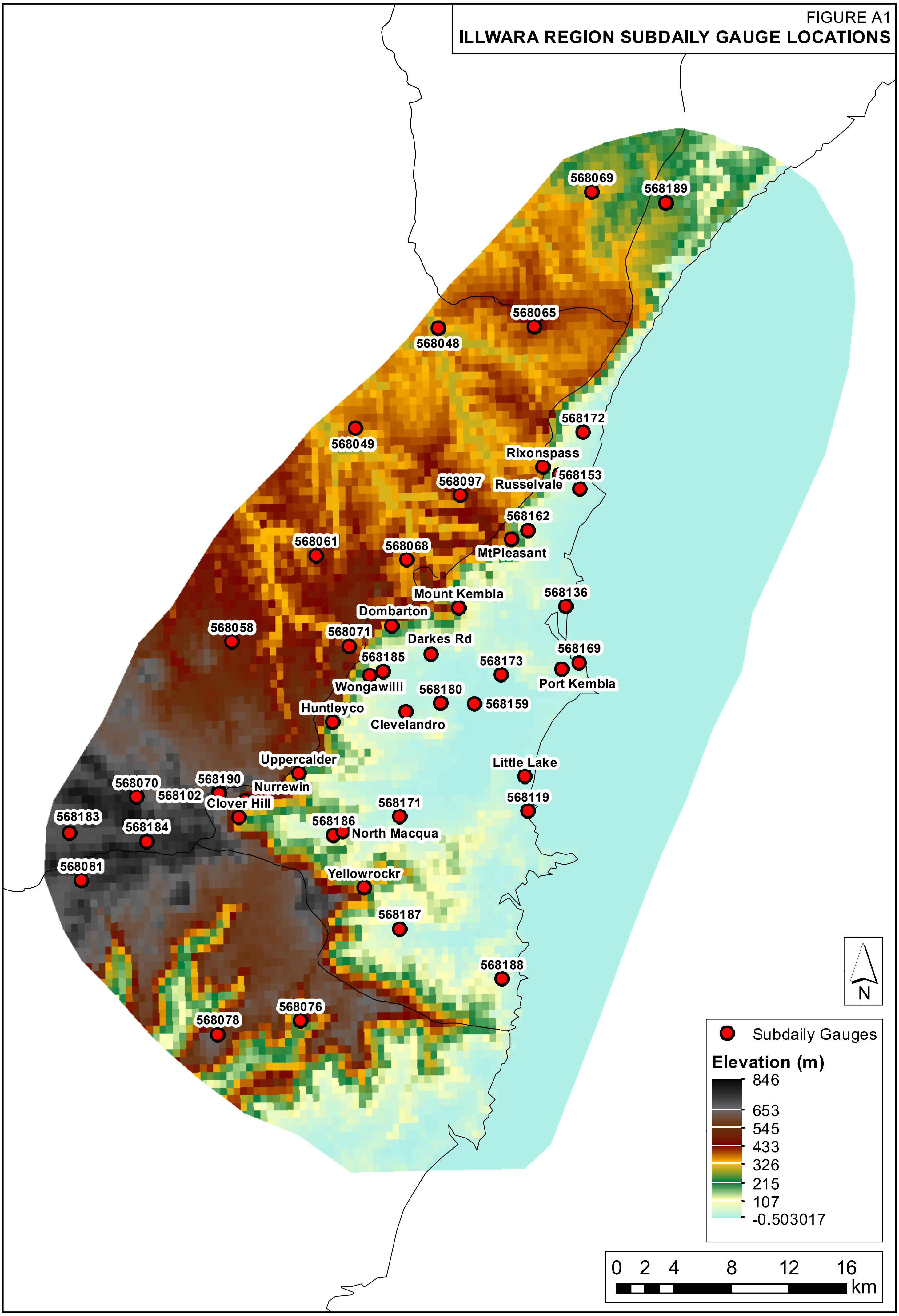

INTERPOLATED REGIONAL IFDS
MAXIMUM OF 2016 AND INTERPOLATED REGIONAL IFDS
INTERPOLATED REGIONAL
OF 2016 IFD MAXIMUM
FIGURE 55
COFFS HARBOUR AREA
1% AEP 3 HOUR IFD GRIDS
Coffs Harbour
Rainfall Depth (mm)
341.392
318
294
270
246
222
199
174.921
Subdaily Sites
Coffs Harbour Escarpment Region
Coffs Harbour Perry Dr
Coffs Harbour Airport Region
Calculated IFDs Used
BOM IFDs Used
N
0
5
10
20
km
J:\Jobs\116105\arcgis\report_mxd\Figure55_CoffsHarbour_3HourIFDGrids_Updated.mxd



MAXIMUM OF 2016 AND INTERPOLATED REGIONAL IFDS
2001 IFDS
PERCENTAGE DIFFERENCE
FIGURE 56
COFFS HARBOUR AREA
PERCENTAGE DIFFERENCE
NEW IFD - 2001 IFD
1% AEP 3 HOUR
Coffs Harbour
Rainfall Depth (mm)
394
360
330
300
270
240
200
175
Subdaily Sites
Coffs Harbour Escarpment Region
Coffs Harbour Perry Dr
Coffs Harbour Airport Region
Percentage Difference
< -30
-30 to -20
-20 to -15
-15 to -10
-10 to -5
-5 to 5
5 to 10
10 to 15
15 to 20
20 to 30
> 30
N
0
5
10
20
km
J:\Jobs\116105\arcgis\report_mxd\Figure56_CoffsHarbour_PDiff_2001_3Hour_Updated.mxd

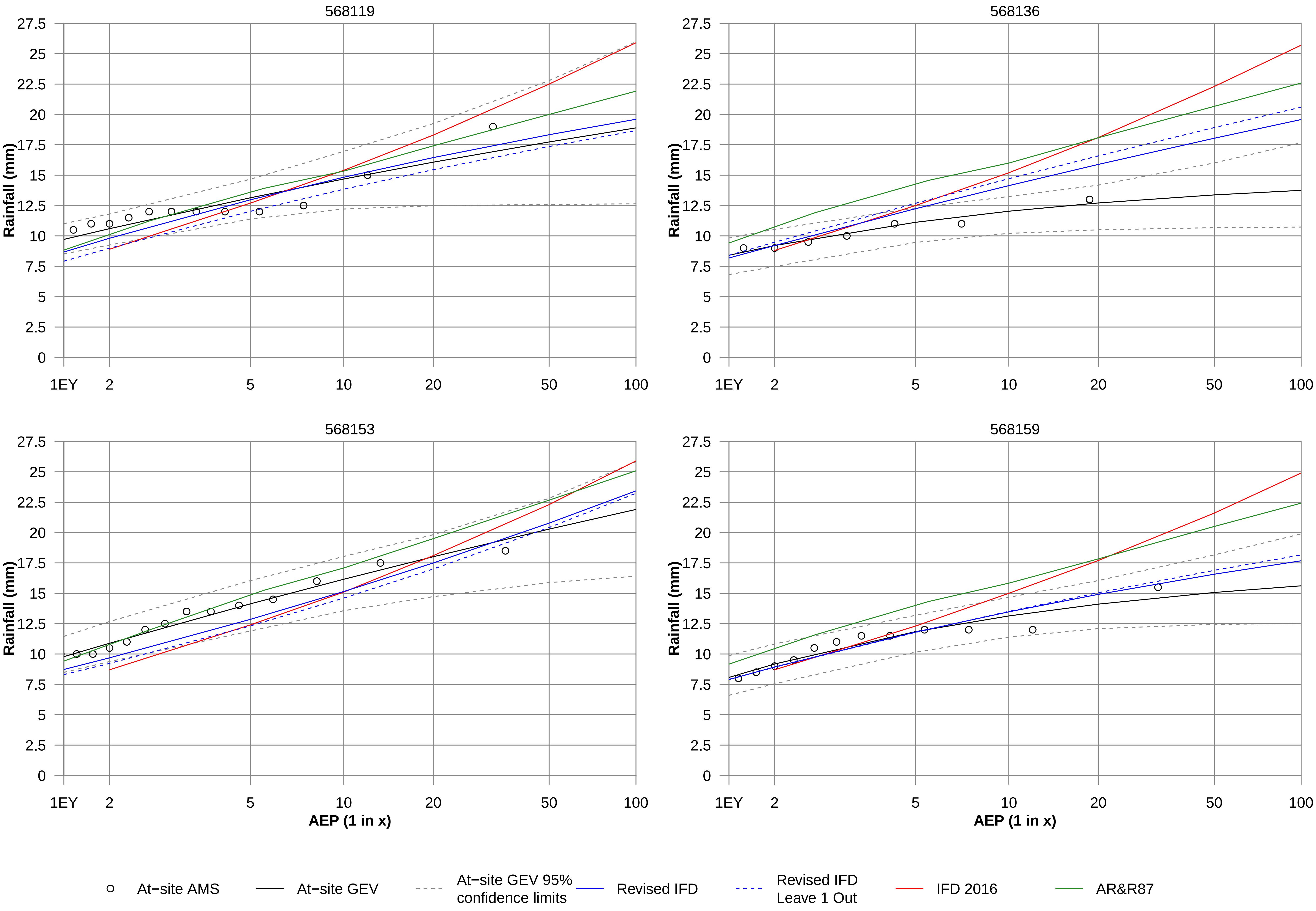
Appendix A

FIGURE A1
ILLWARA REGION SUBDAILY GAUGE LOCATIONS



J:\Jobs\116105\arcgis\report_mxd\WollongongReport\FigureA1_Wollongong_SubdailyGauge_Locations_Updated.mxd

WOLLONGONG AREA STATIONS
5 MINUTES IFD COMPARISON



WOLLONGONG AREA STATIONS
5 MINUTES IFD COMPARISON

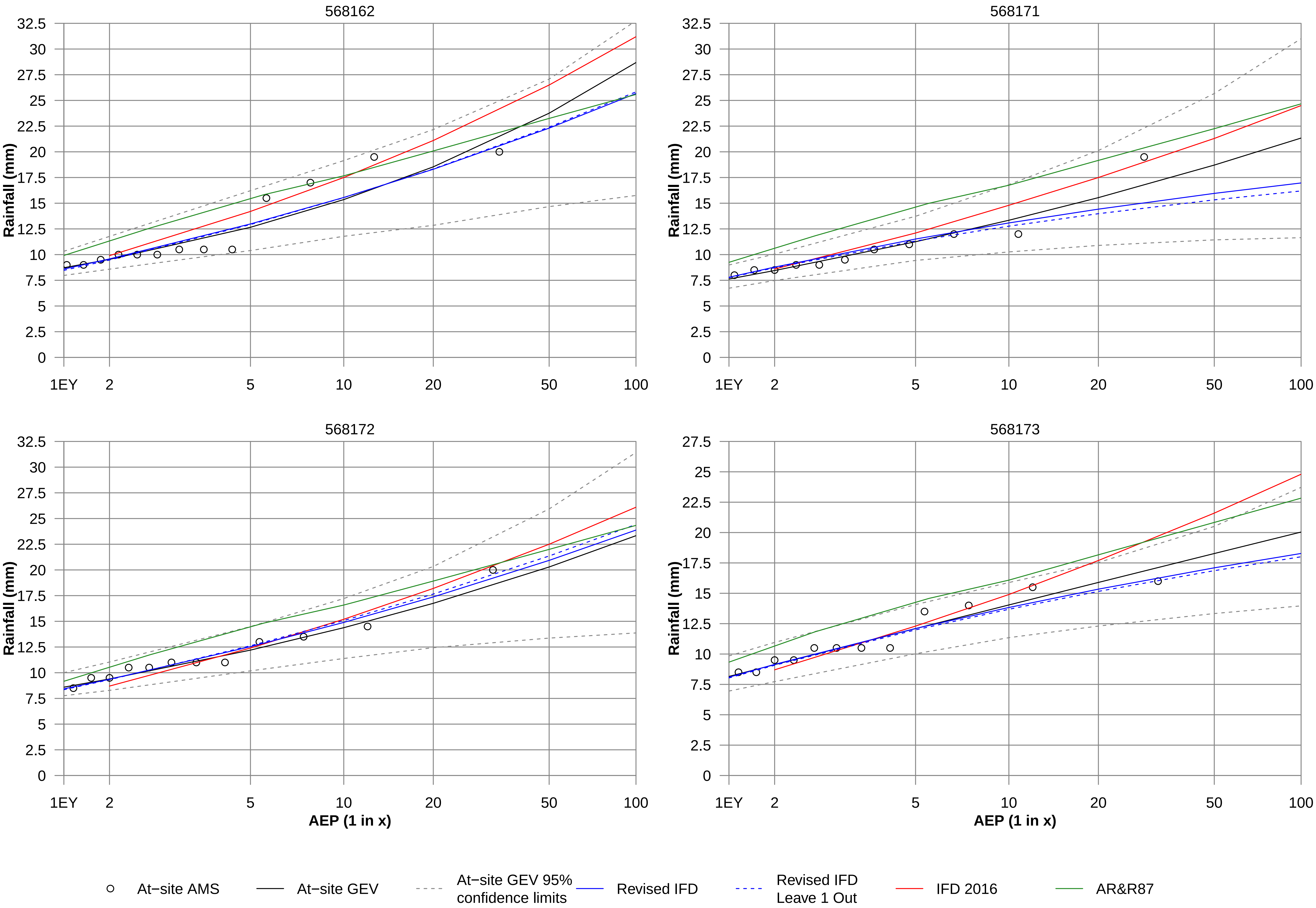
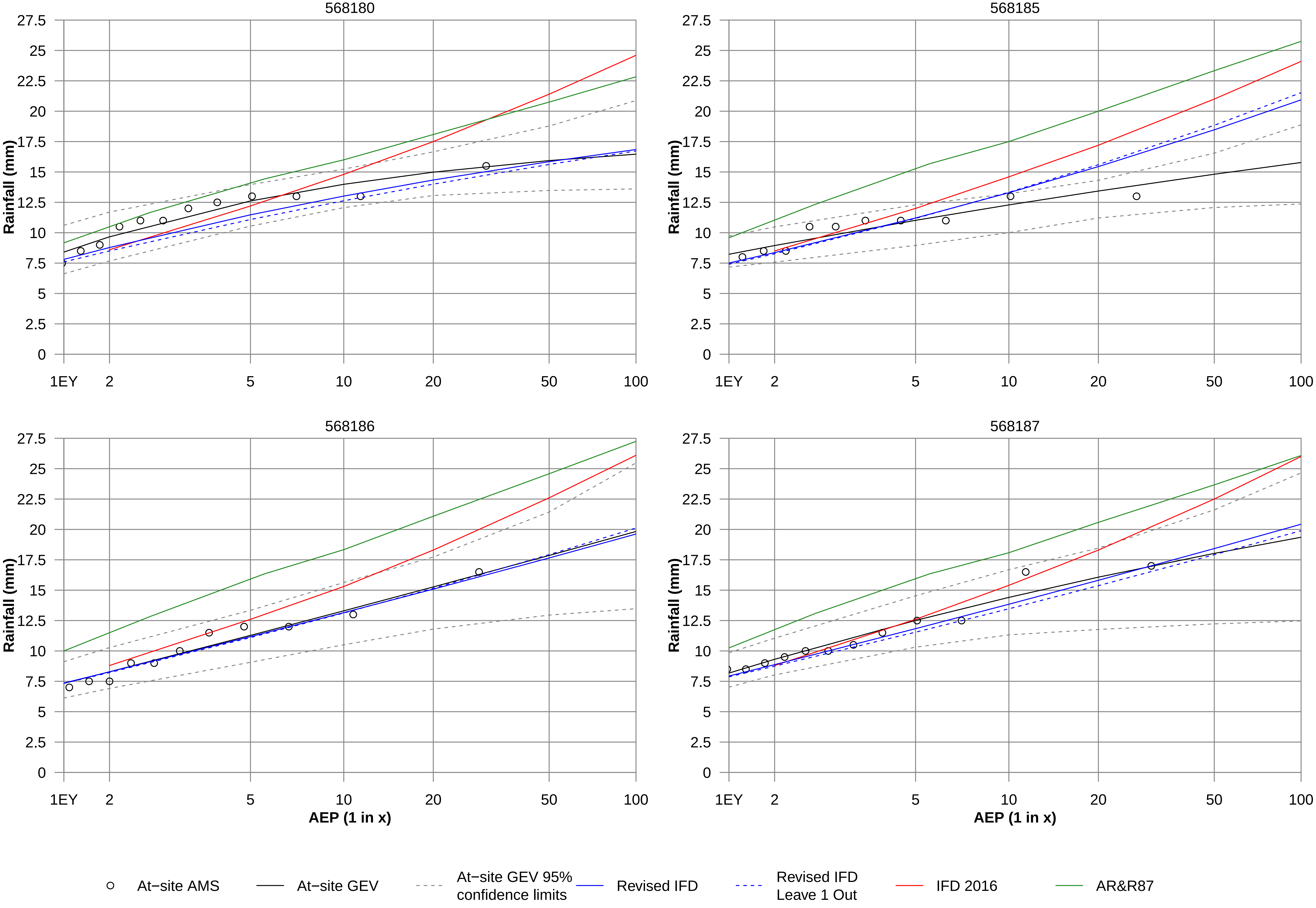
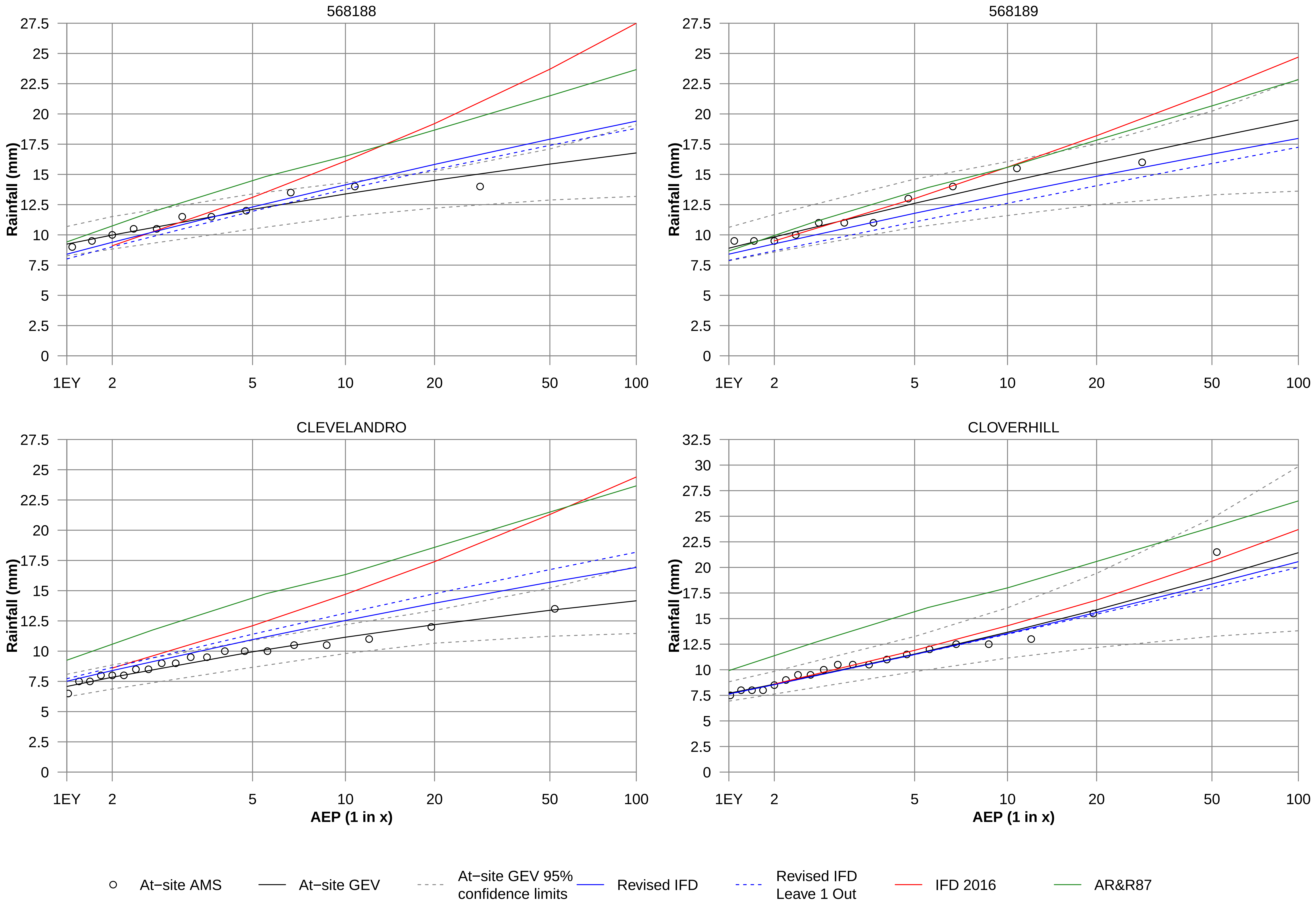


FIGURE A4
WOLLONGONG AREA STATIONS
5 MINUTES IFD COMPARISON



WOLLONGONG AREA STATIONS
5 MINUTES IFD COMPARISON



WOLLONGONG AREA STATIONS
5 MINUTES IFD COMPARISON

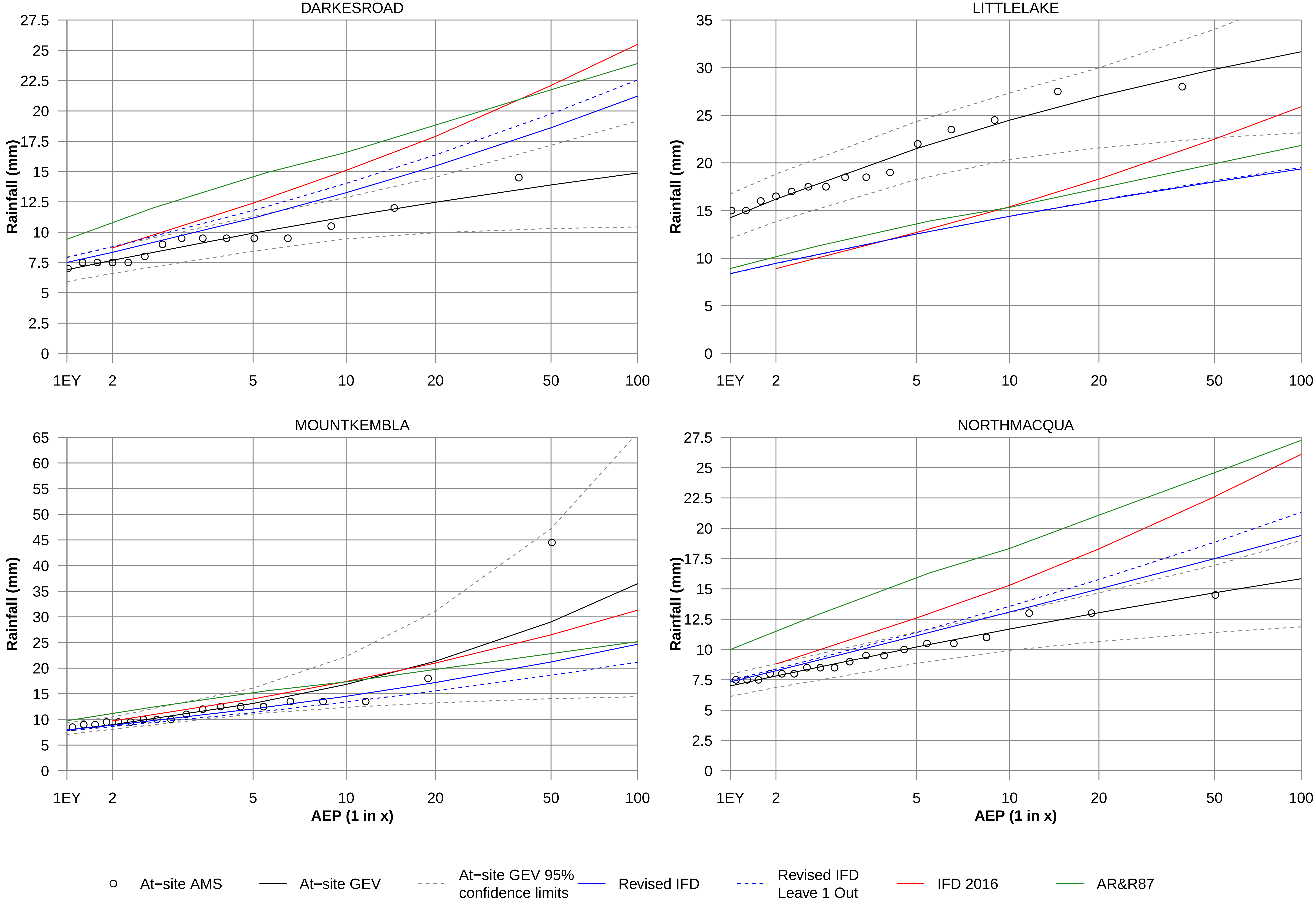


FIGURE A7

WOLLONGONG AREA STATIONS

5 MINUTES IFD COMPARISON

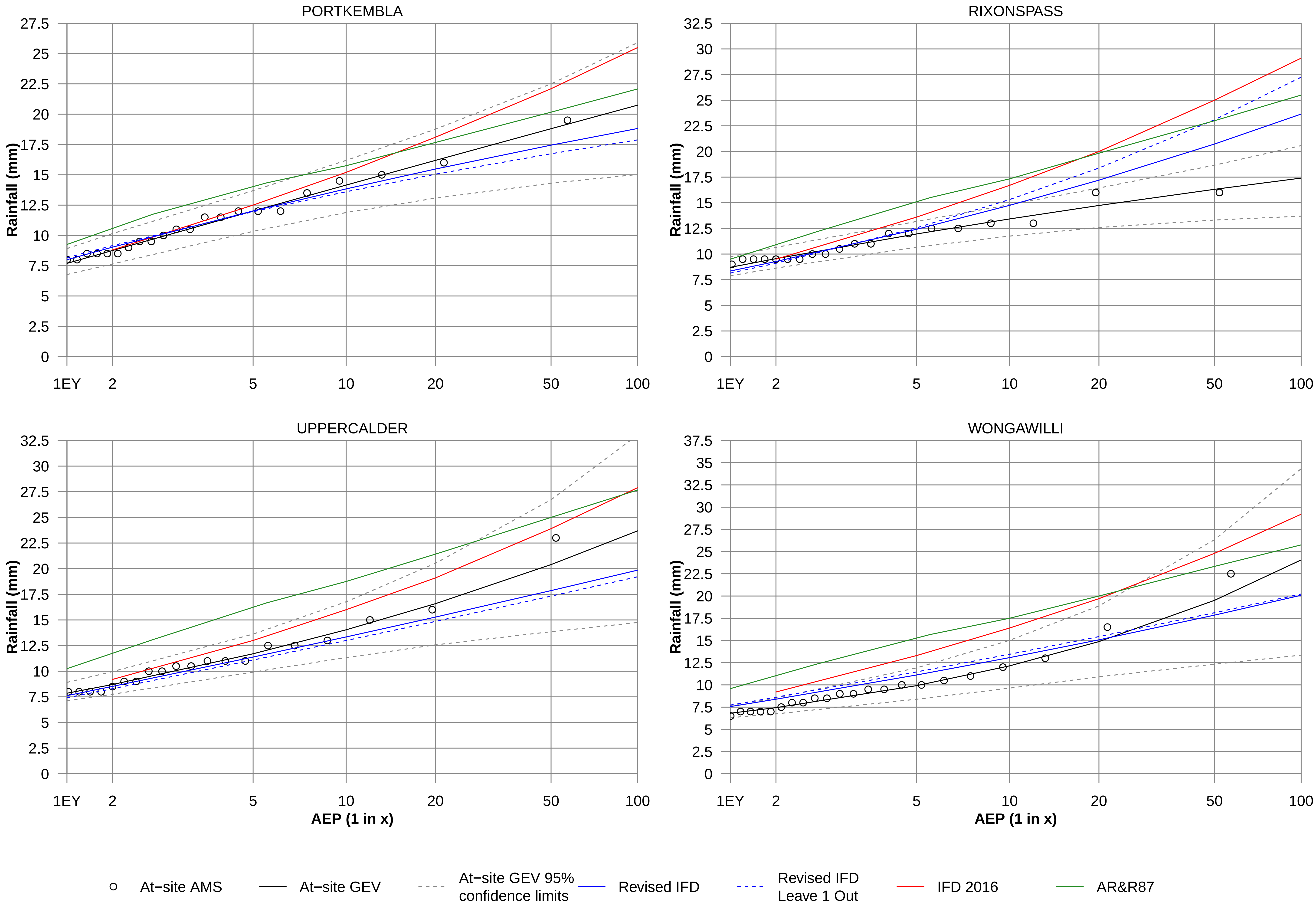


FIGURE A8
WOLLONGONG AREA STATIONS
5 MINUTES IFD COMPARISON

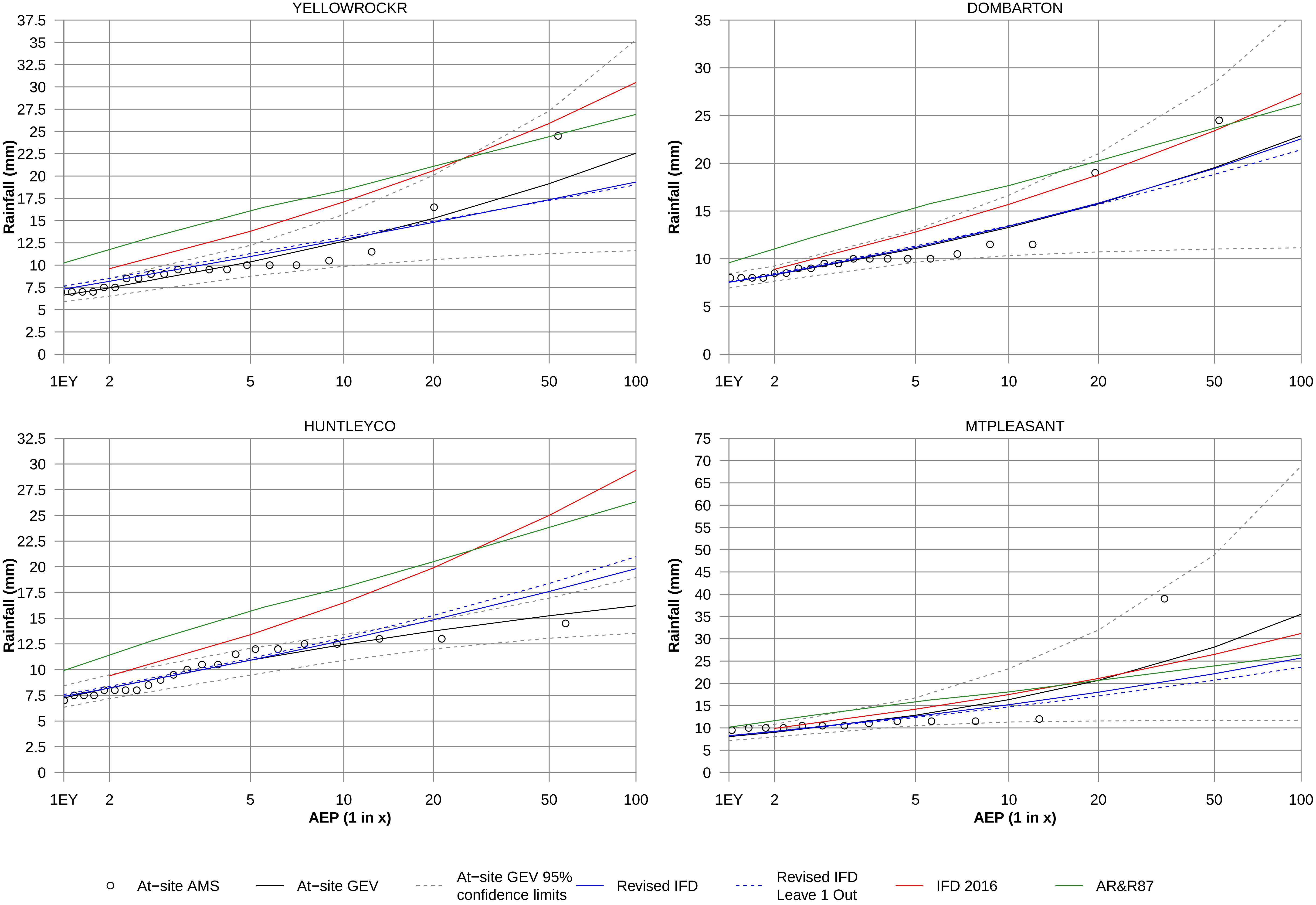
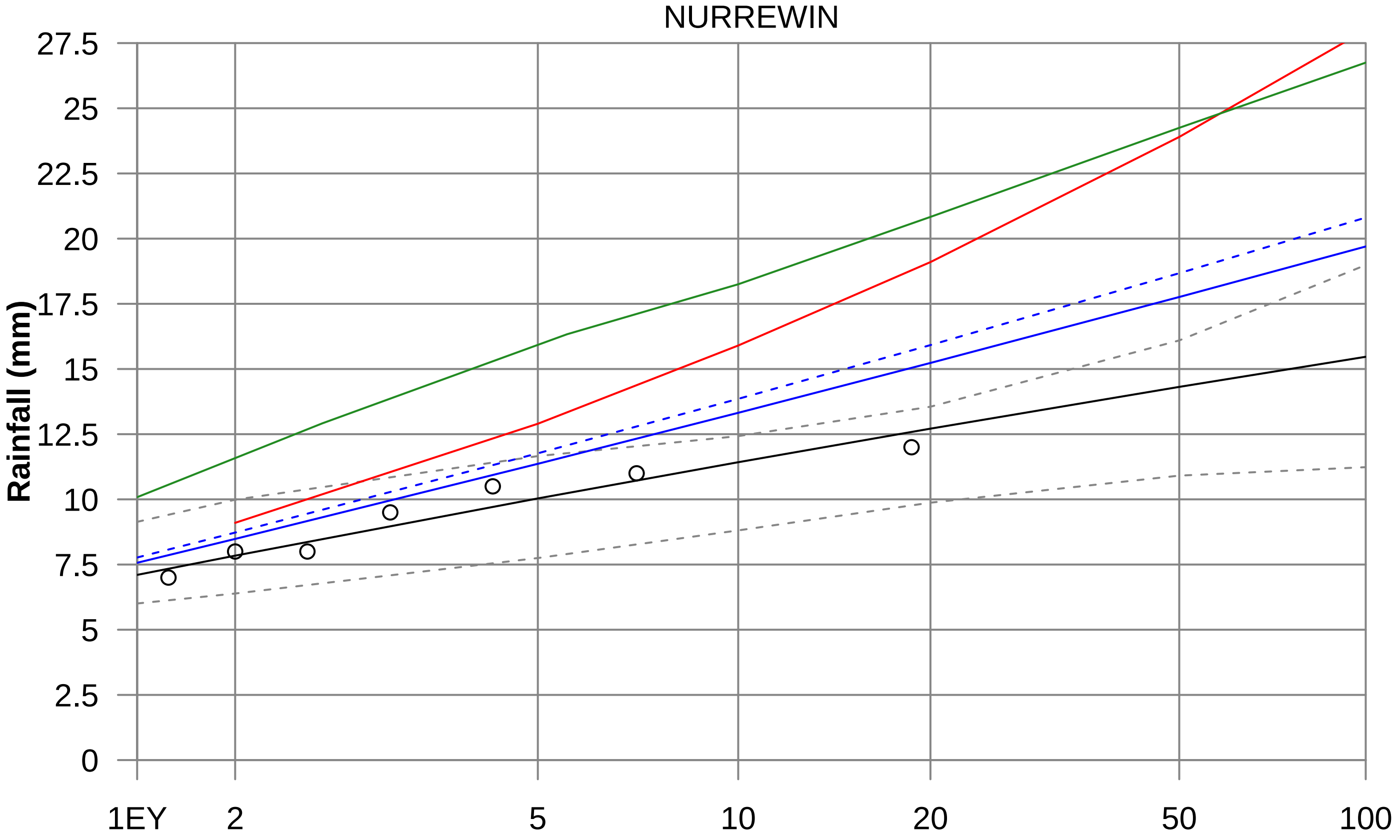


FIGURE A9
WOLLONGONG AREA STATIONS
5 MINUTES IFD COMPARISON



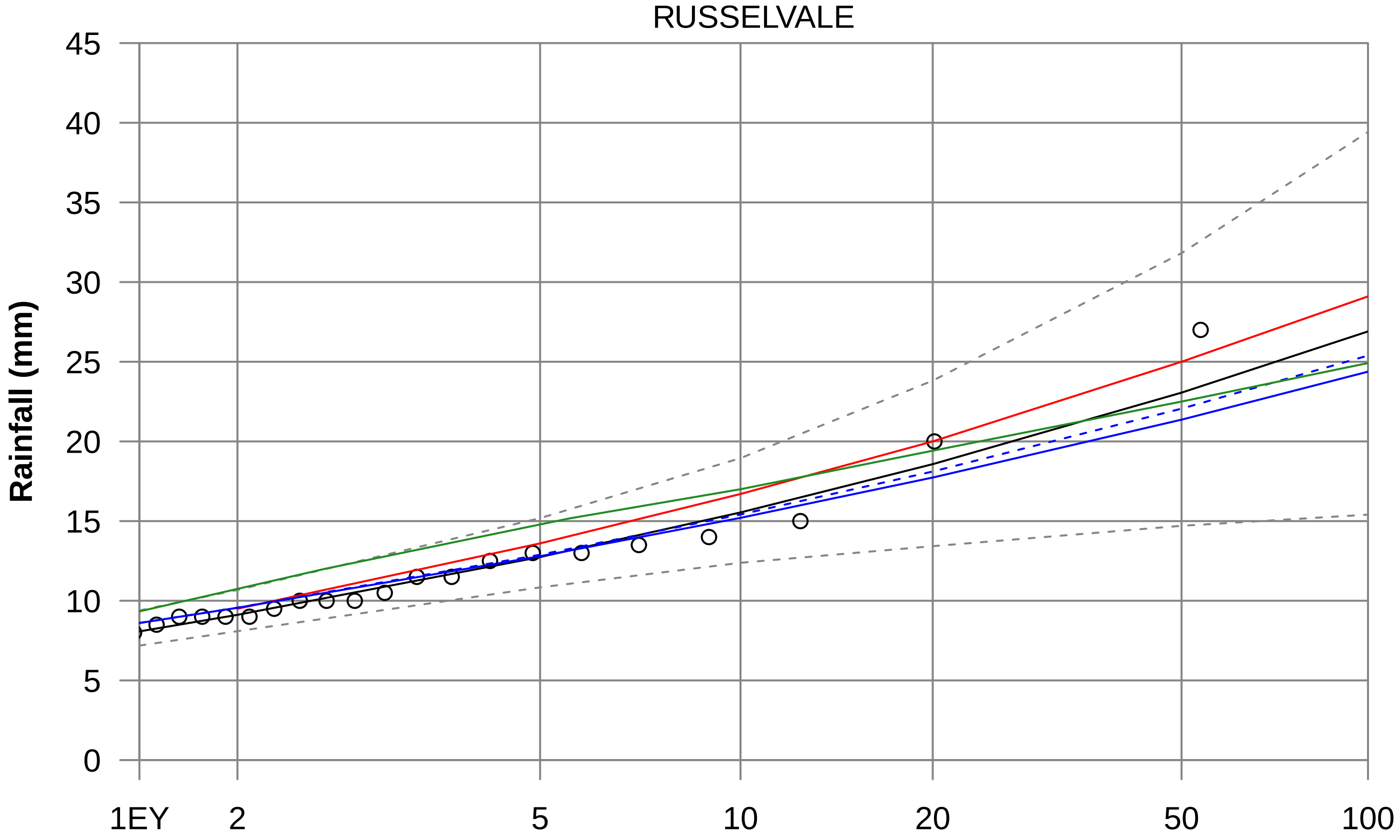
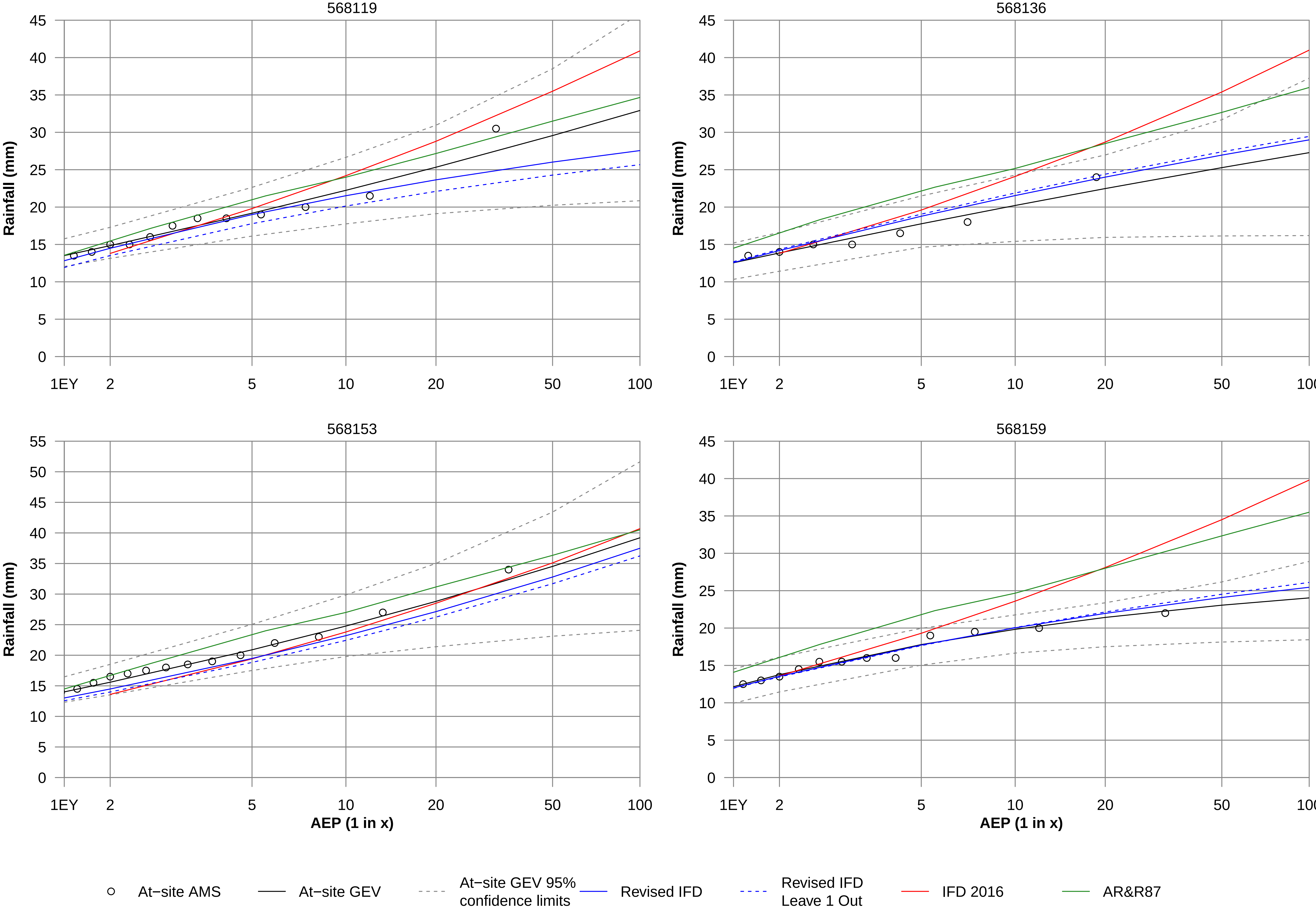


FIGURE A10
WOLLONGONG AREA STATIONS
10 MINUTES IFD COMPARISON



WOLLONGONG AREA STATIONS
10 MINUTES IFD COMPARISON

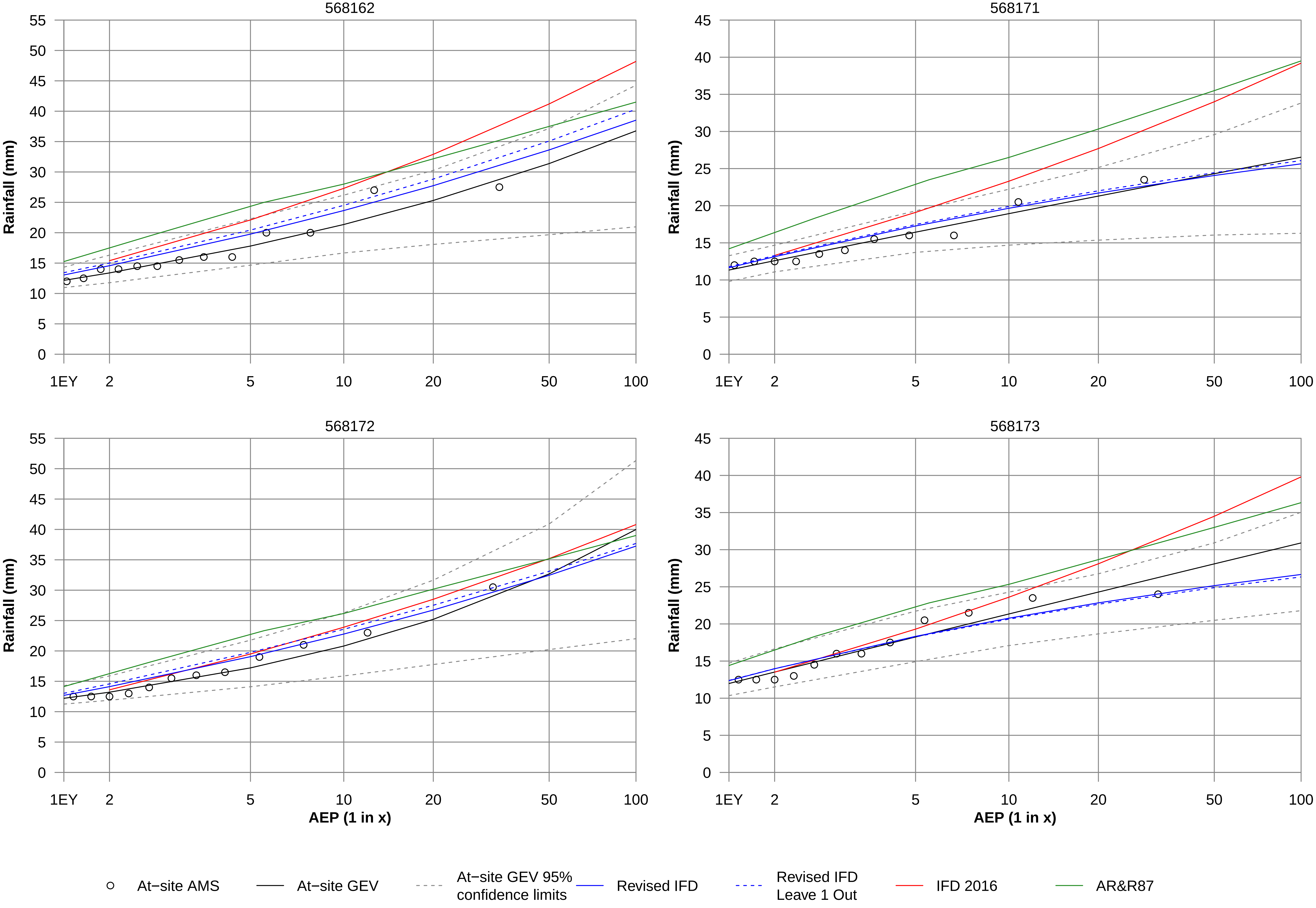


FIGURE A12

WOLLONGONG AREA STATIONS

10 MINUTES IFD COMPARISON

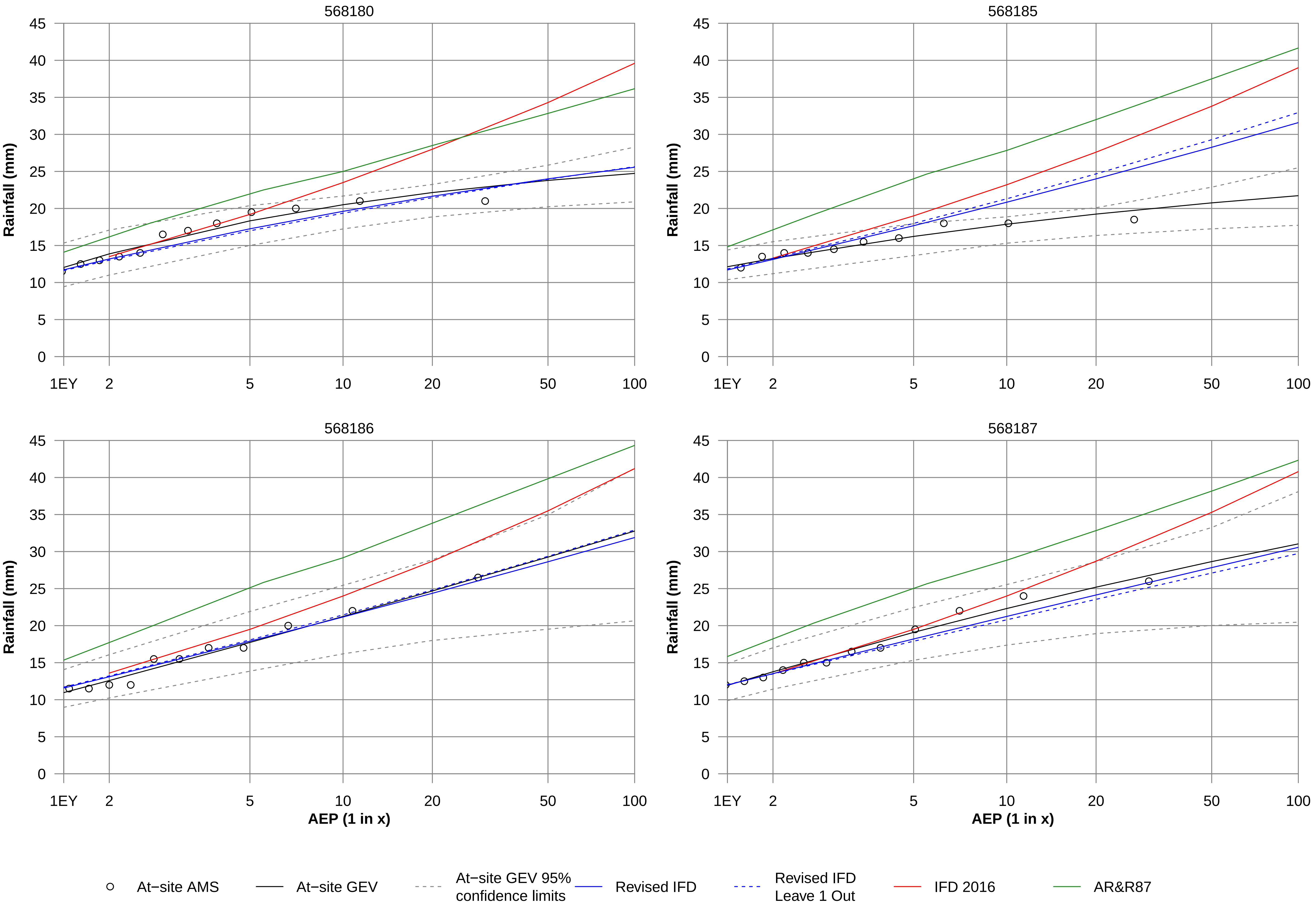
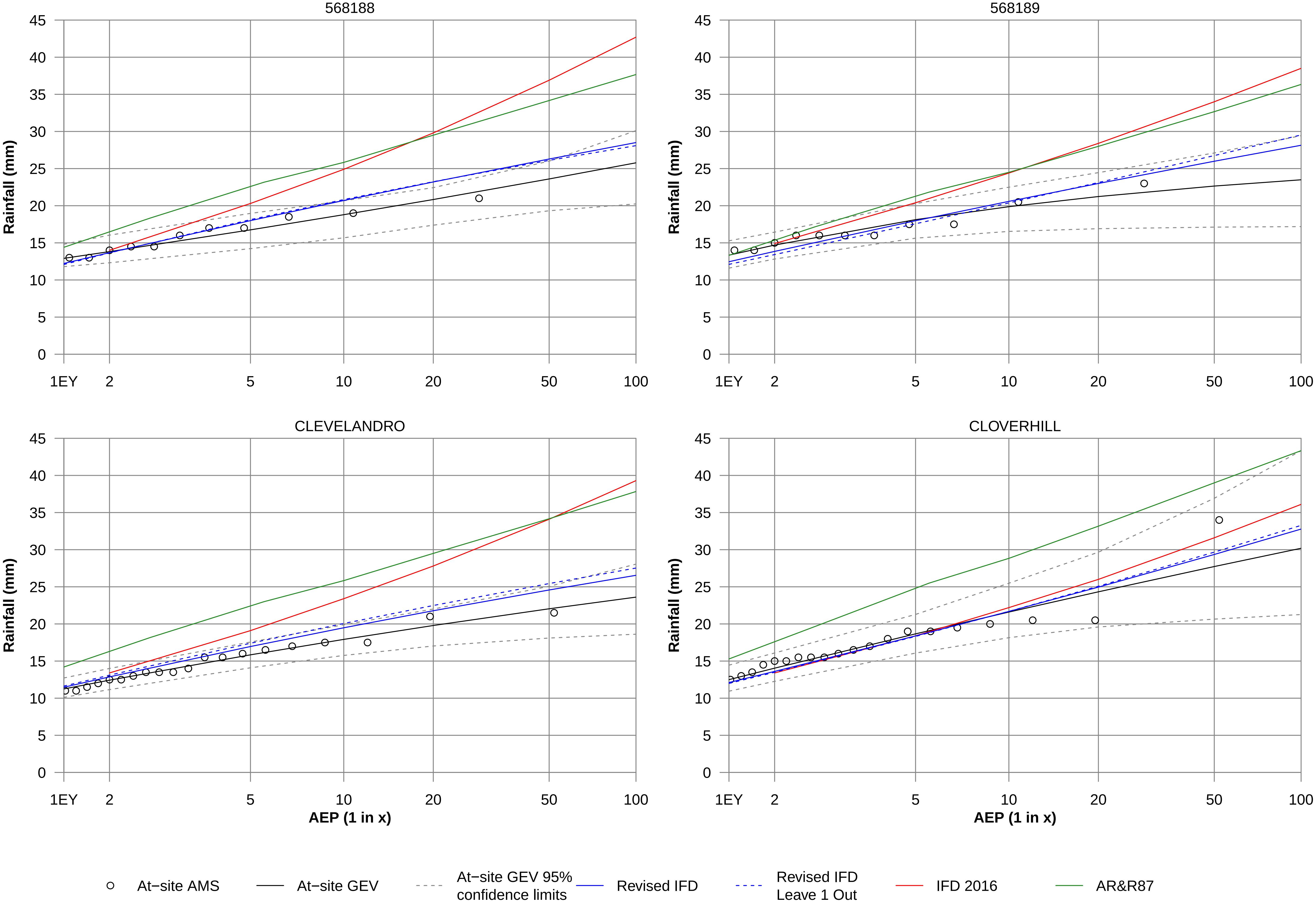


FIGURE A13
WOLLONGONG AREA STATIONS
10 MINUTES IFD COMPARISON



WOLLONGONG AREA STATIONS
10 MINUTES IFD COMPARISON

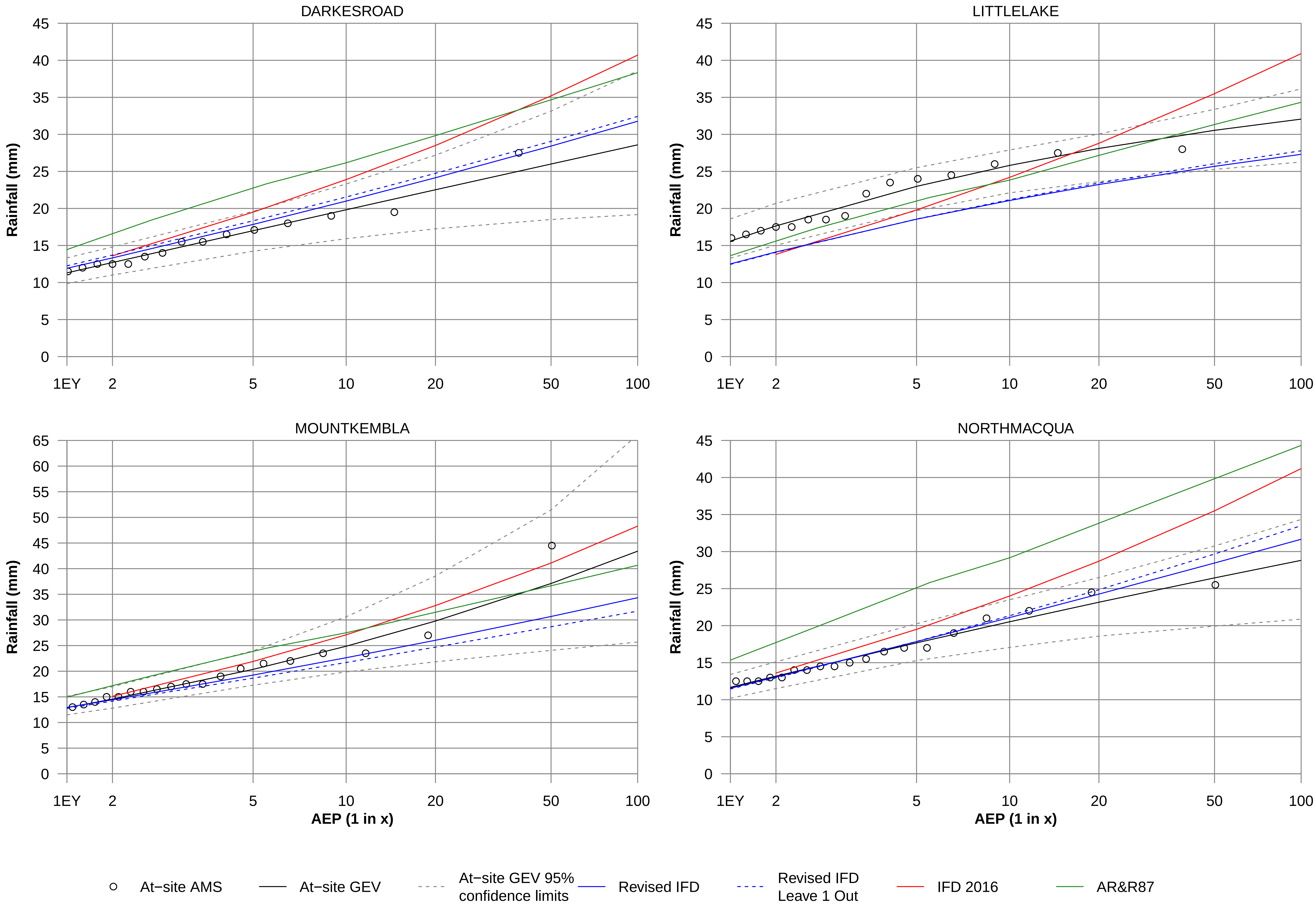


FIGURE A15
WOLLONGONG AREA STATIONS
10 MINUTES IFD COMPARISON

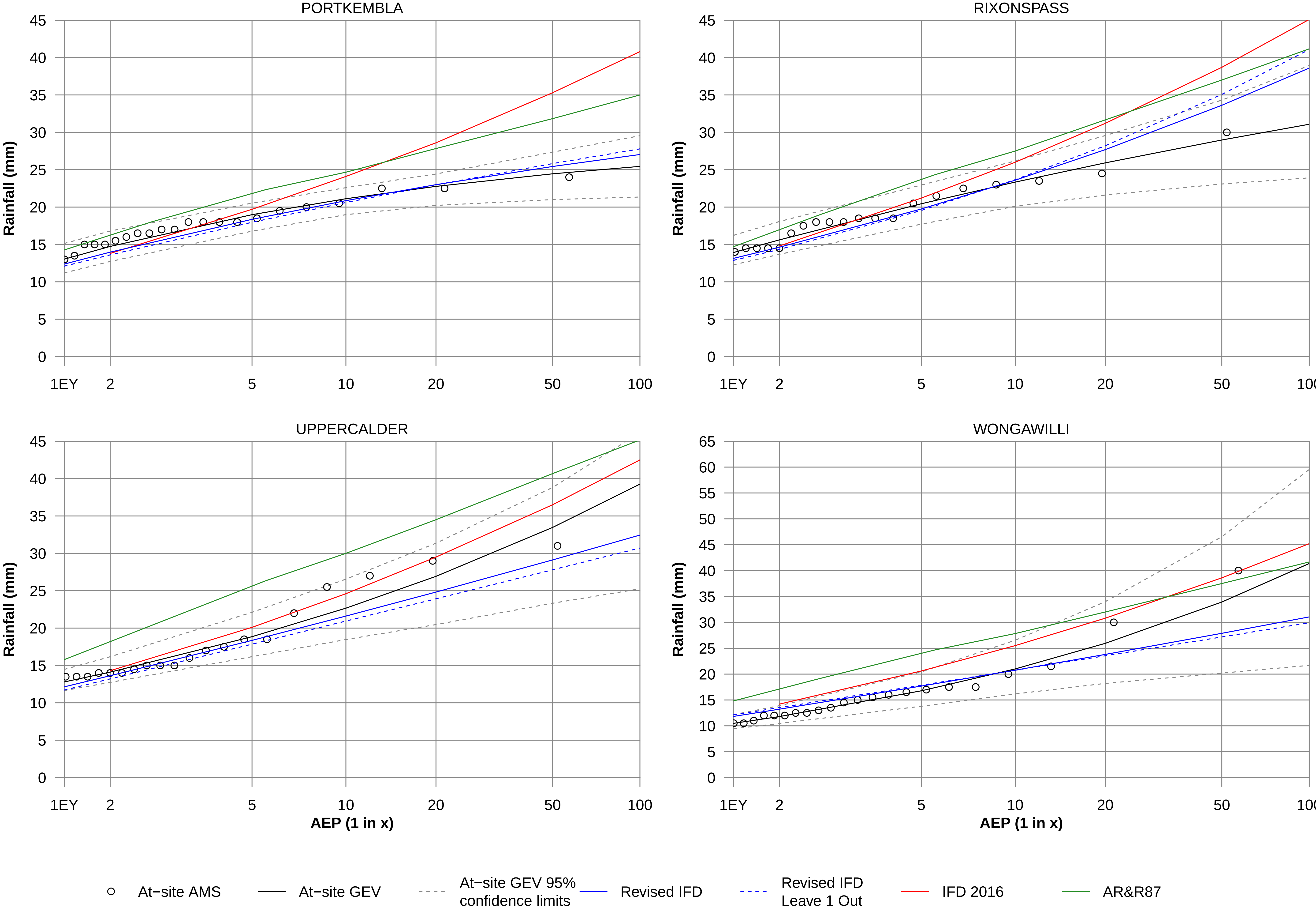


FIGURE A16
WOLLONGONG AREA STATIONS
10 MINUTES IFD COMPARISON

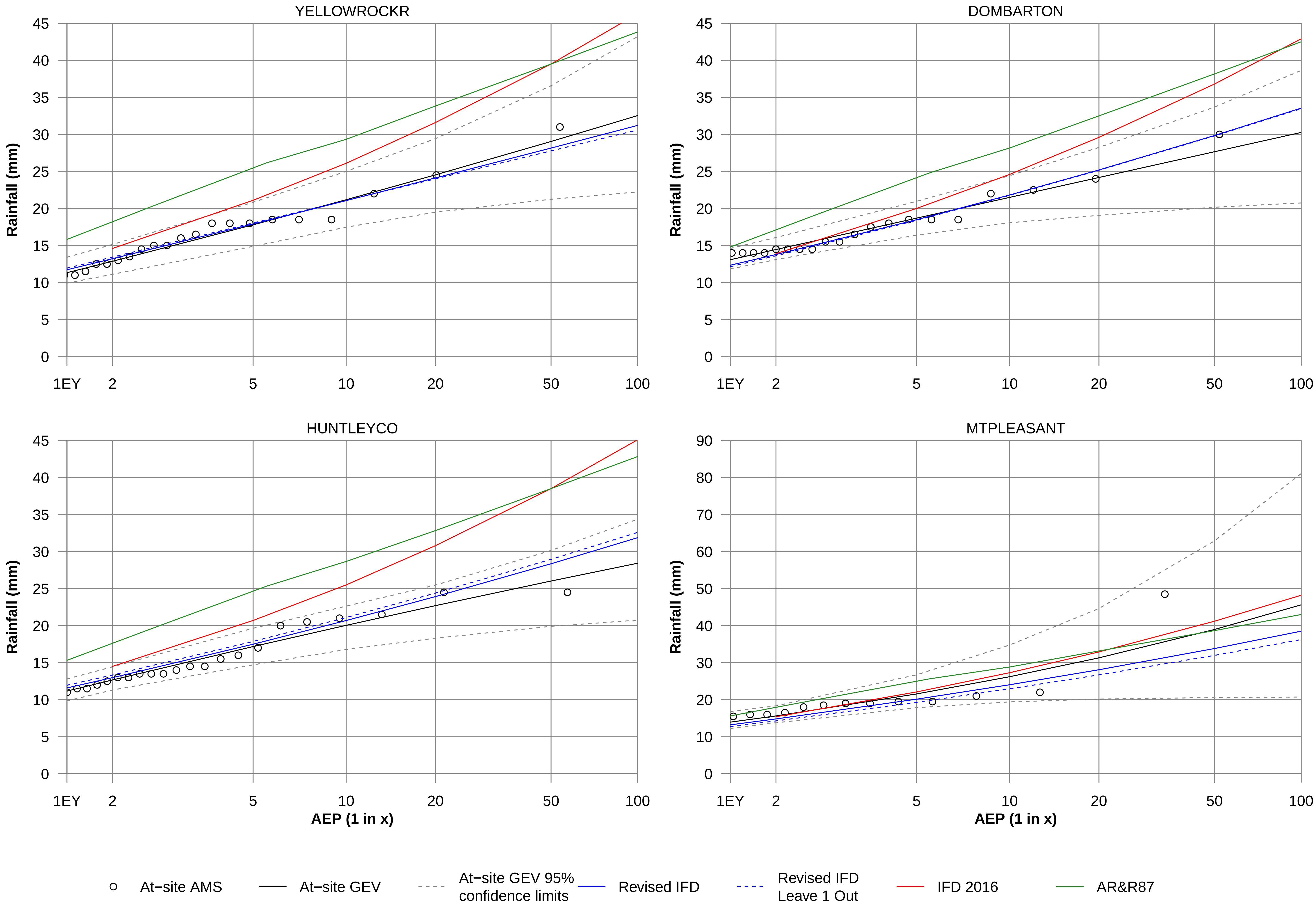
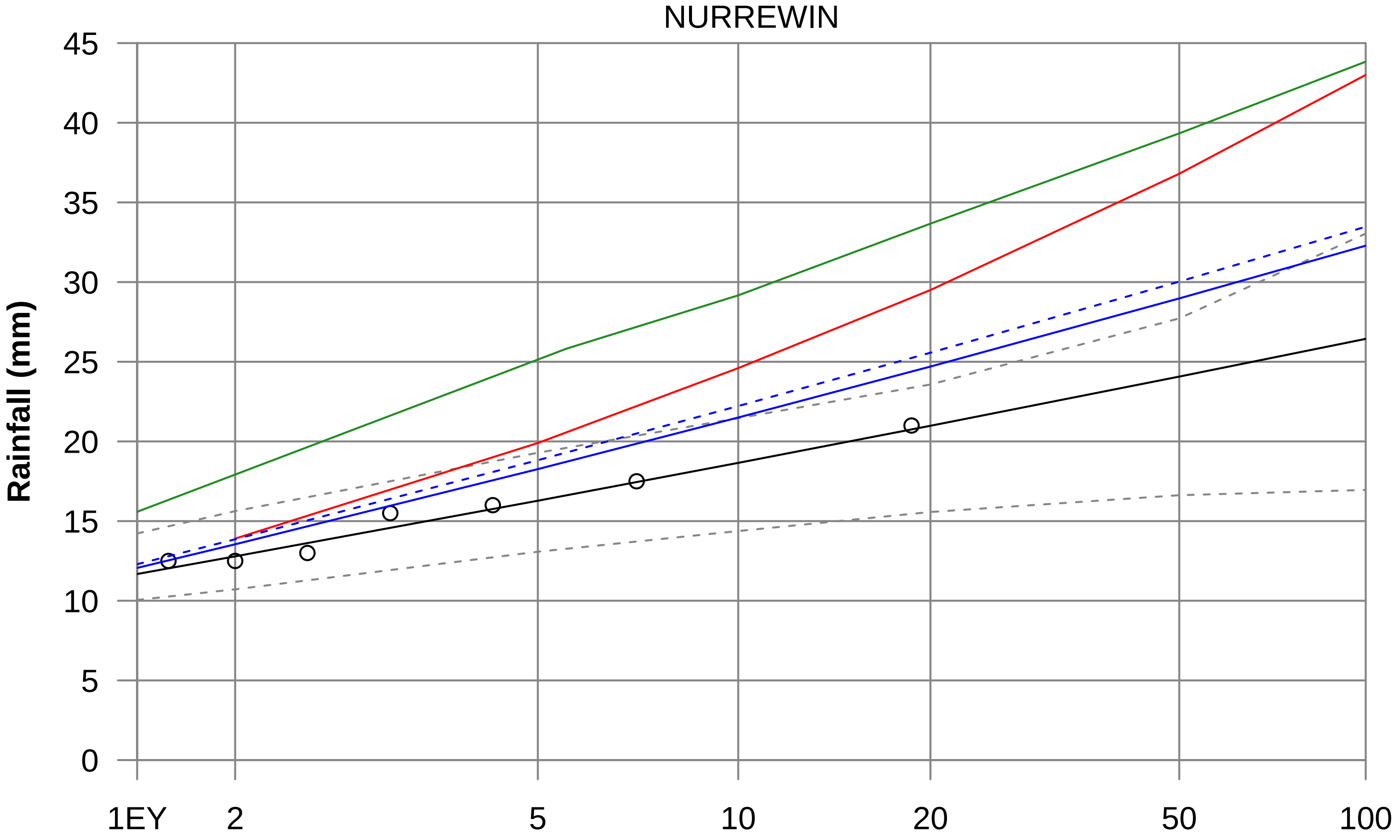


FIGURE A17
WOLLONGONG AREA STATIONS
10 MINUTES IFD COMPARISON



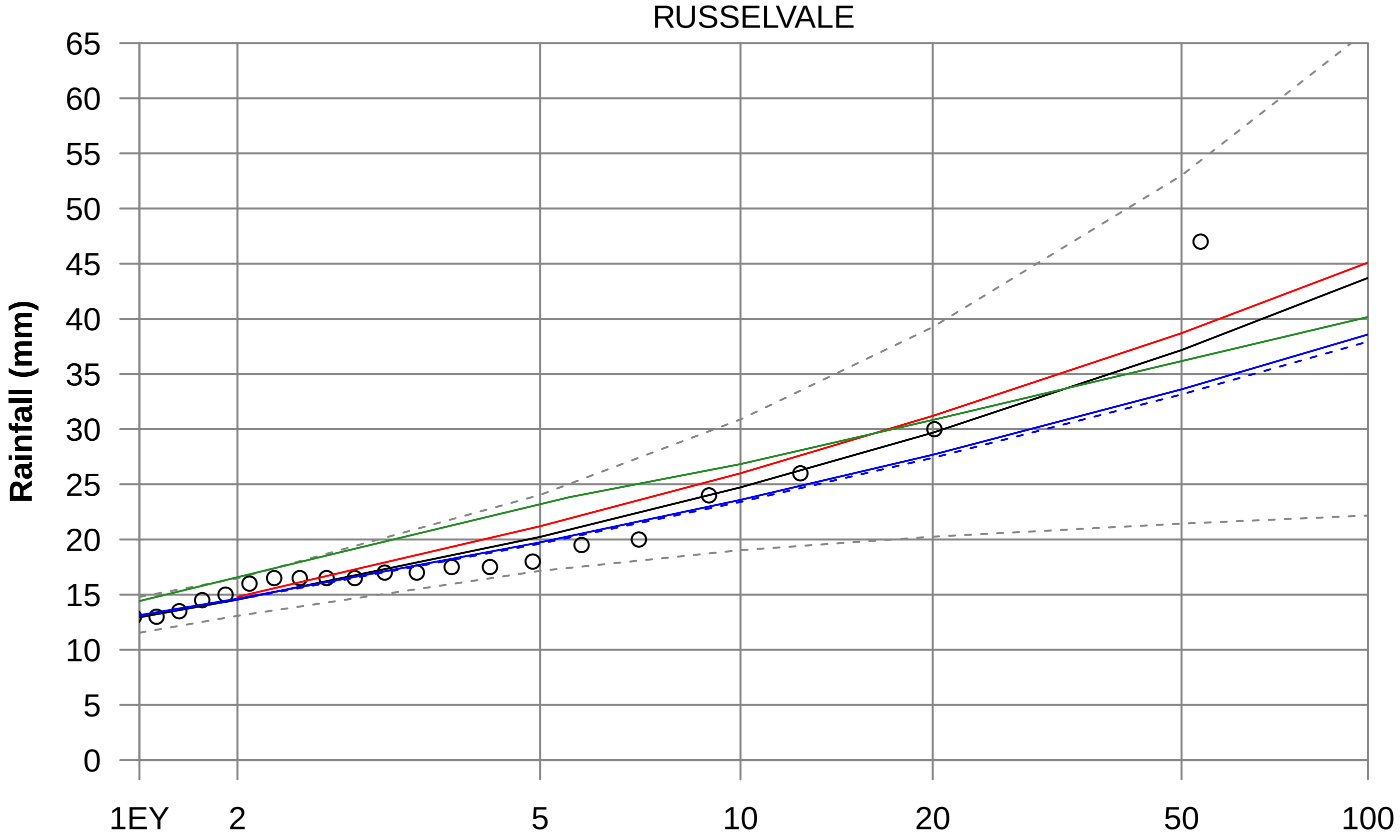


FIGURE A18

WOLLONGONG AREA STATIONS

30 MINUTES IFD COMPARISON

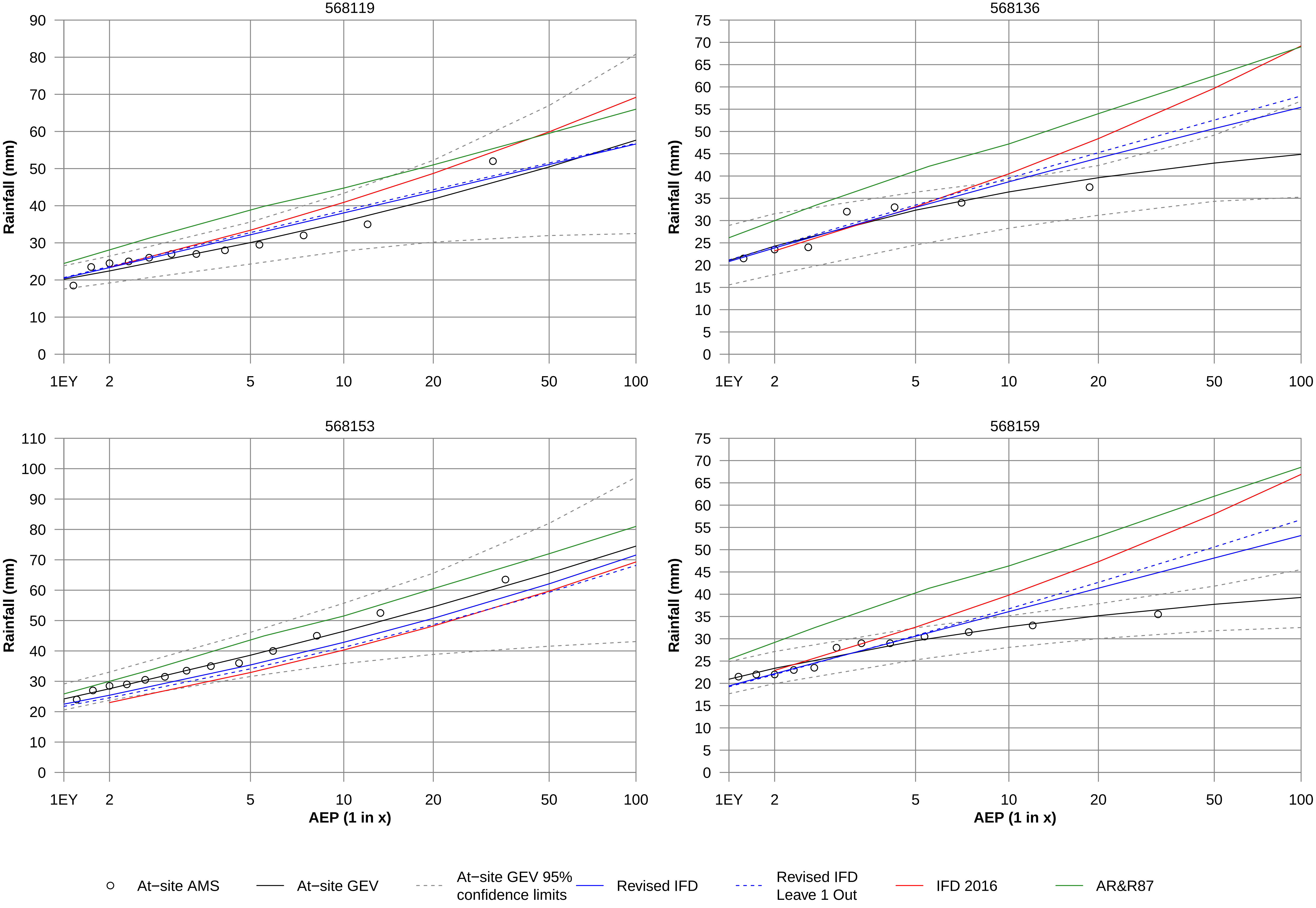


FIGURE A19
WOLLONGONG AREA STATIONS
30 MINUTES IFD COMPARISON

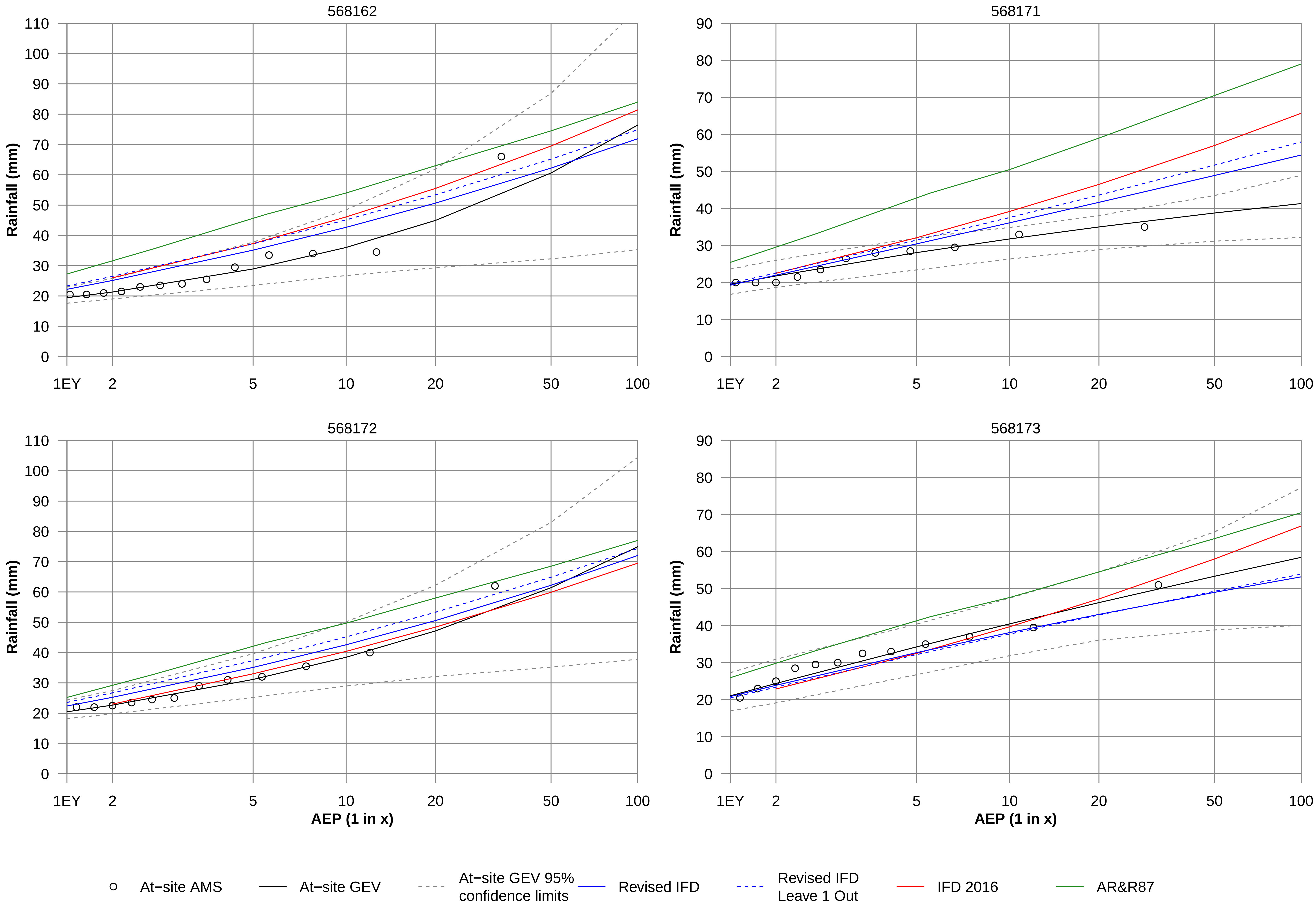


FIGURE A20
WOLLONGONG AREA STATIONS
30 MINUTES IFD COMPARISON

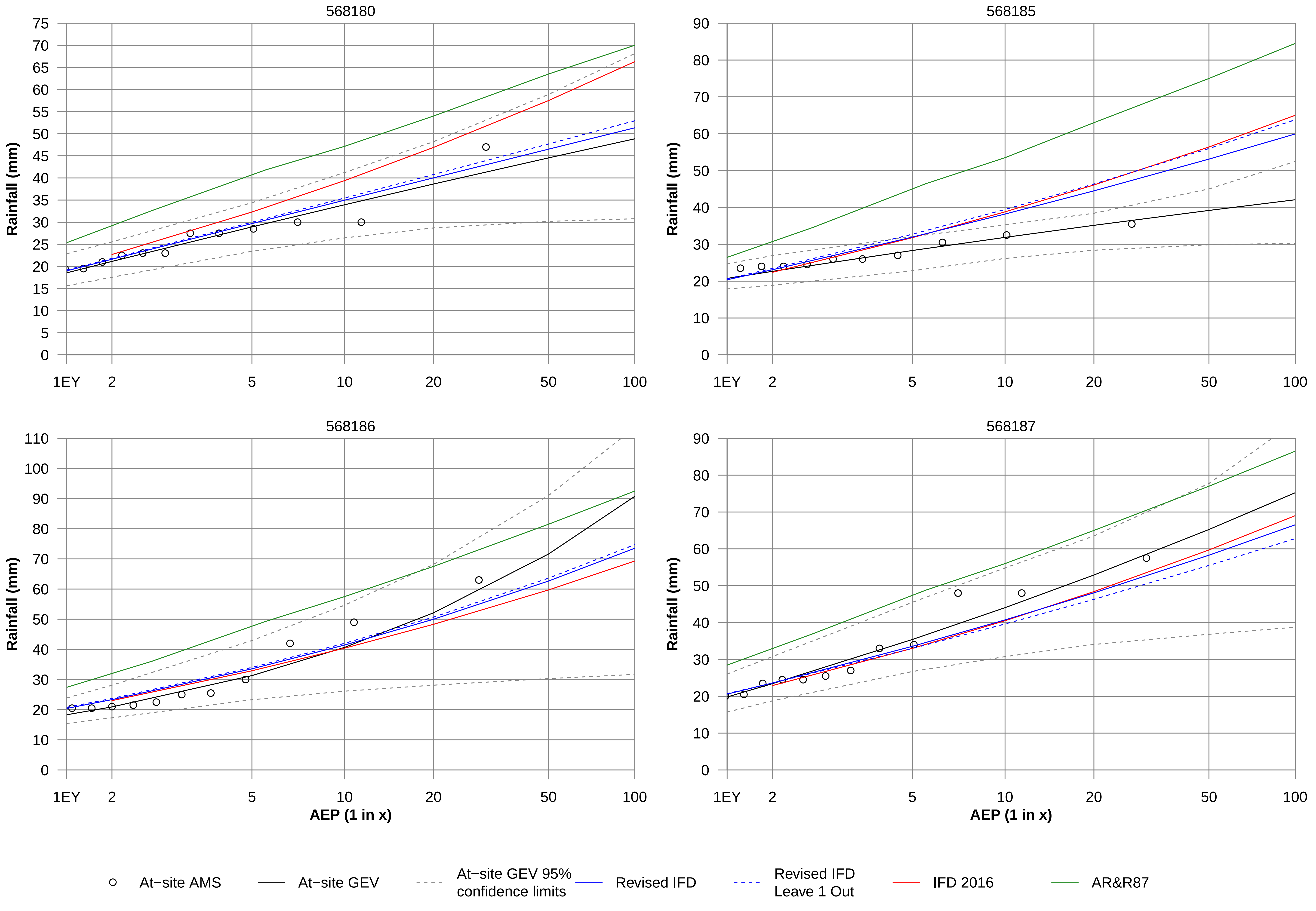


FIGURE A21
WOLLONGONG AREA STATIONS
30 MINUTES IFD COMPARISON

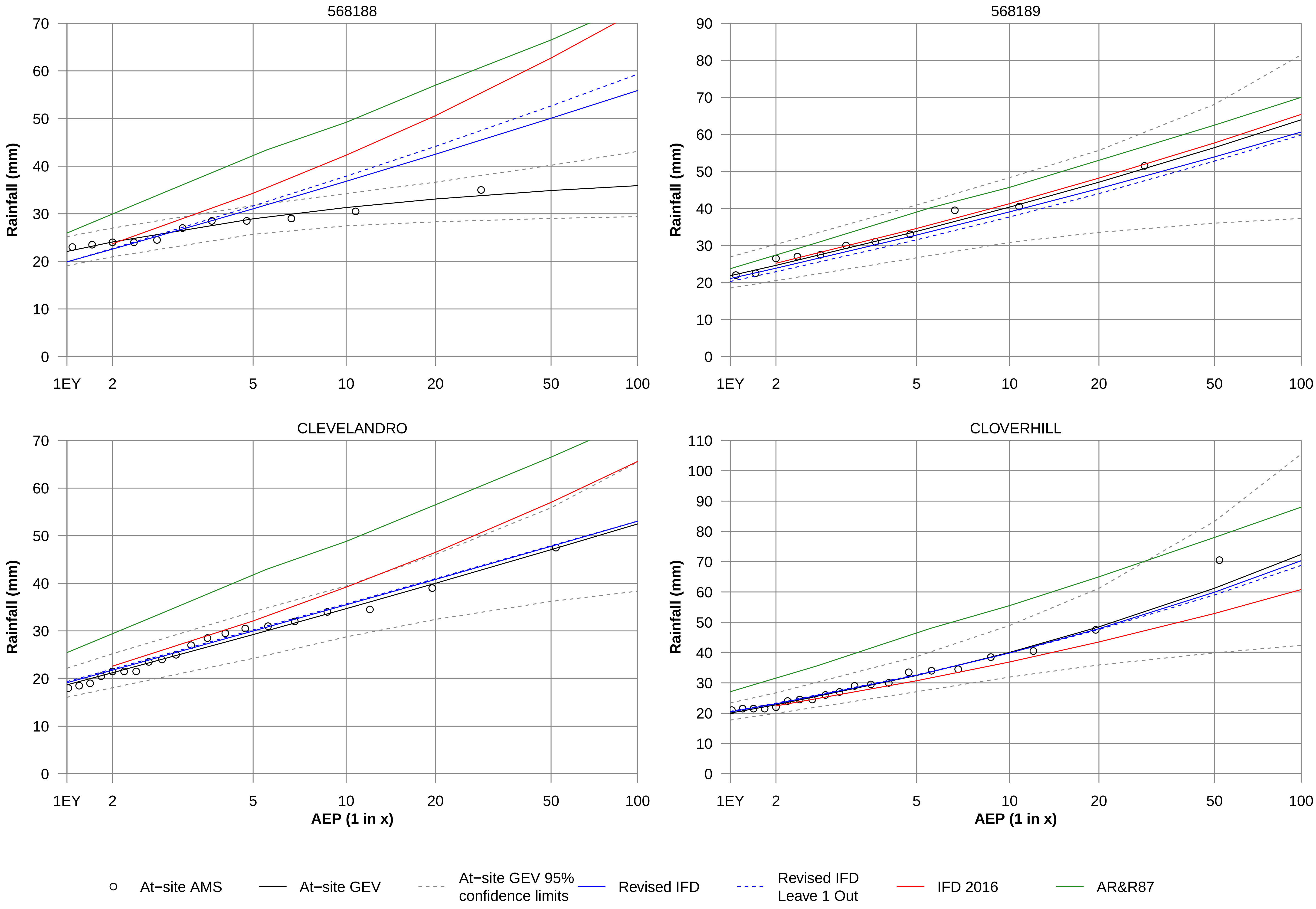
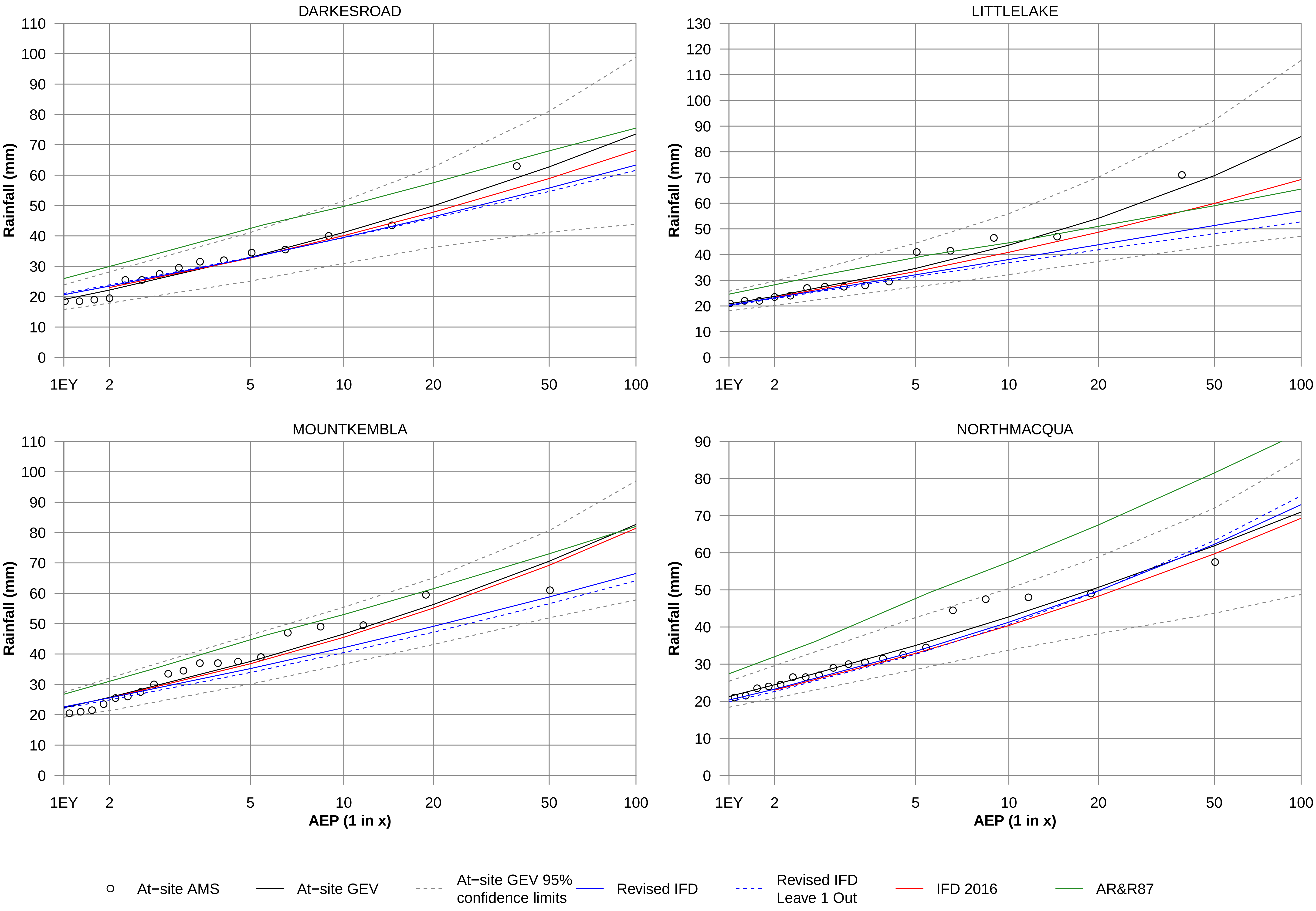
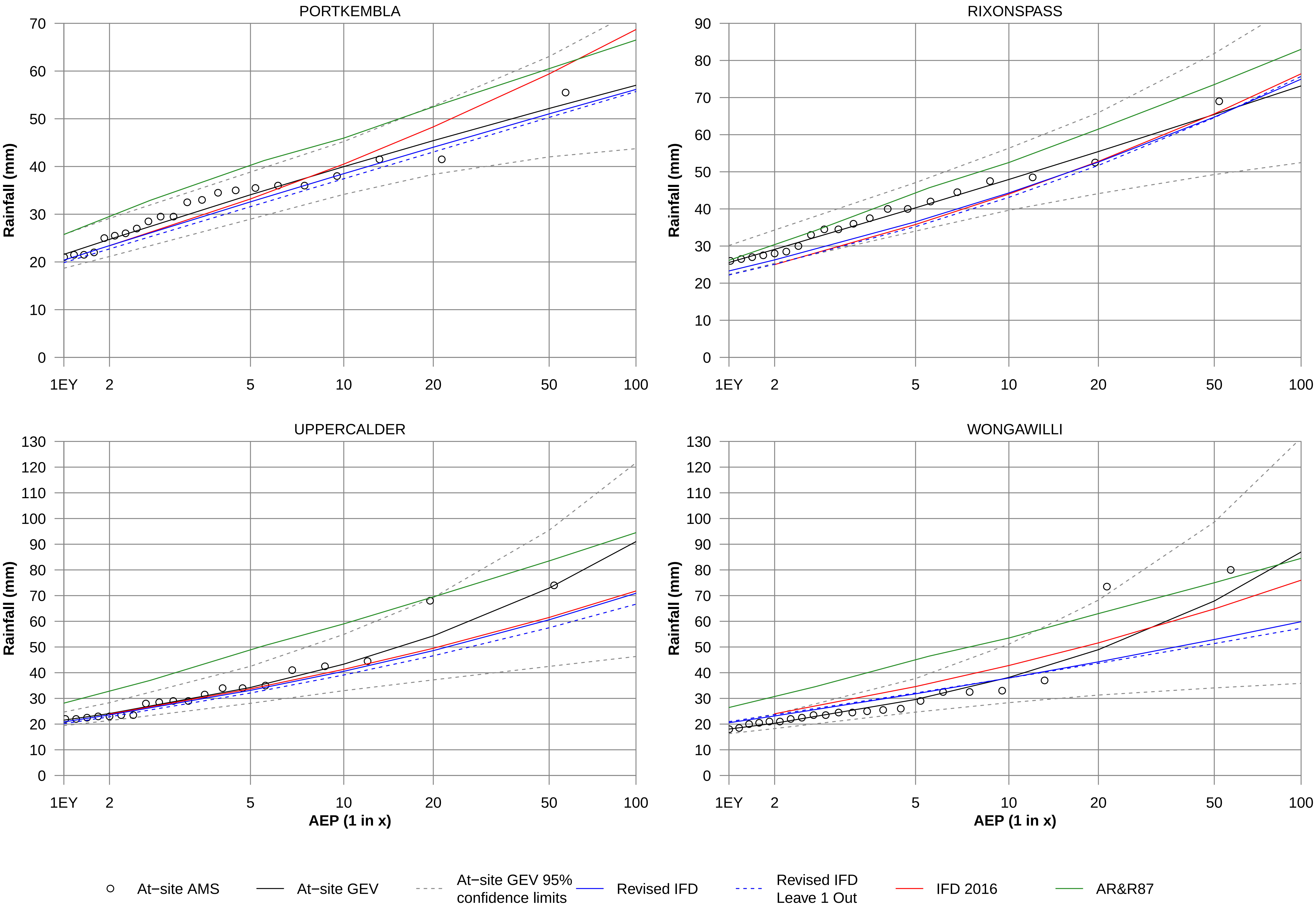


FIGURE A22
WOLLONGONG AREA STATIONS
30 MINUTES IFD COMPARISON



WOLLONGONG AREA STATIONS
30 MINUTES IFD COMPARISON



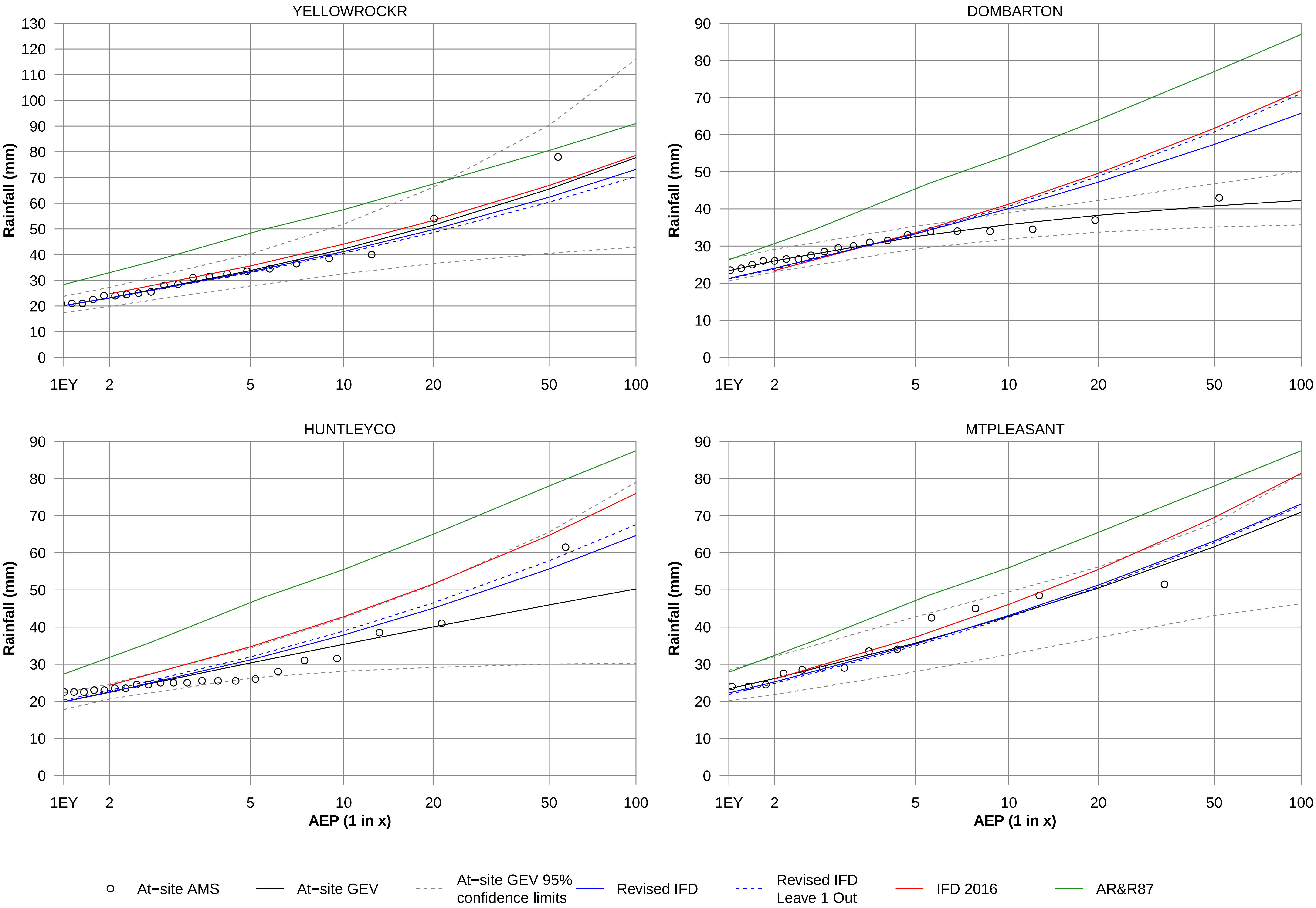
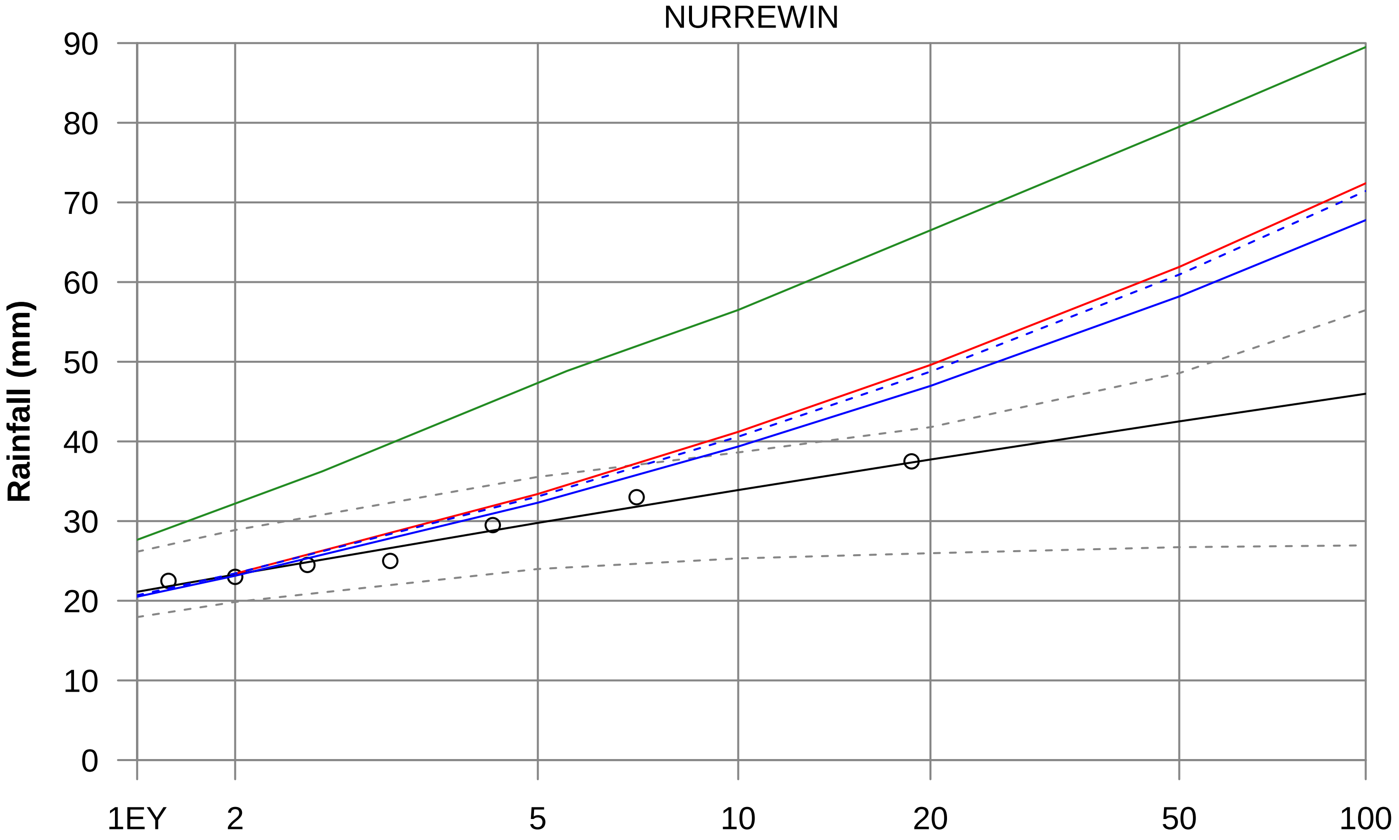
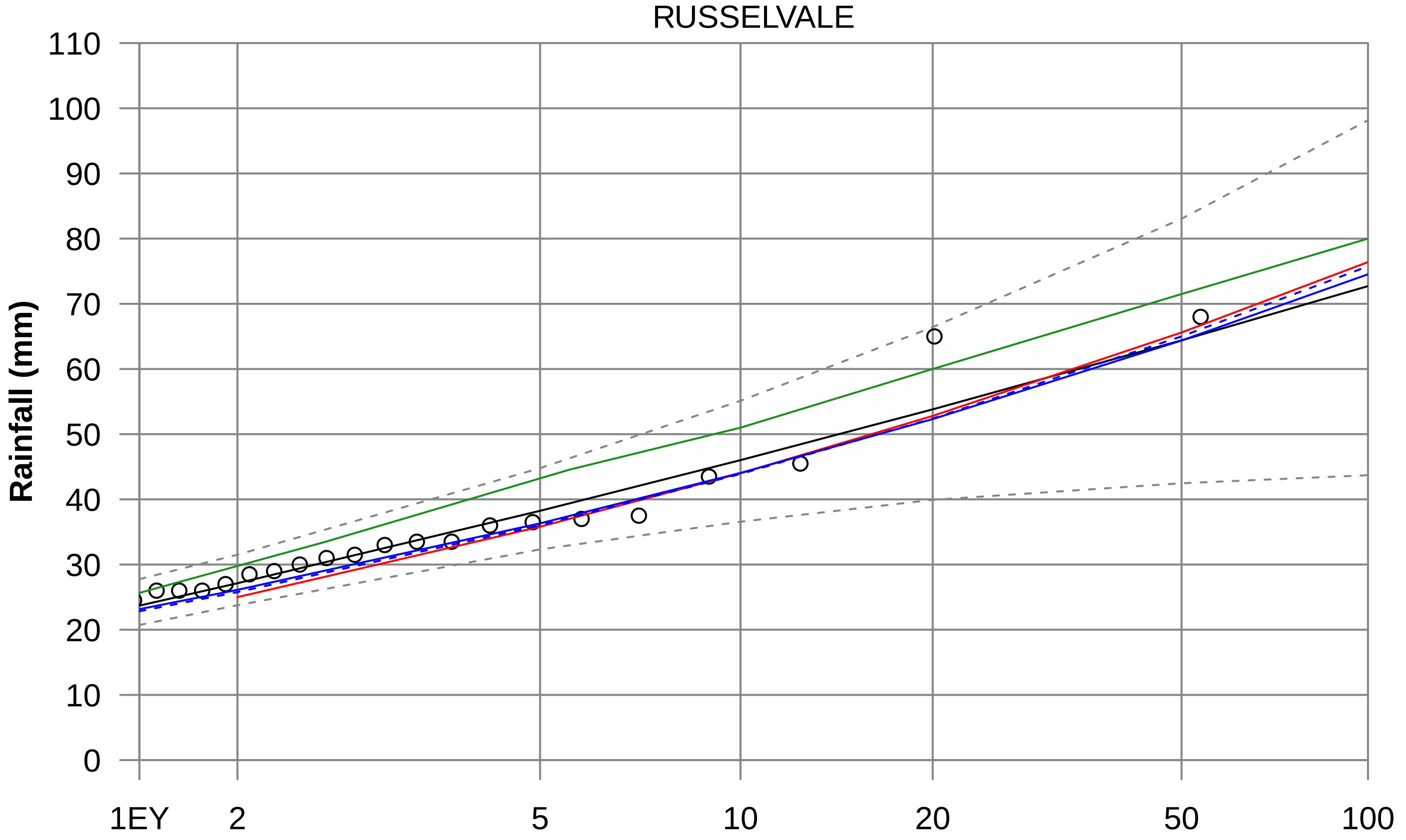
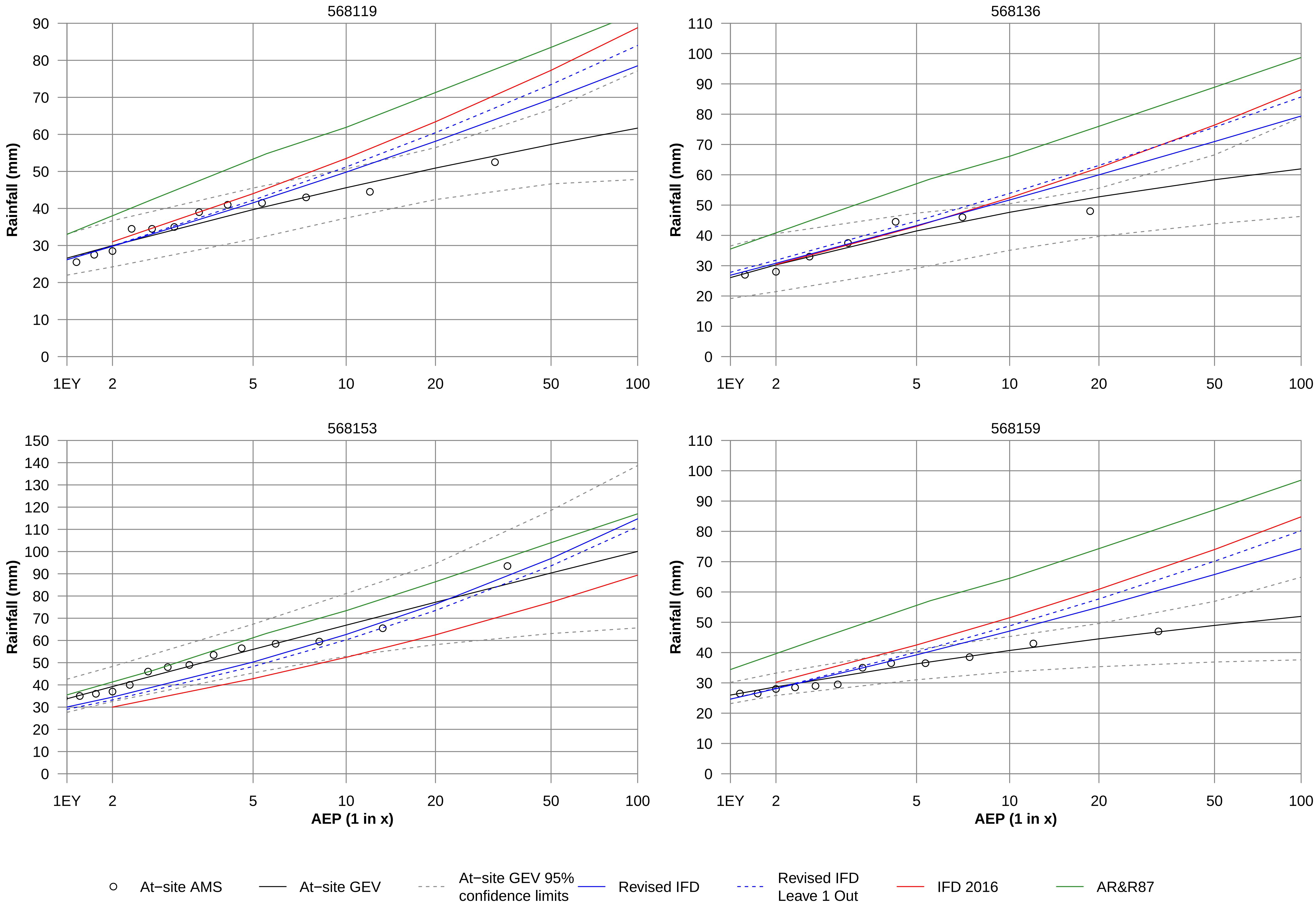

YELLOWROCKR
DOMBARTON
HUNTLEYCO
MTPLEASANT
Rainfall (mm)
AEP (1 in x)
1EY
2
5
10
20
50
100
At−site AMS
At−site GEV
At−site GEV 95% confidence limits
Revised IFD
Revised IFD Leave 1 Out
IFD 2016
AR&R87

FIGURE A25
WOLLONGONG AREA STATIONS
30 MINUTES IFD COMPARISON





WOLLONGONG AREA STATIONS
1 HOUR IFD COMPARISON



WOLLONGONG AREA STATIONS
1 HOUR IFD COMPARISON

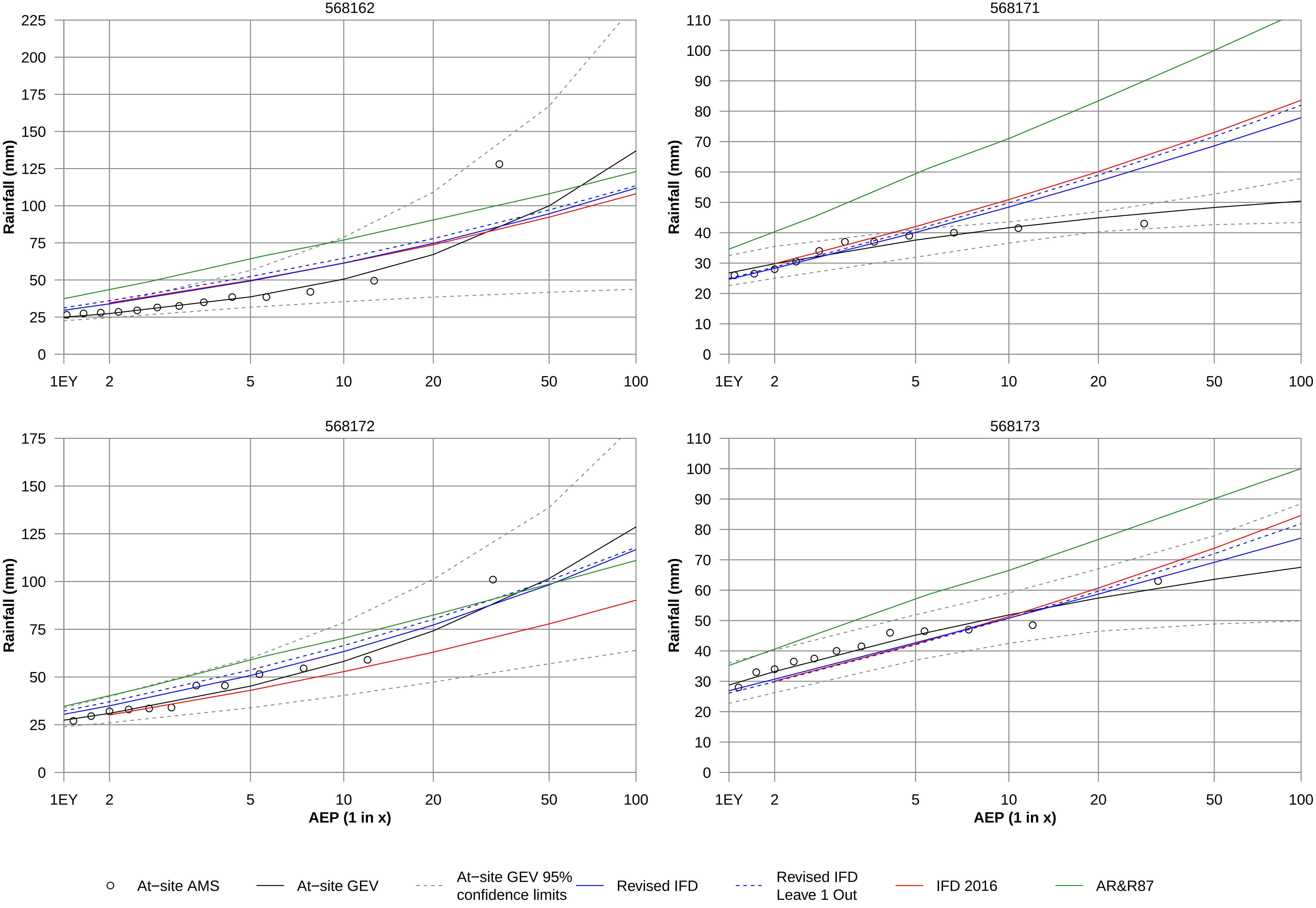
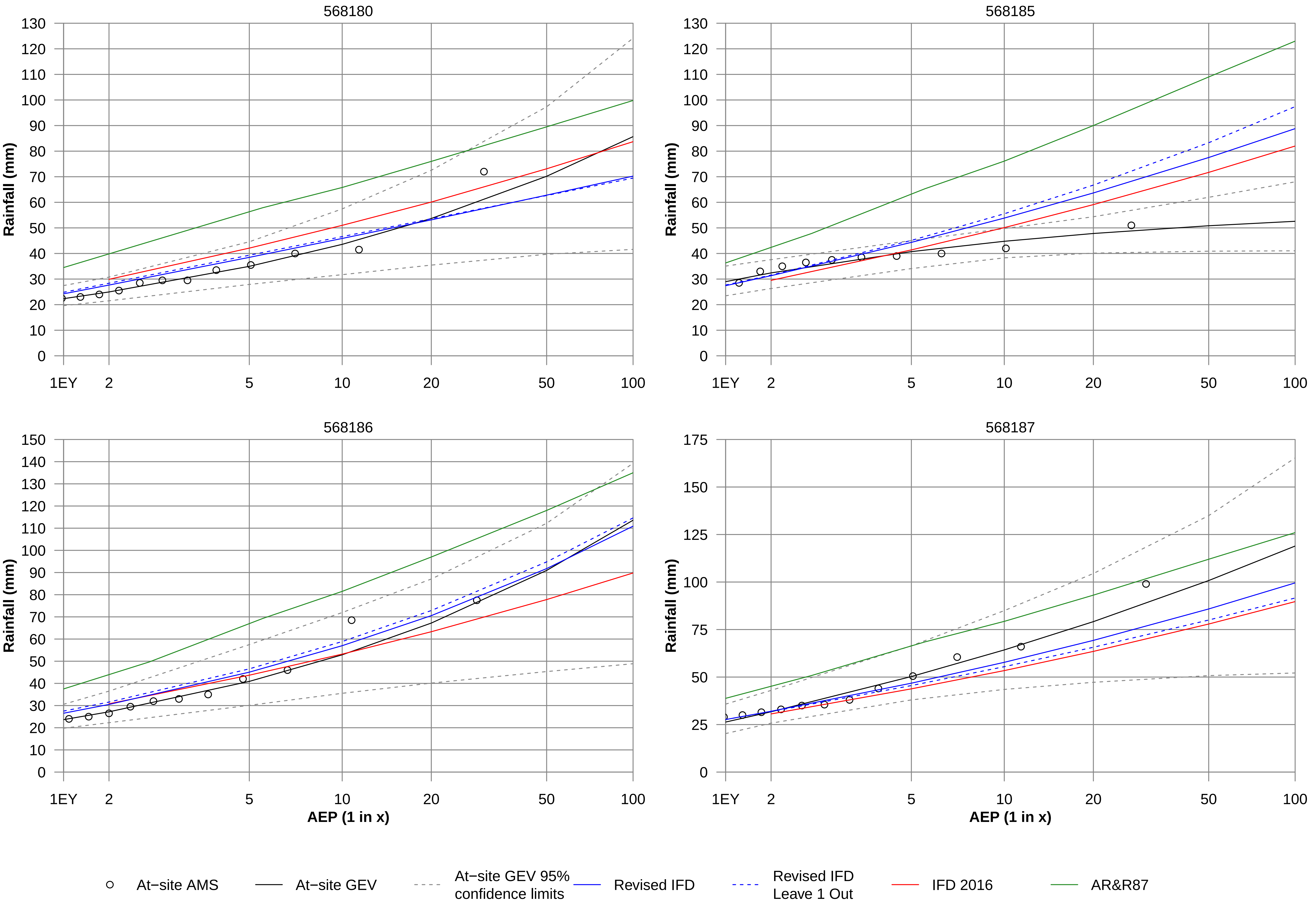


FIGURE A28
WOLLONGONG AREA STATIONS
1 HOUR IFD COMPARISON



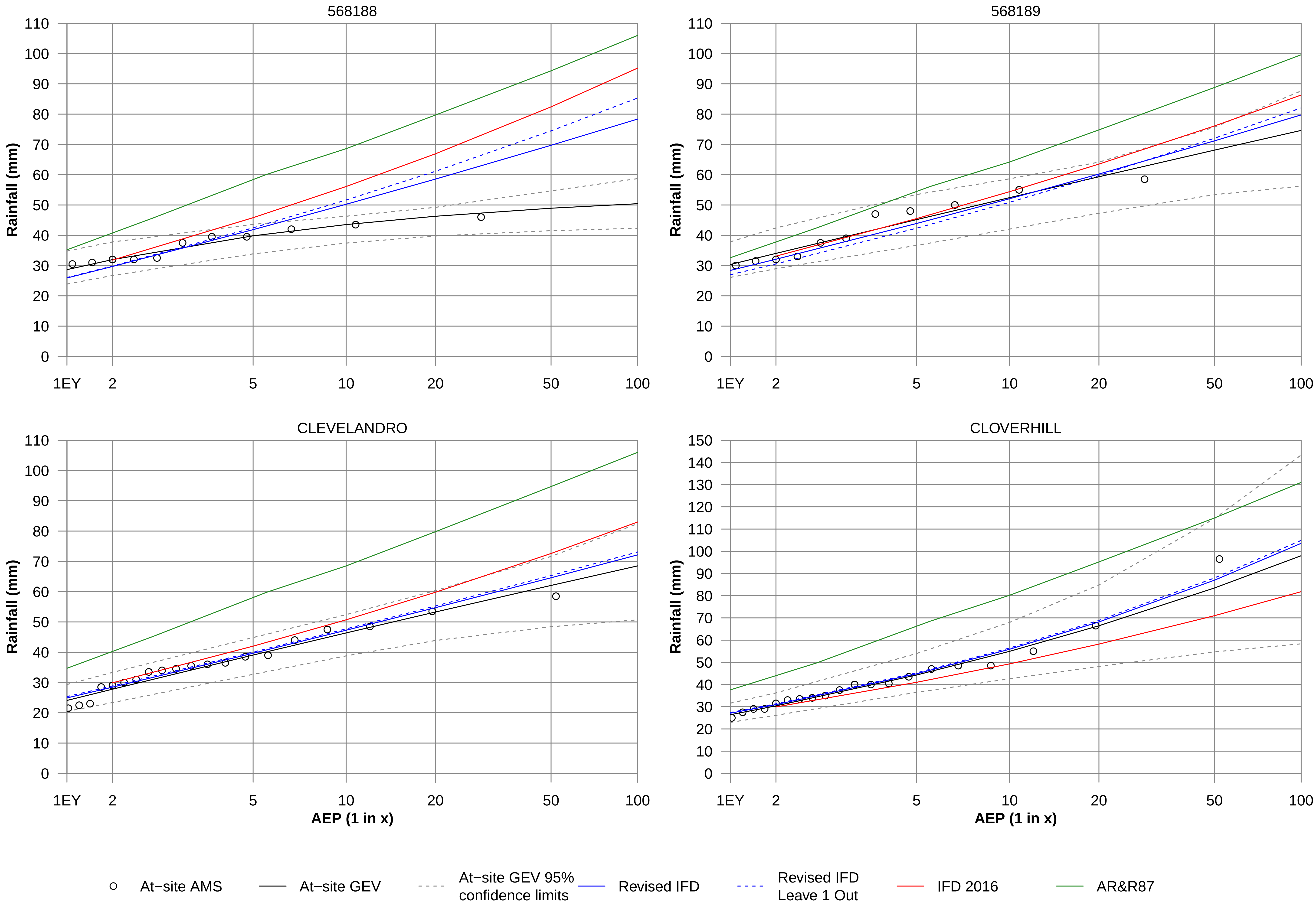

568188
568189
CLEVELANDRO
CLOVERHILL
Rainfall (mm)
AEP (1 in x)
1EY
2
5
10
20
50
100
At−site AMS
At−site GEV
At−site GEV 95% confidence limits
Revised IFD
Revised IFD Leave 1 Out
IFD 2016
AR&R87

FIGURE A30
WOLLONGONG AREA STATIONS
1 HOUR IFD COMPARISON

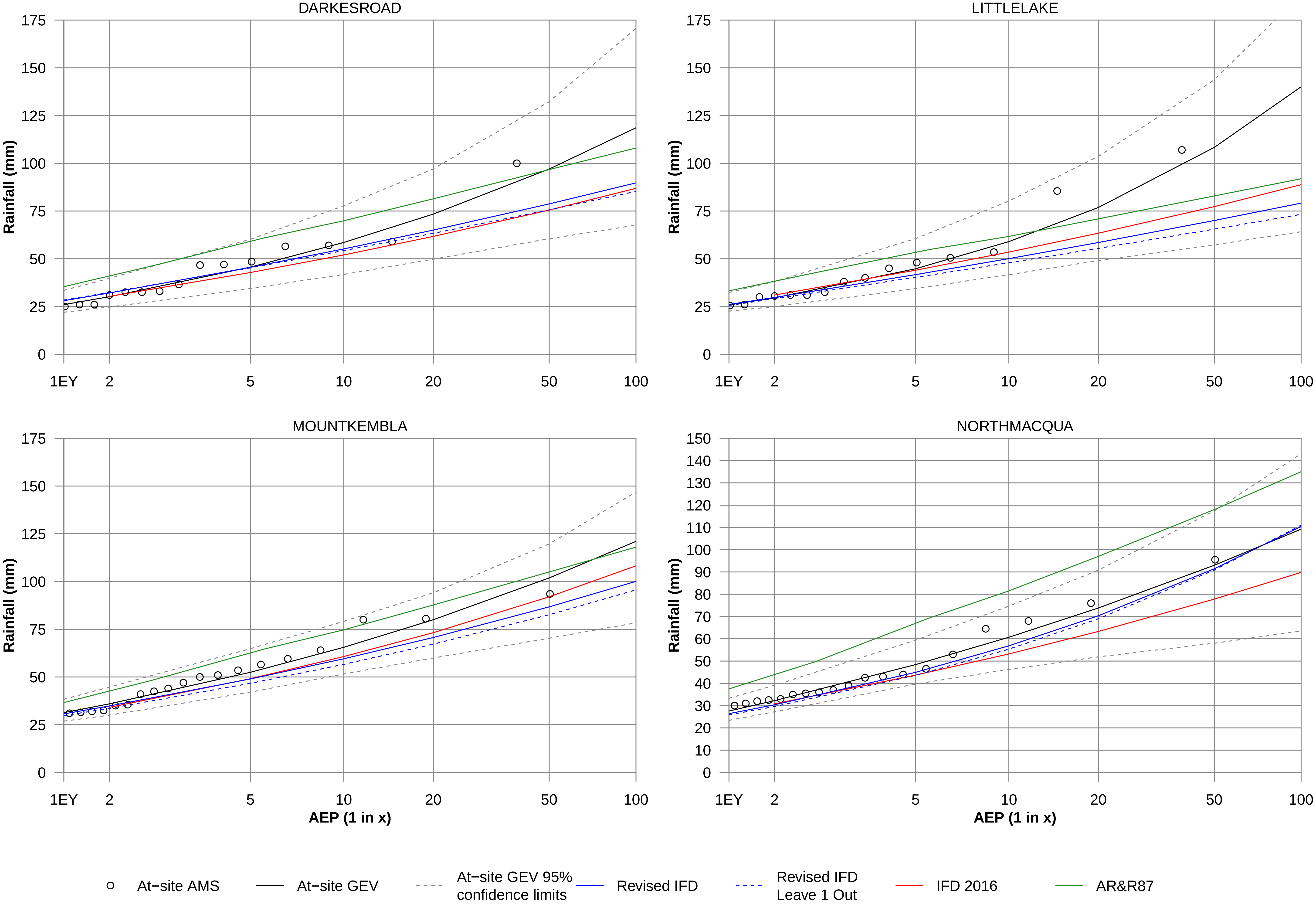


FIGURE A31
WOLLONGONG AREA STATIONS
1 HOUR IFD COMPARISON

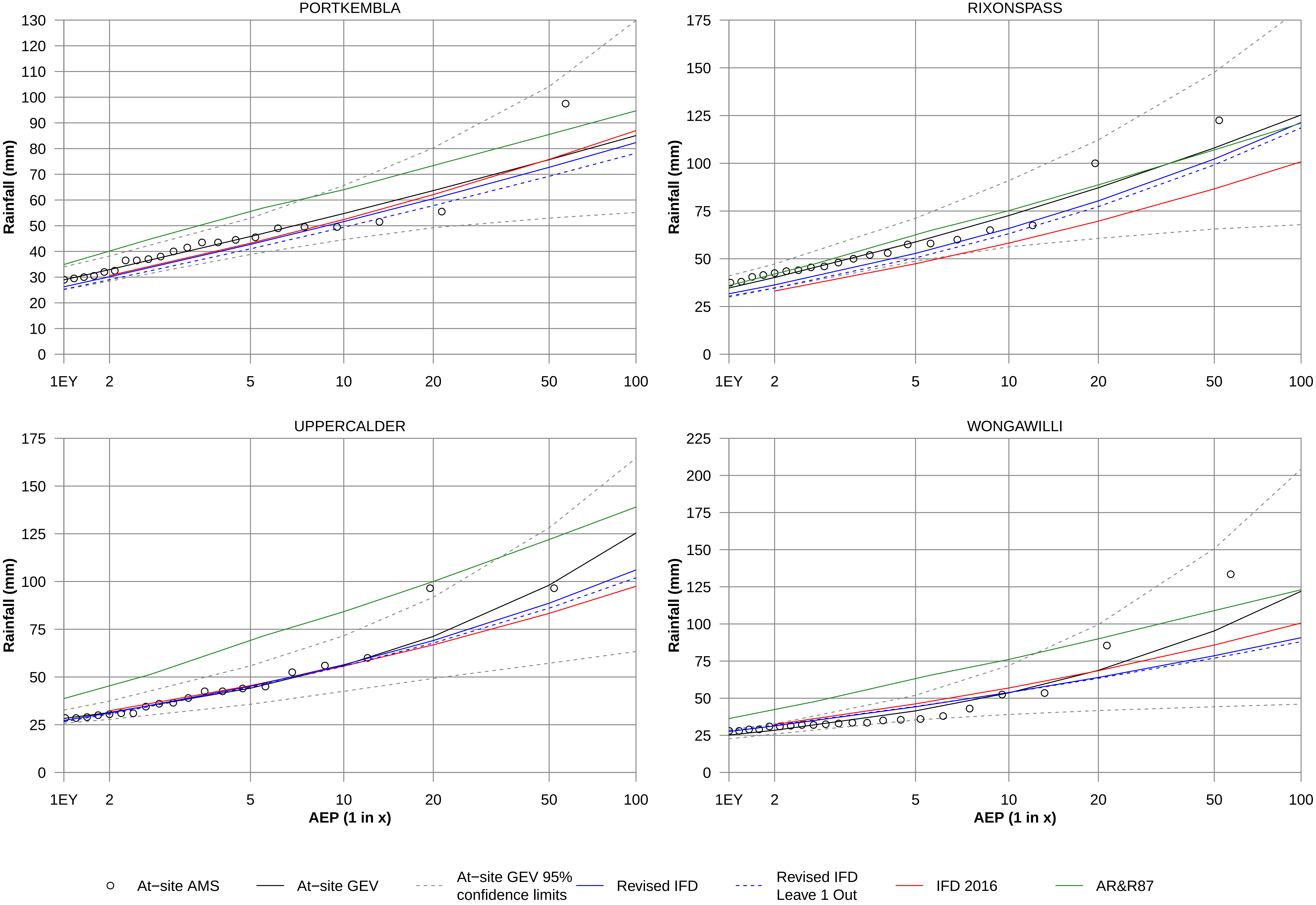


FIGURE A32
WOLLONGONG AREA STATIONS
1 HOUR IFD COMPARISON

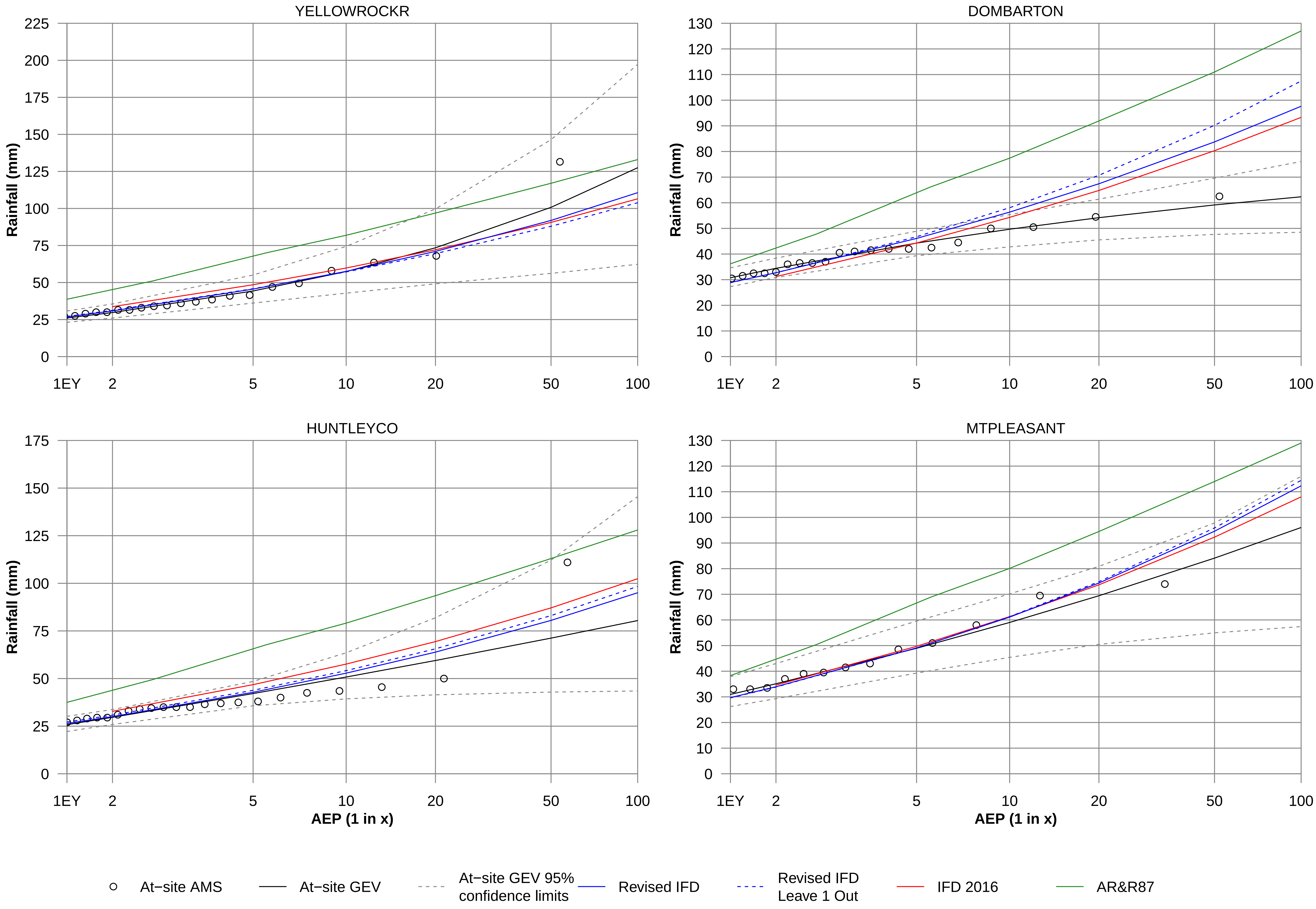
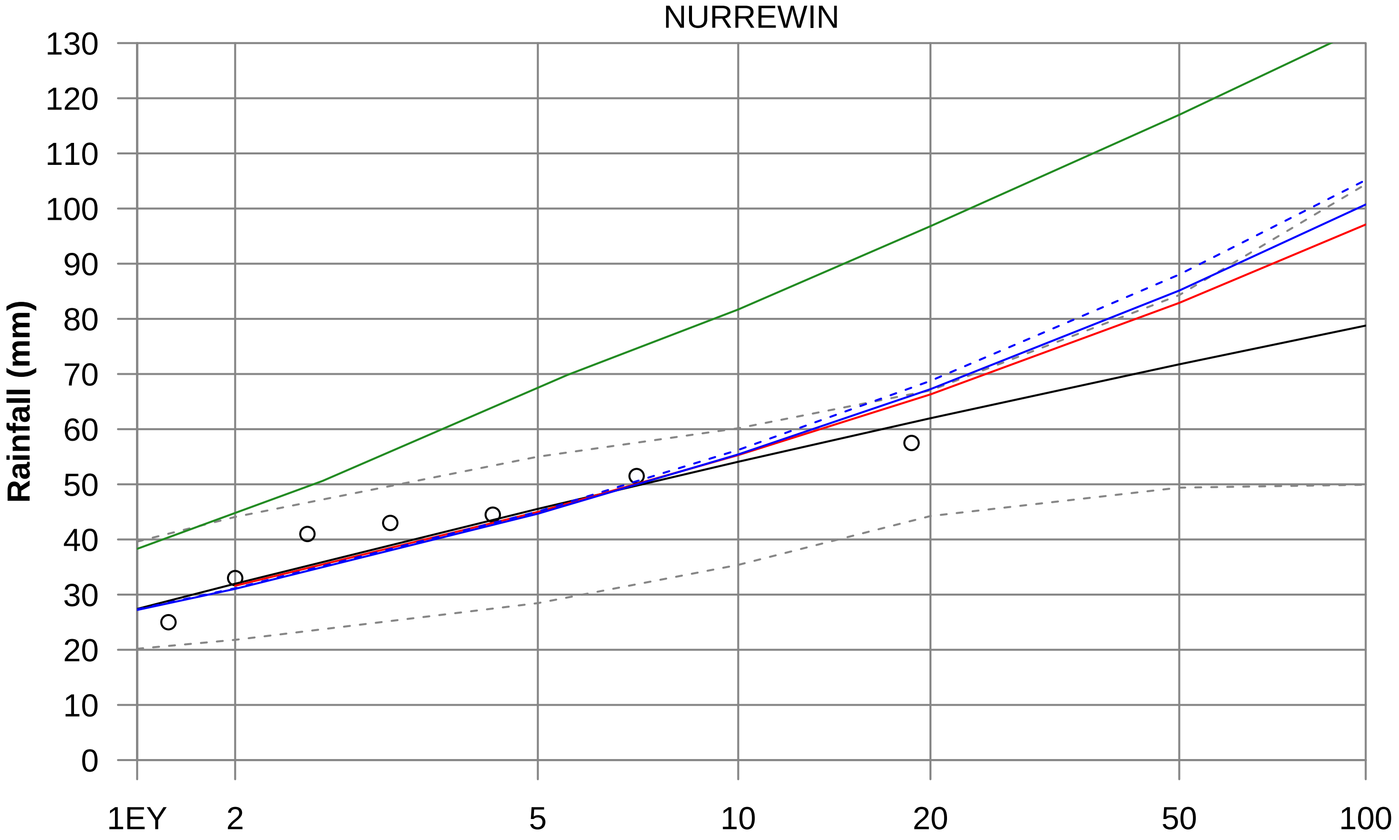
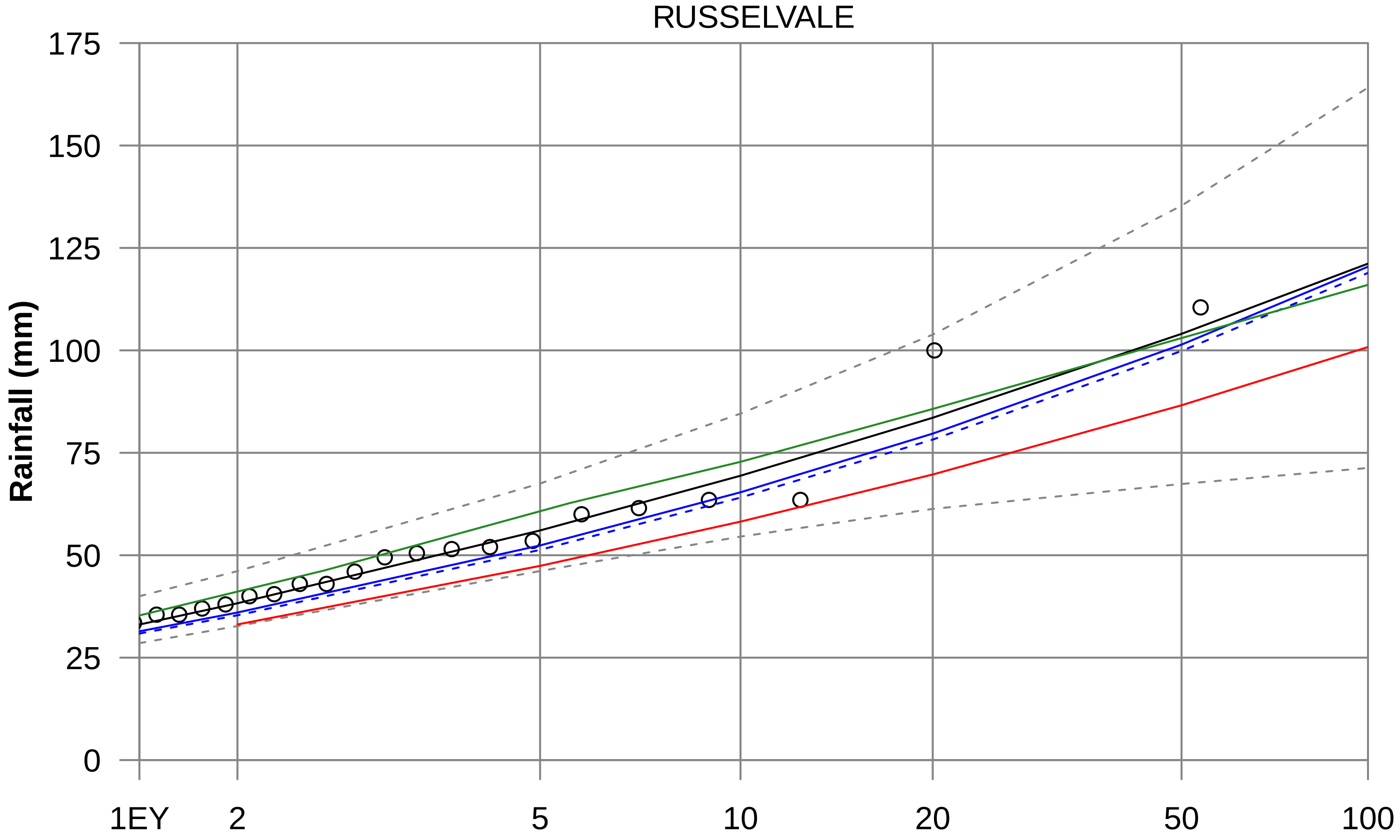
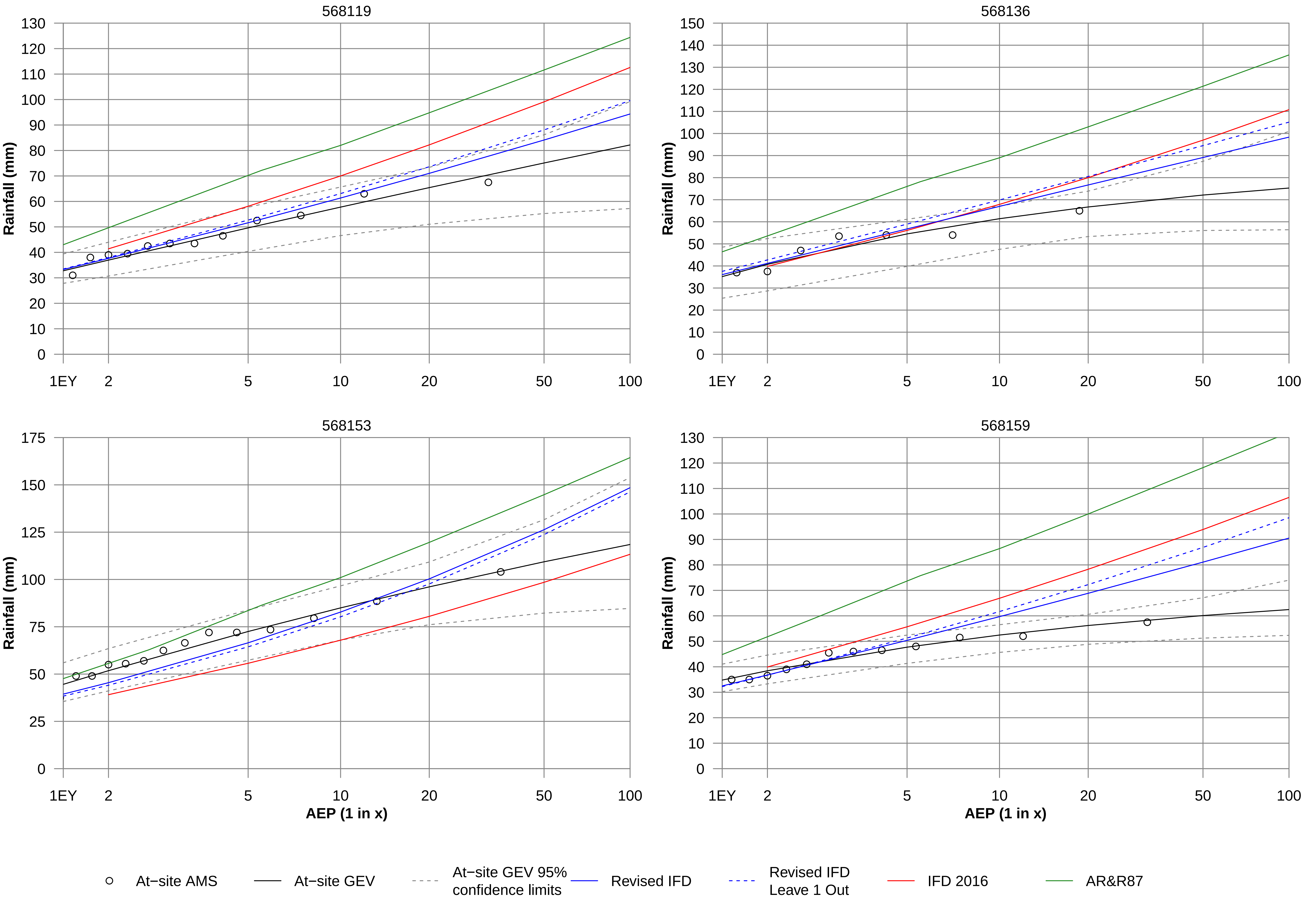


FIGURE A33
WOLLONGONG AREA STATIONS
1 HOUR IFD COMPARISON





WOLLONGONG AREA STATIONS
2 HOUR IFD COMPARISON



WOLLONGONG AREA STATIONS
2 HOUR IFD COMPARISON

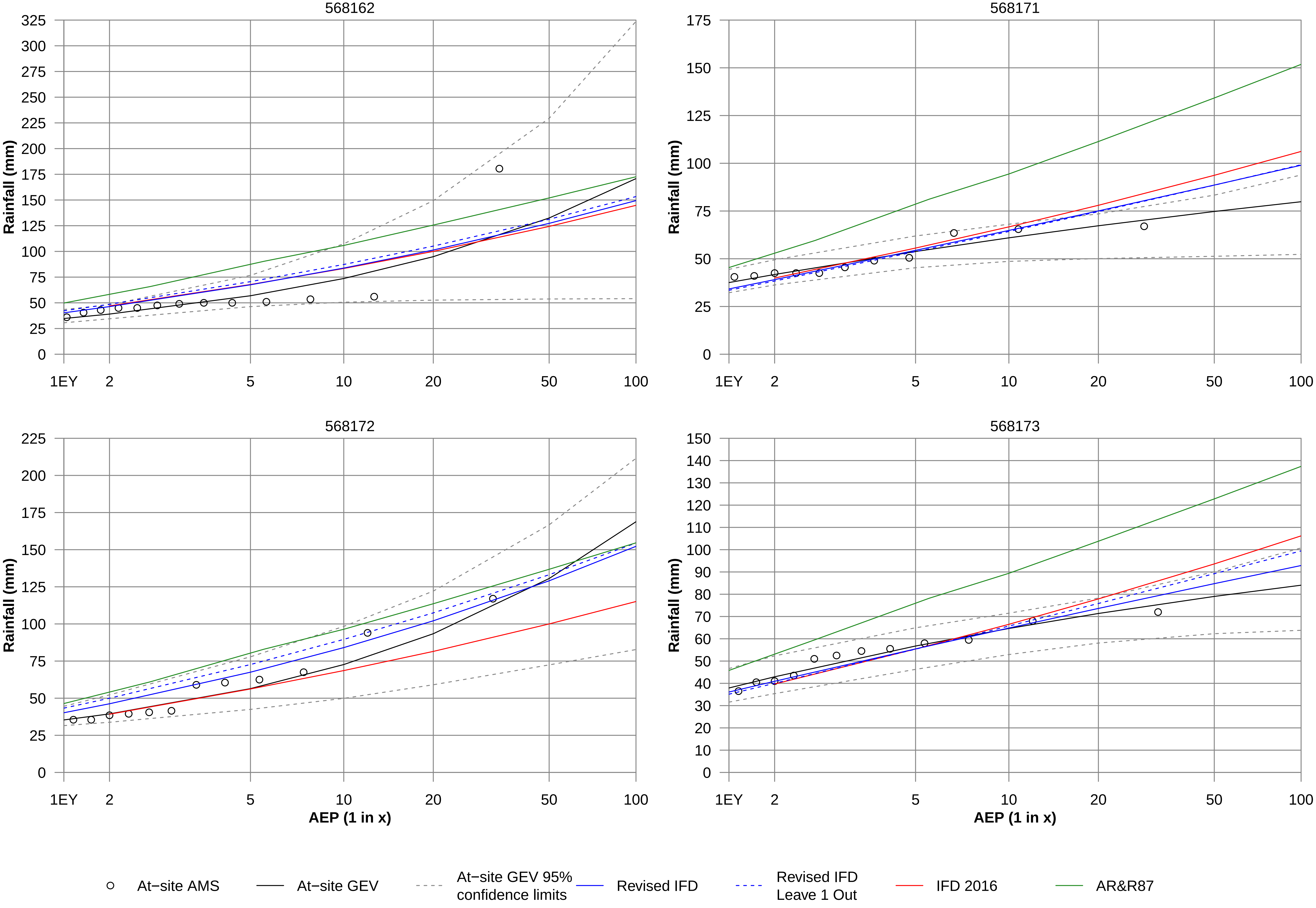
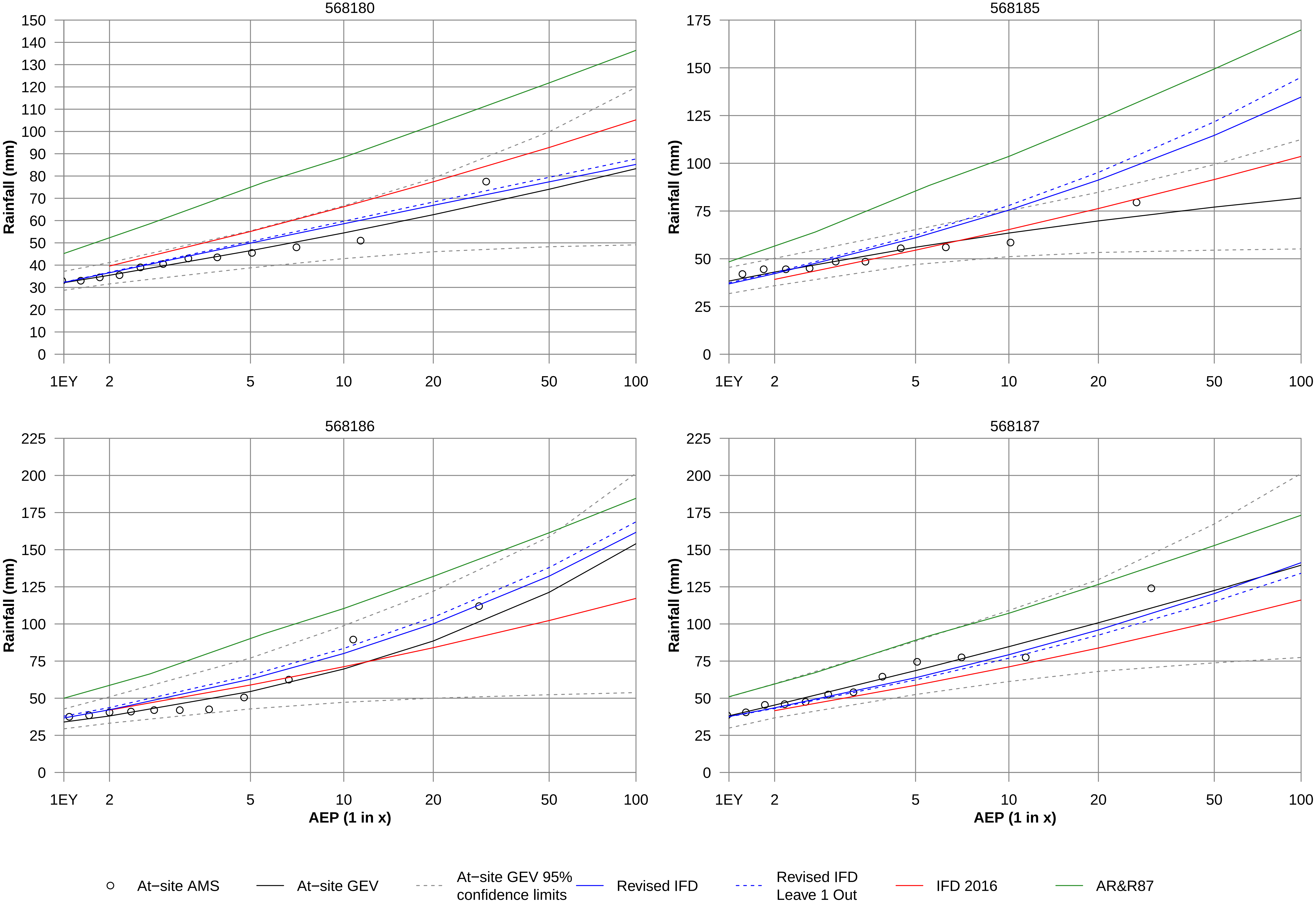


FIGURE A36

WOLLONGONG AREA STATIONS

2 HOUR IFD COMPARISON



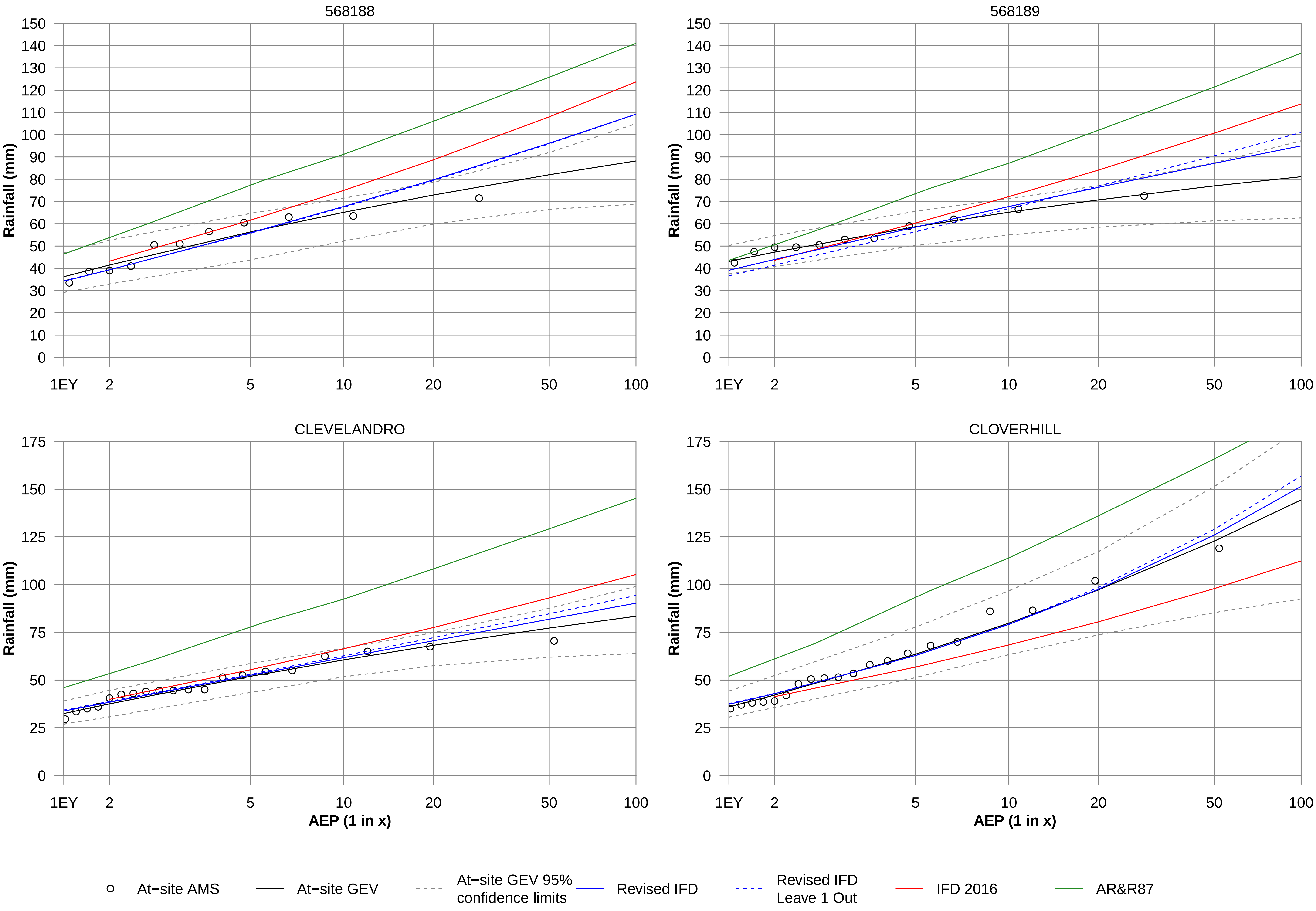
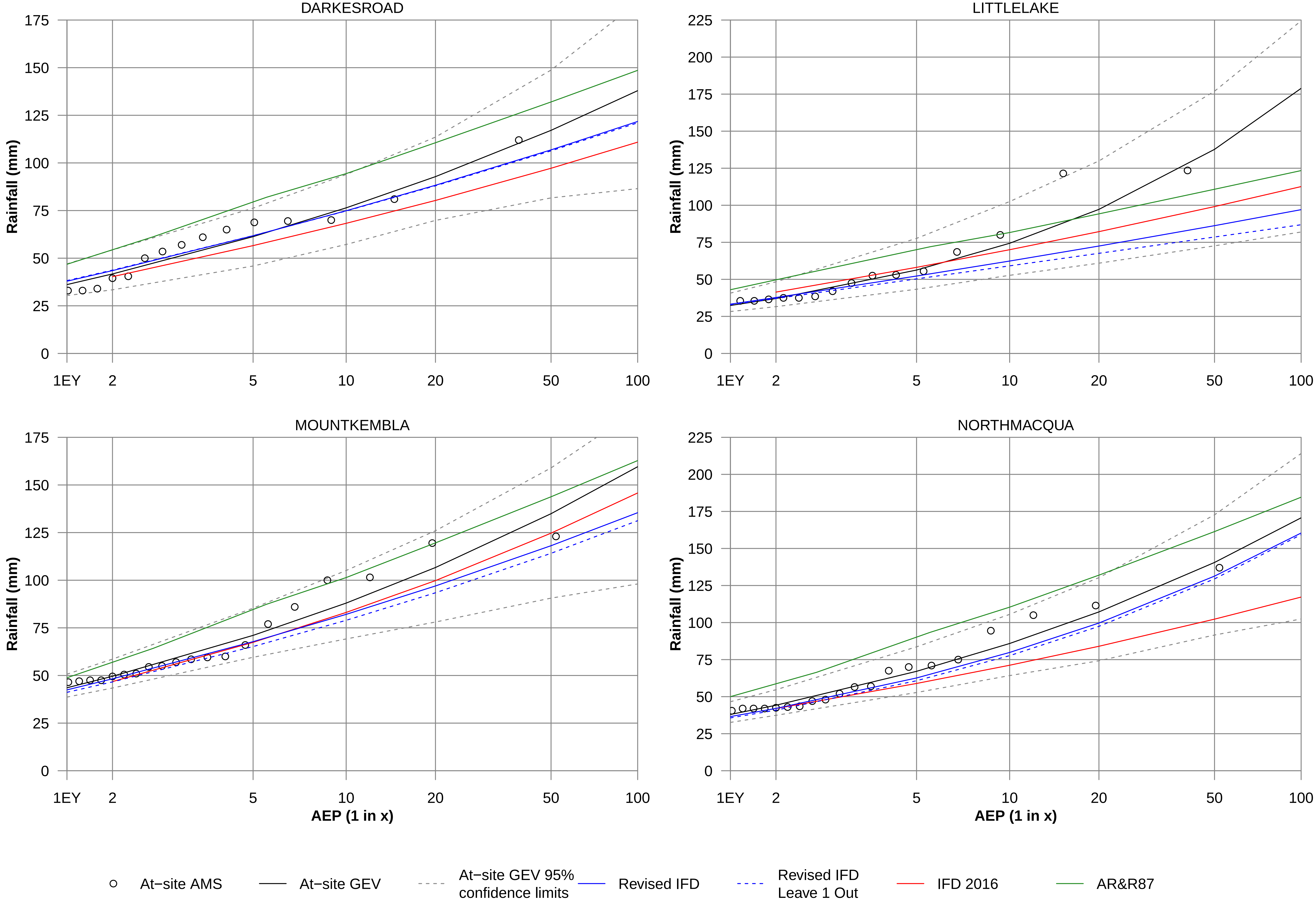

568188
568189
CLEVELANDRO
CLOVERHILL
Rainfall (mm)
AEP (1 in x)
1EY
2
5
10
20
50
100
At−site AMS
At−site GEV
At−site GEV 95% confidence limits
Revised IFD
Revised IFD Leave 1 Out
IFD 2016
AR&R87

FIGURE A38
WOLLONGONG AREA STATIONS
2 HOUR IFD COMPARISON



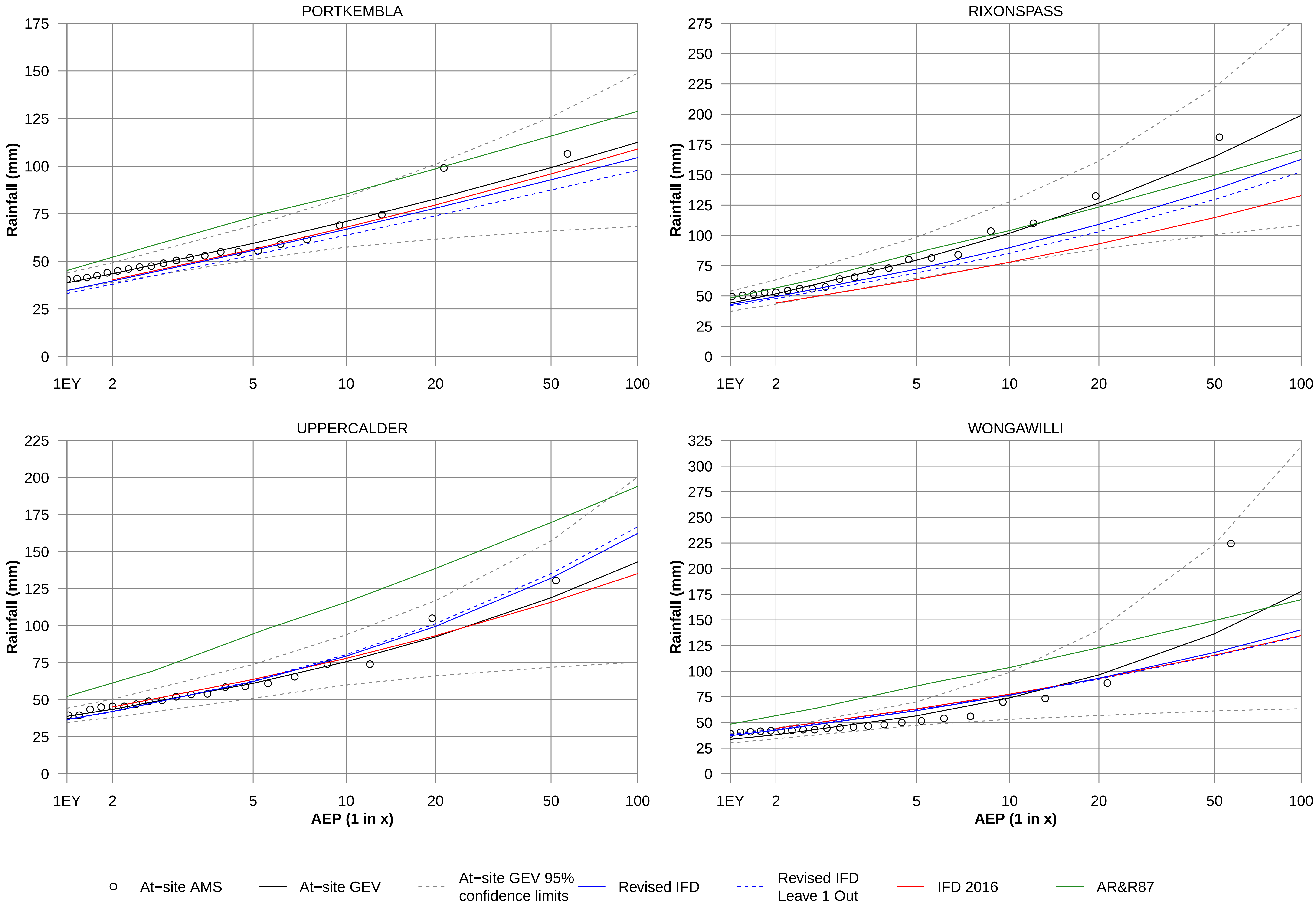

PORTKEMBLA
RIXONSPASS
UPPERCALDER
WONGAWILLI
Rainfall (mm)
AEP (1 in x)
1EY
2
5
10
20
50
100
At−site AMS
At−site GEV
At−site GEV 95% confidence limits
Revised IFD
Revised IFD Leave 1 Out
IFD 2016
AR&R87

FIGURE A40
WOLLONGONG AREA STATIONS
2 HOUR IFD COMPARISON

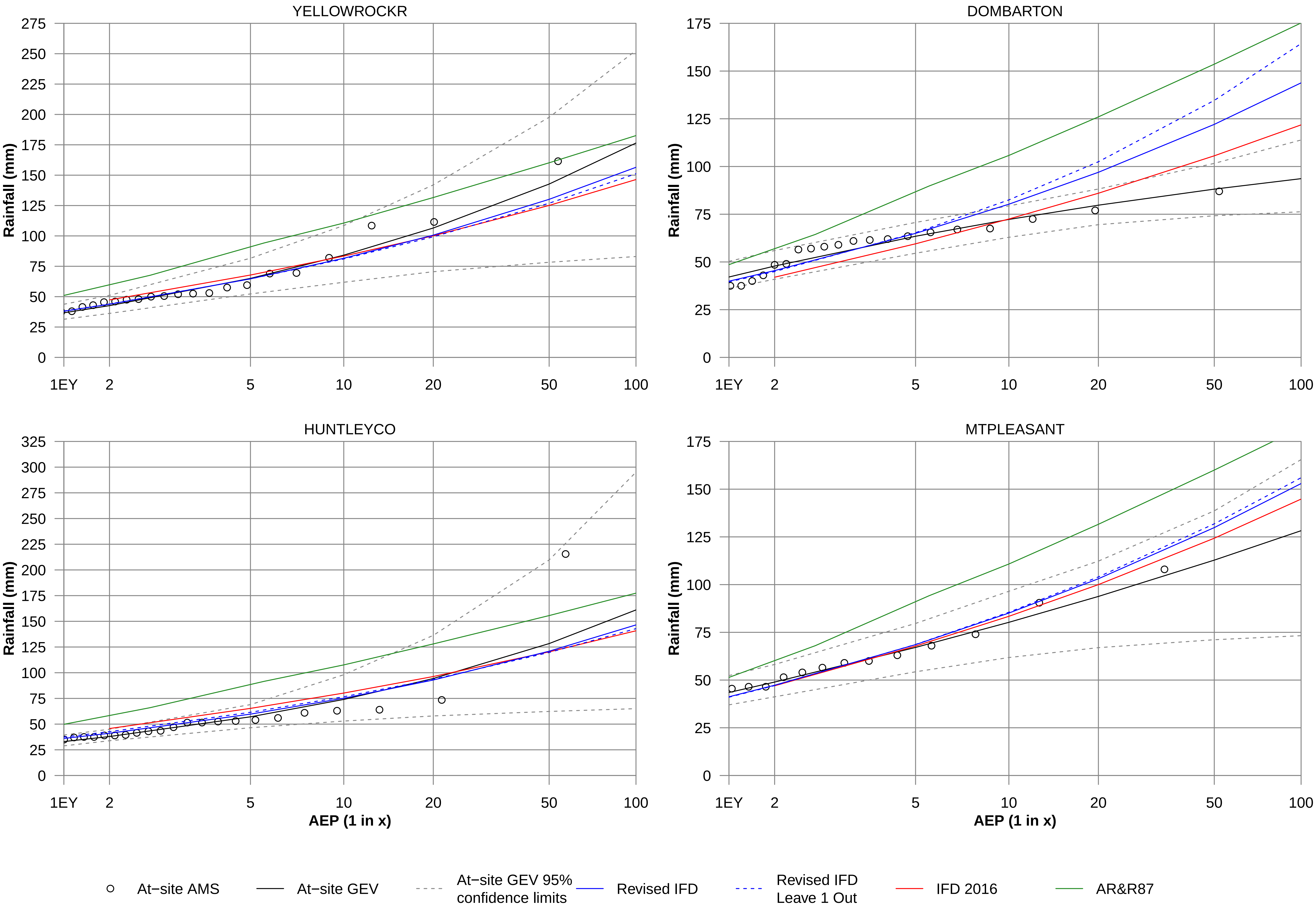
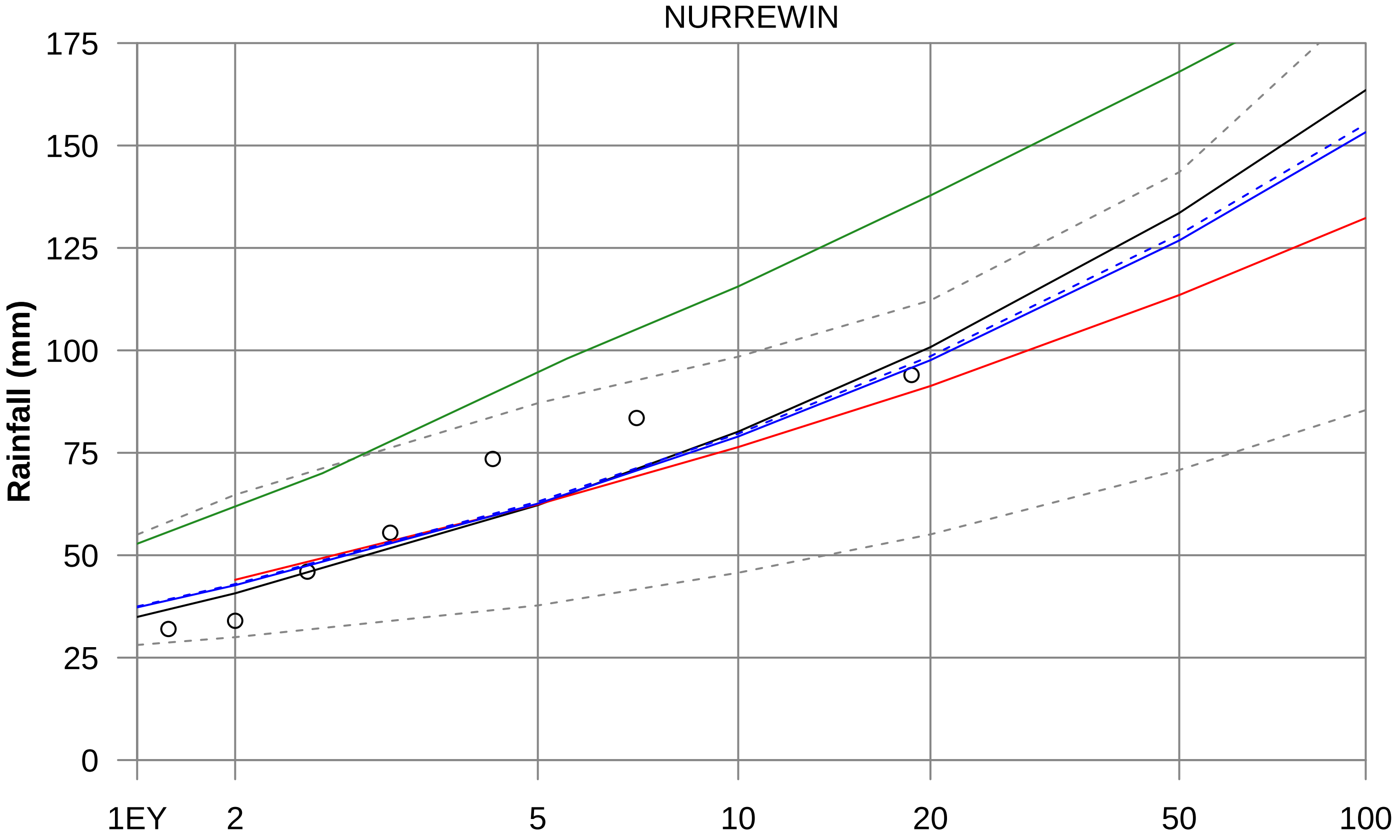


FIGURE A41
WOLLONGONG AREA STATIONS
2 HOUR IFD COMPARISON



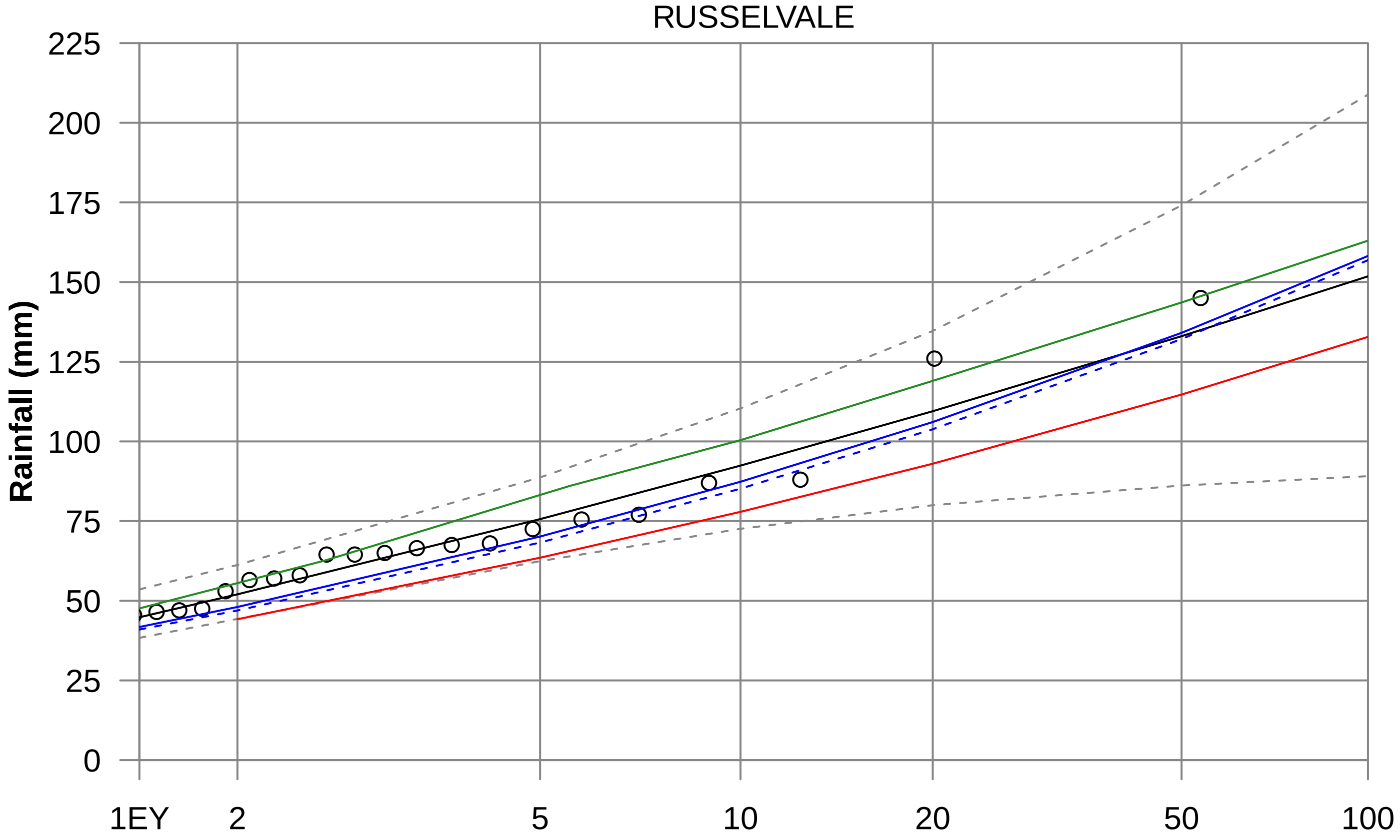


FIGURE A42
WOLLONGONG AREA STATIONS
3 HOUR IFD COMPARISON

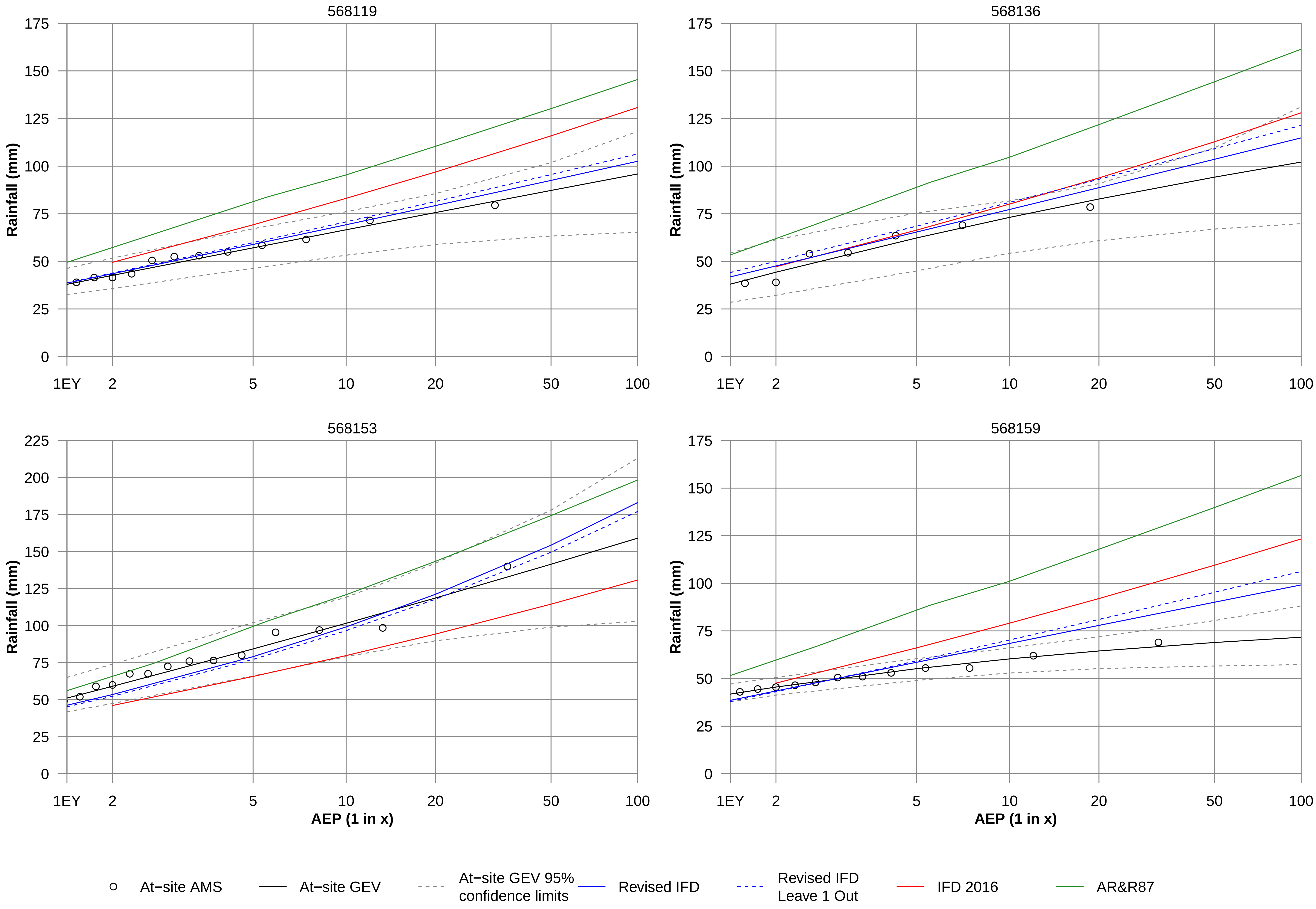
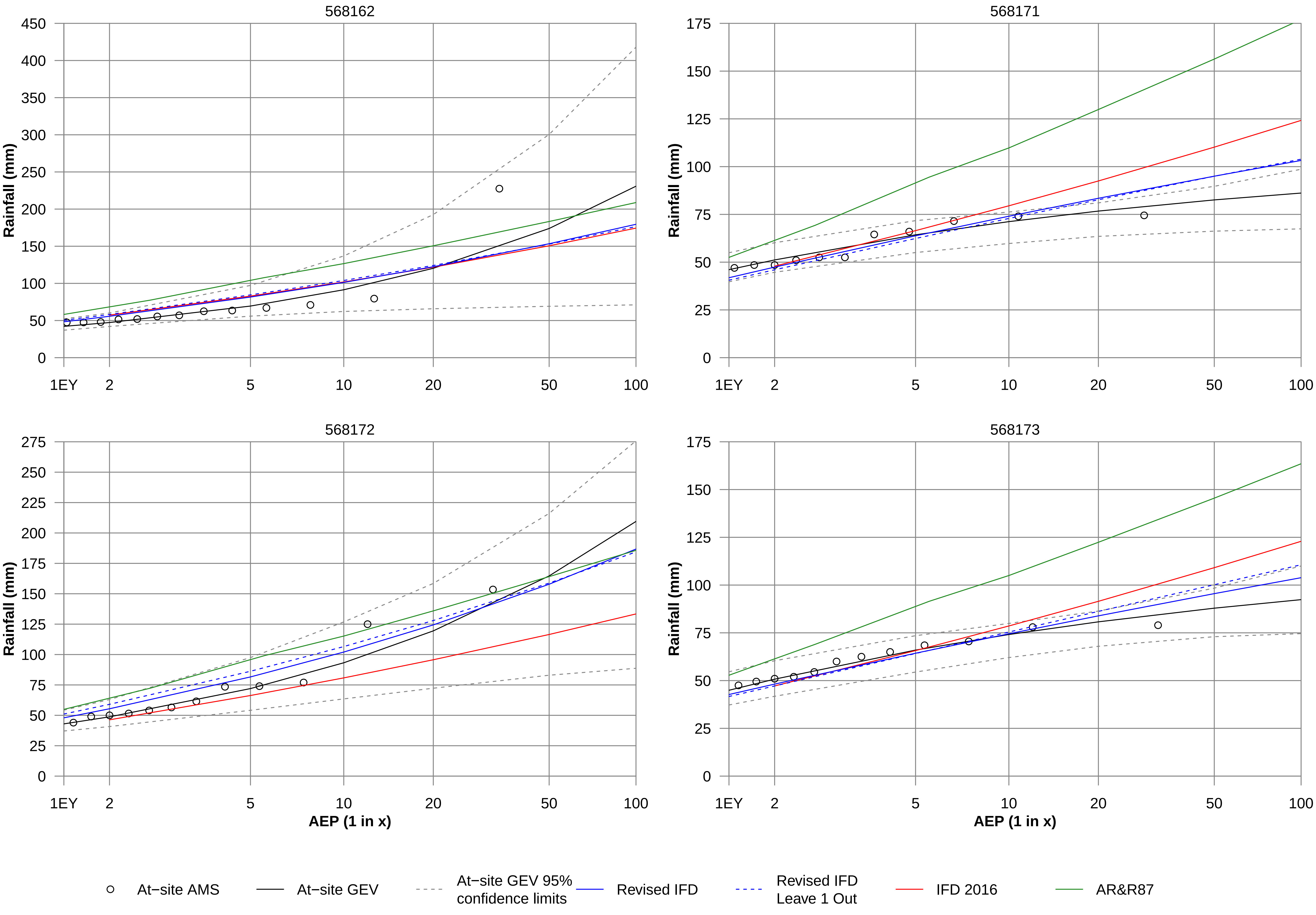


FIGURE A43
WOLLONGONG AREA STATIONS
3 HOUR IFD COMPARISON



WOLLONGONG AREA STATIONS
3 HOUR IFD COMPARISON

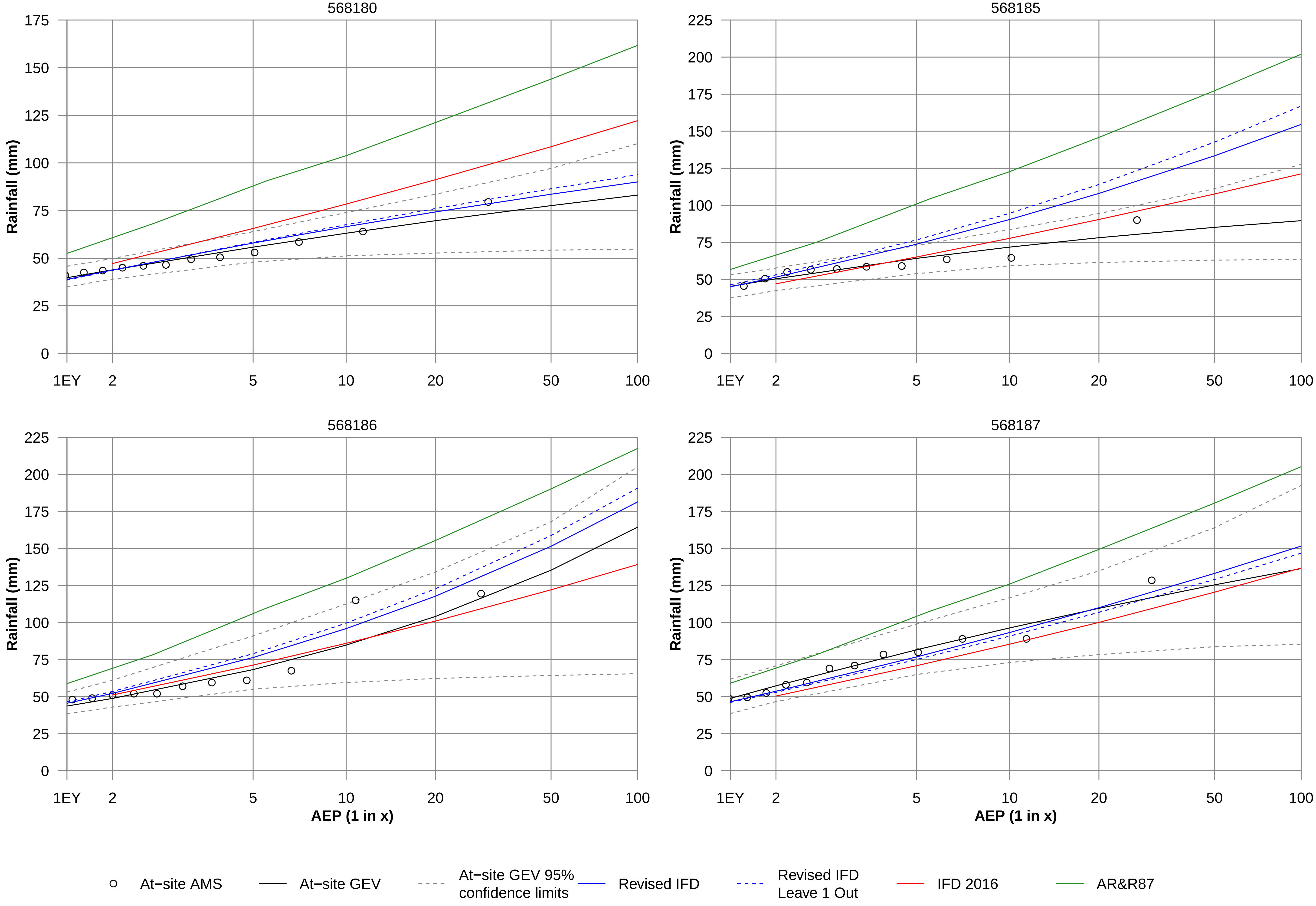


FIGURE A45
WOLLONGONG AREA STATIONS
3 HOUR IFD COMPARISON

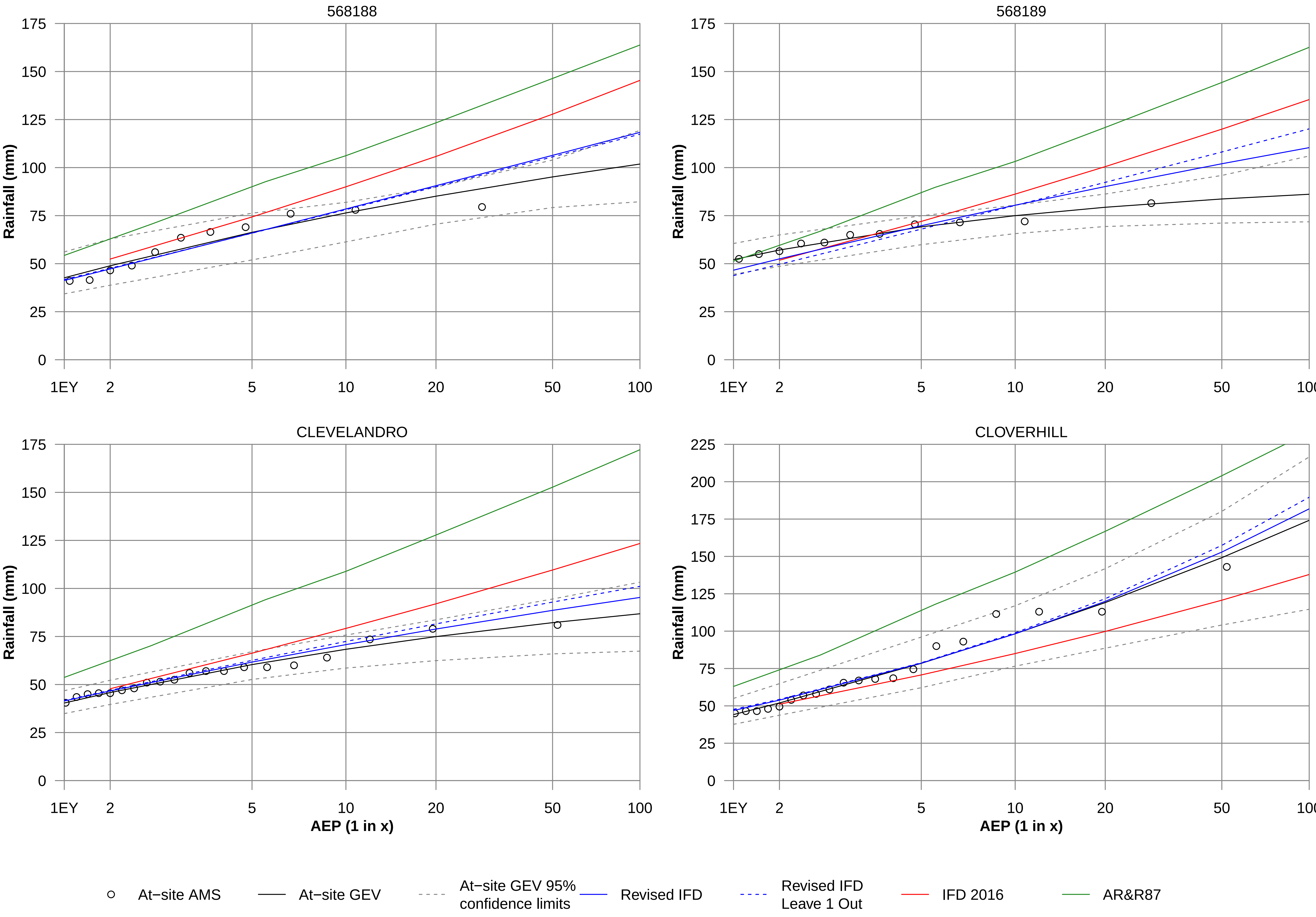


FIGURE A46
WOLLONGONG AREA STATIONS
3 HOUR IFD COMPARISON

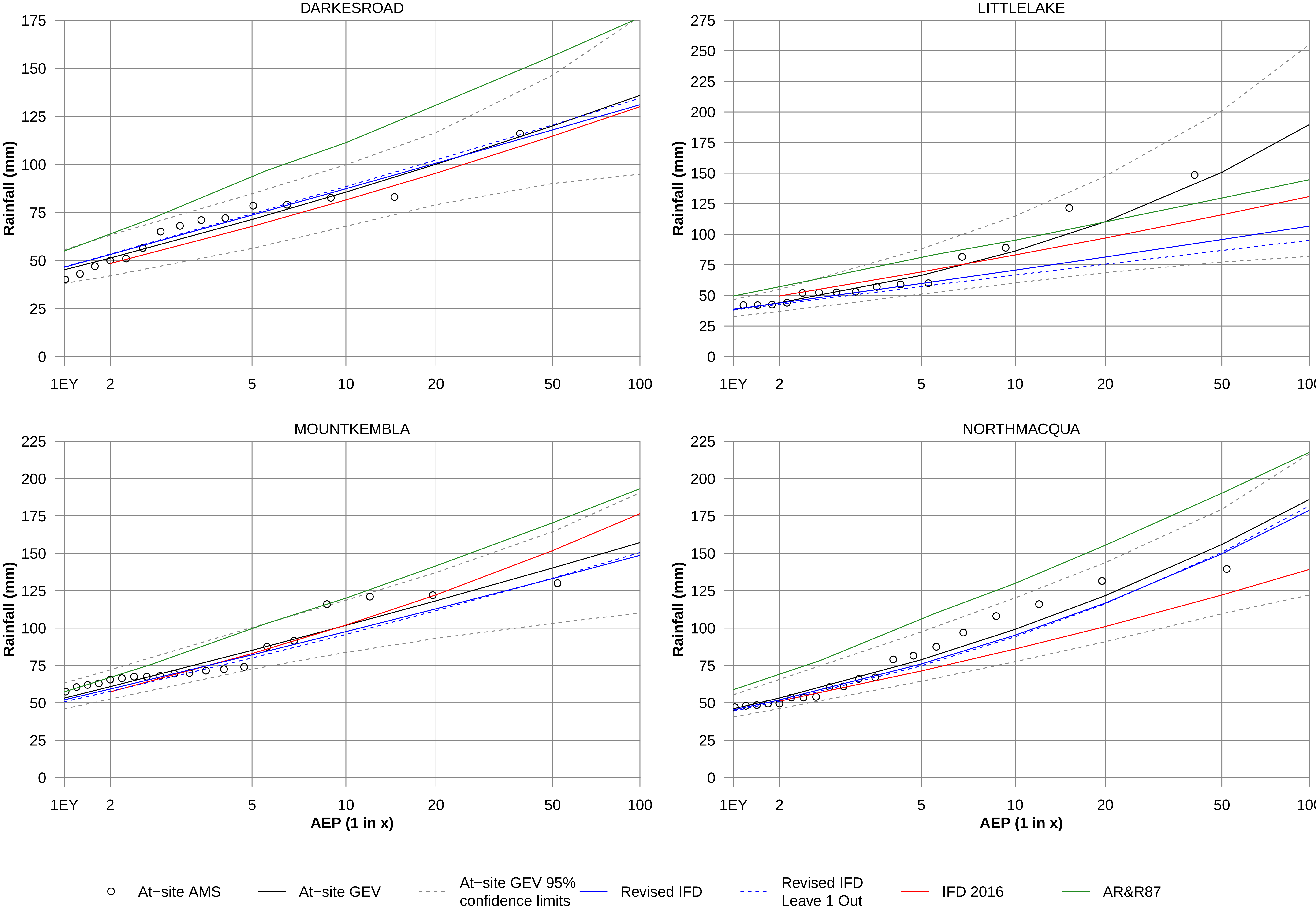


FIGURE A47
WOLLONGONG AREA STATIONS
3 HOUR IFD COMPARISON

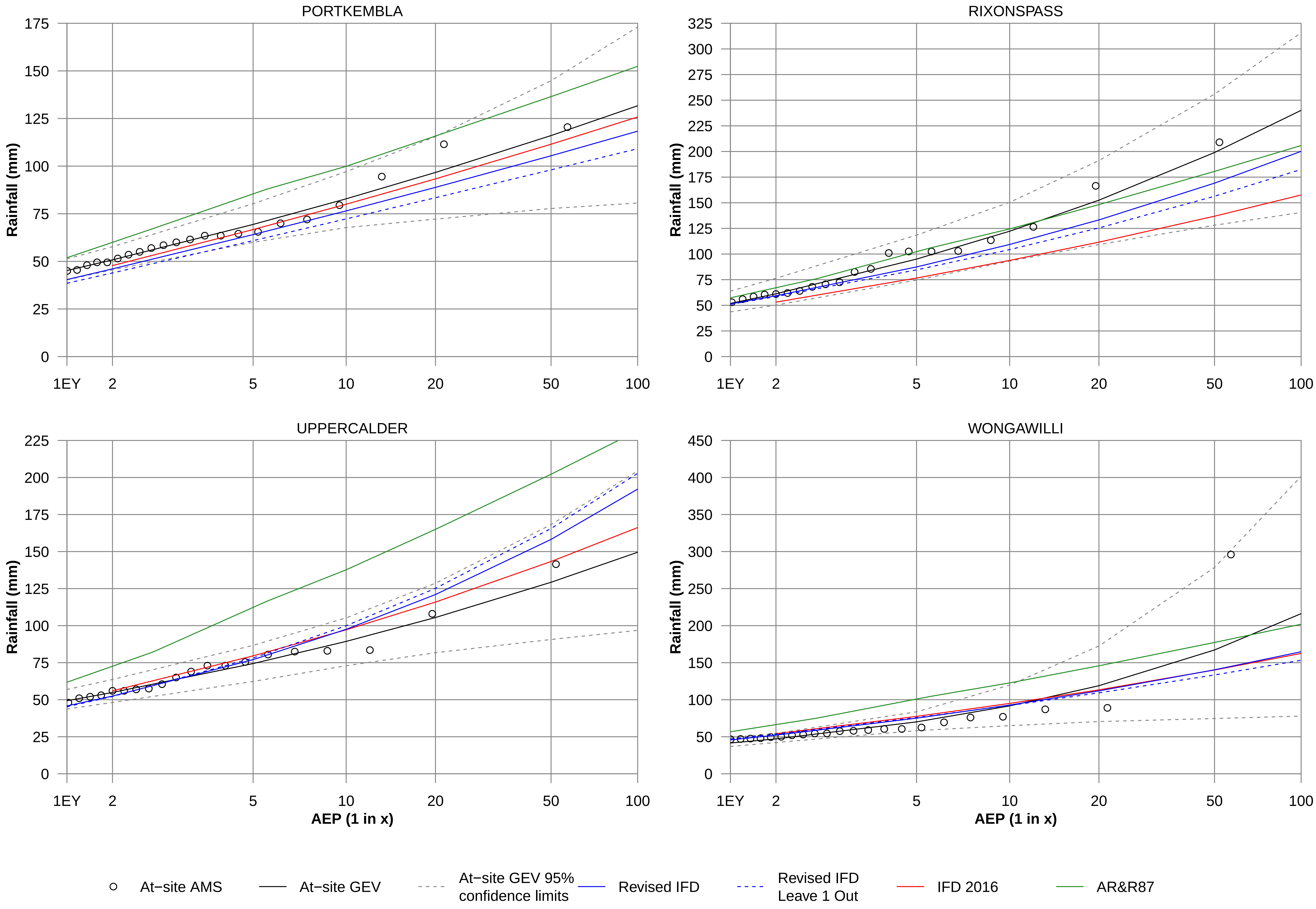


FIGURE A48
WOLLONGONG AREA STATIONS
3 HOUR IFD COMPARISON

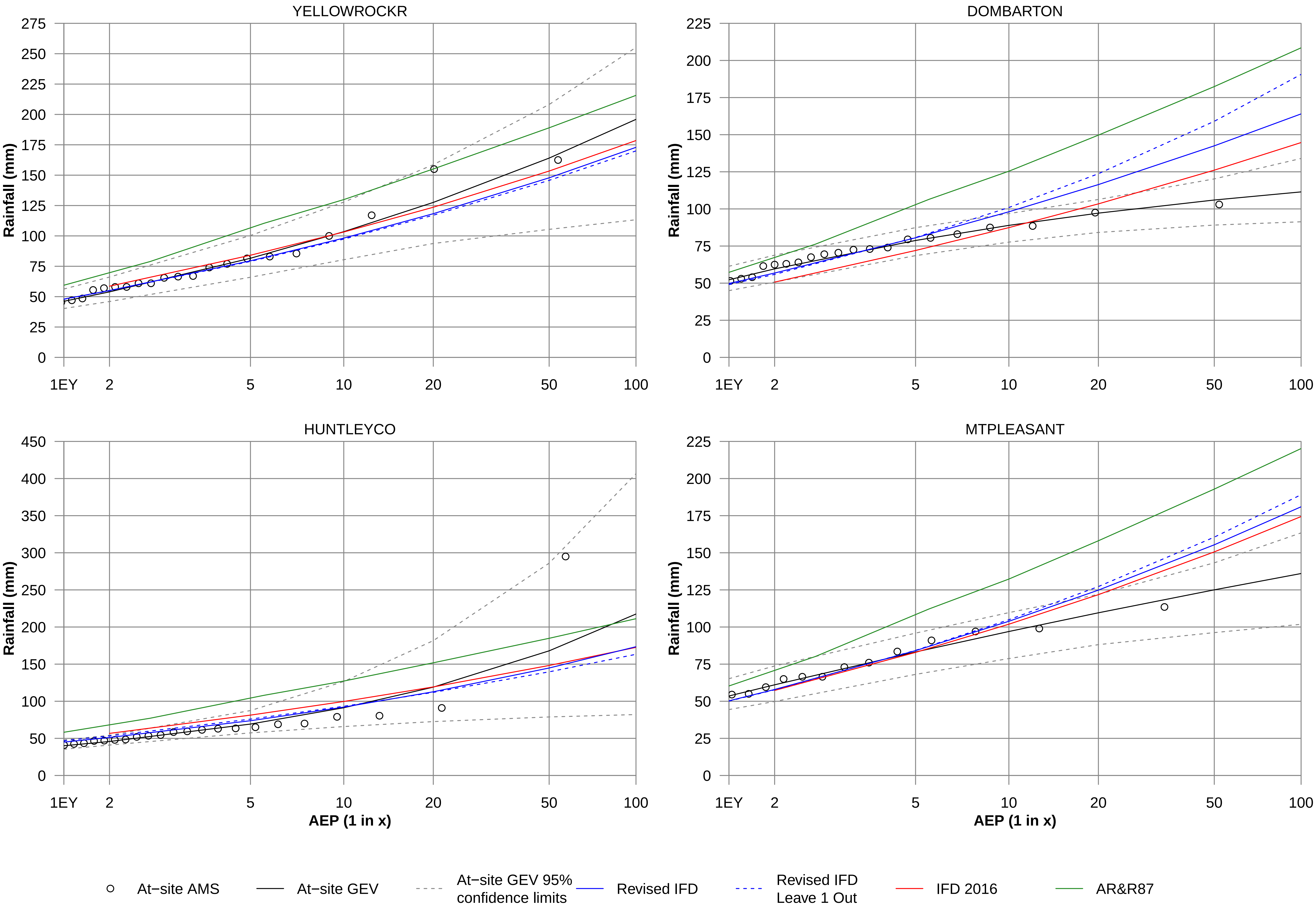
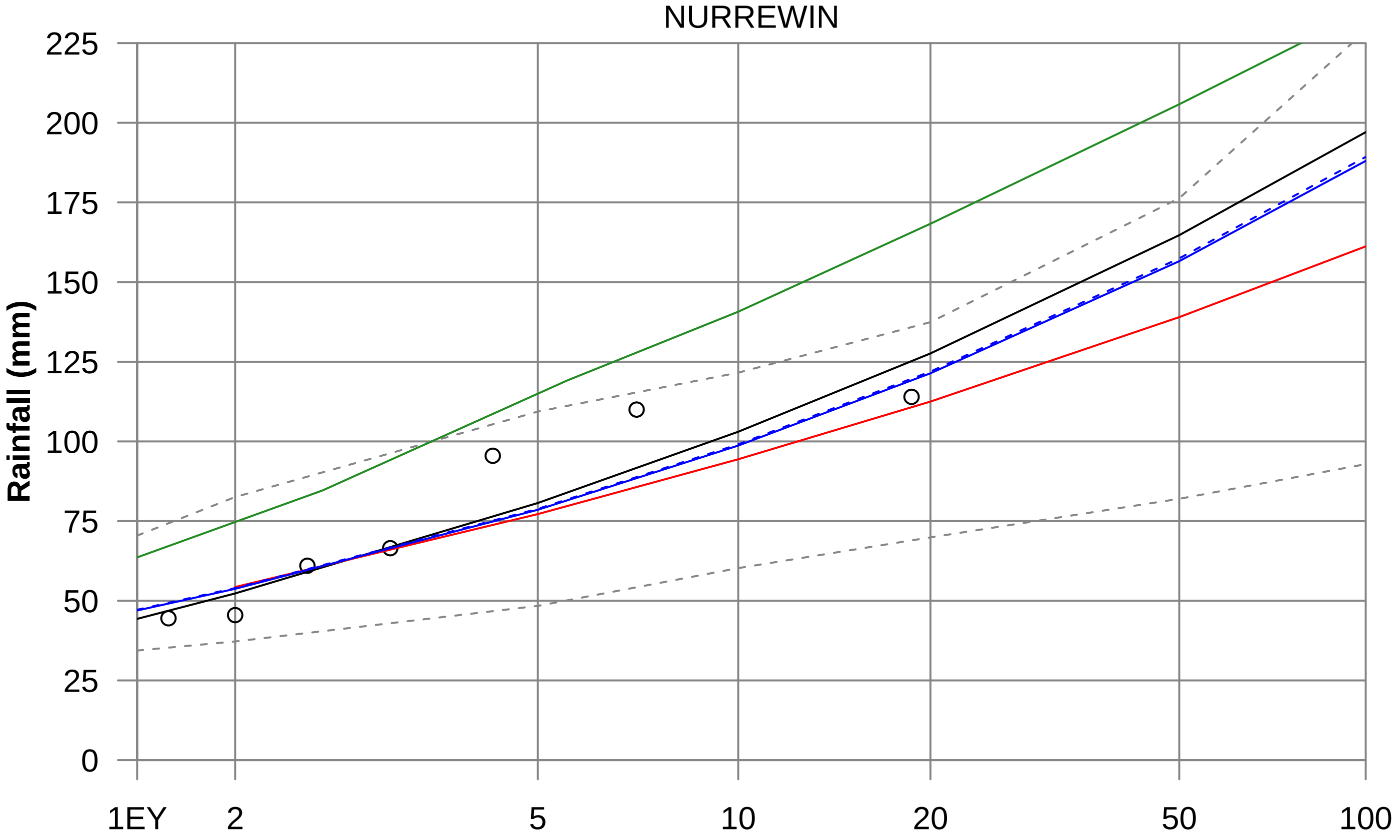
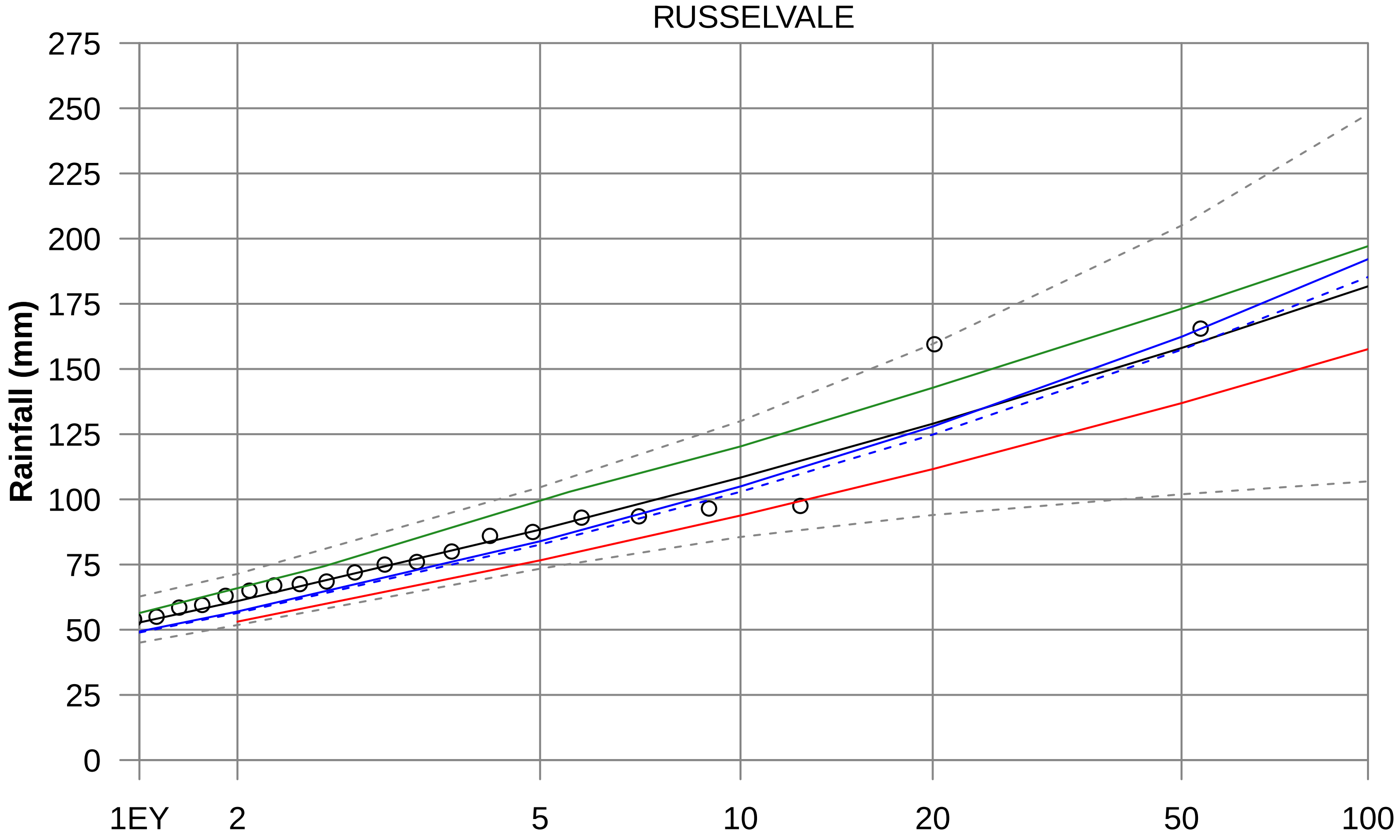


FIGURE A49
WOLLONGONG AREA STATIONS
3 HOUR IFD COMPARISON





WOLLONGONG AREA STATIONS
6 HOUR IFD COMPARISON

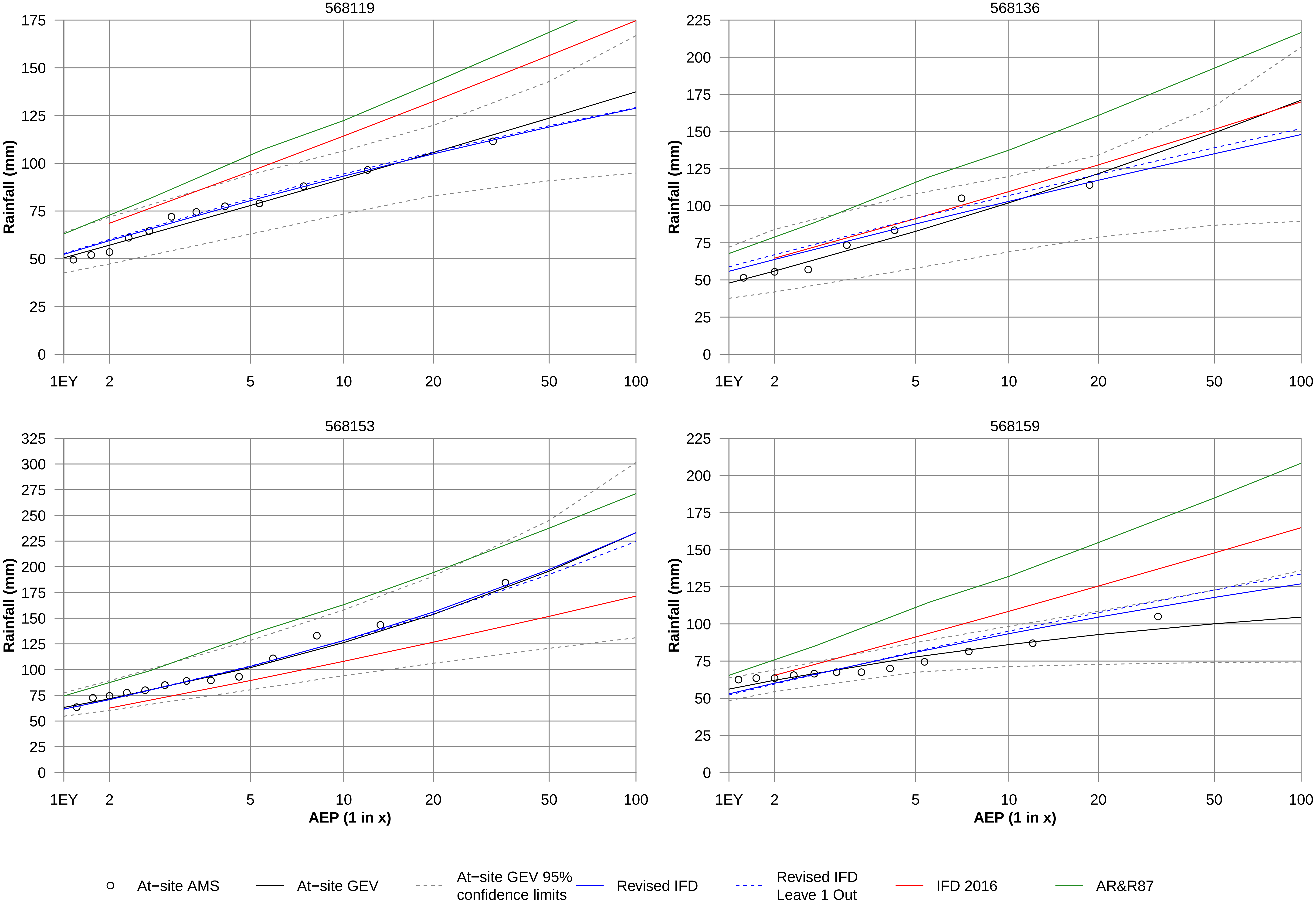


FIGURE A51
WOLLONGONG AREA STATIONS
6 HOUR IFD COMPARISON

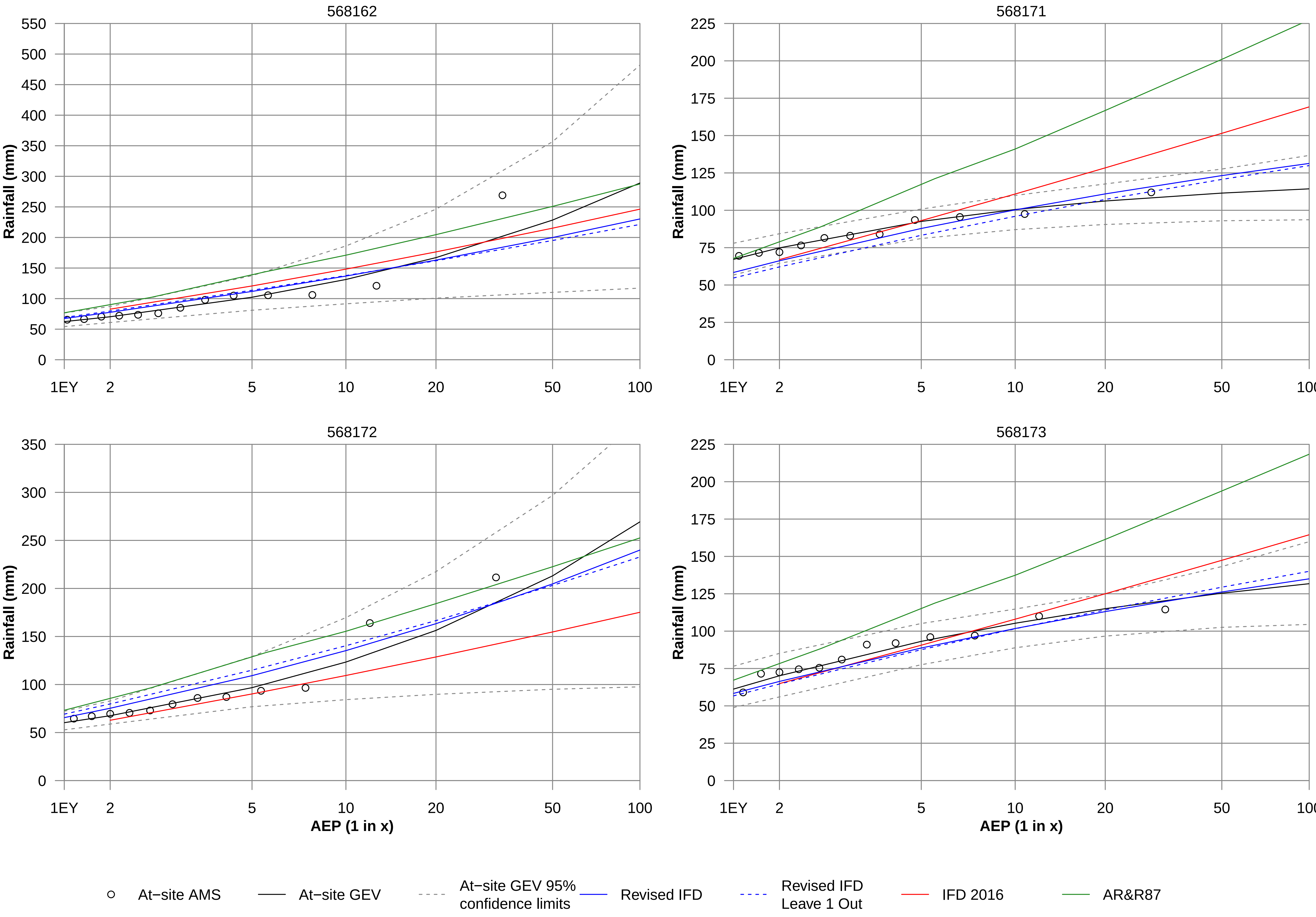


FIGURE A52

WOLLONGONG AREA STATIONS

6 HOUR IFD COMPARISON

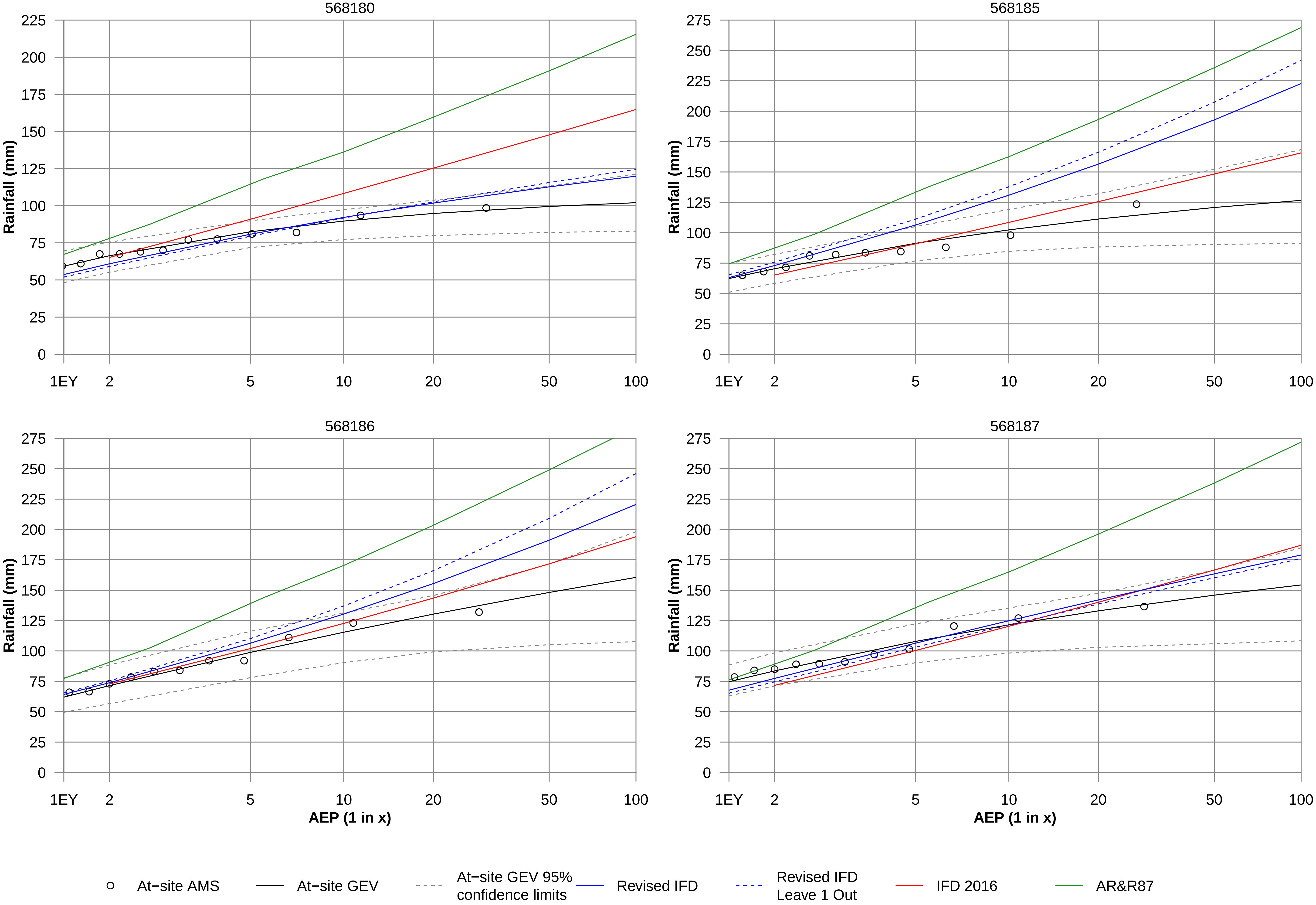


FIGURE A53
WOLLONGONG AREA STATIONS
6 HOUR IFD COMPARISON

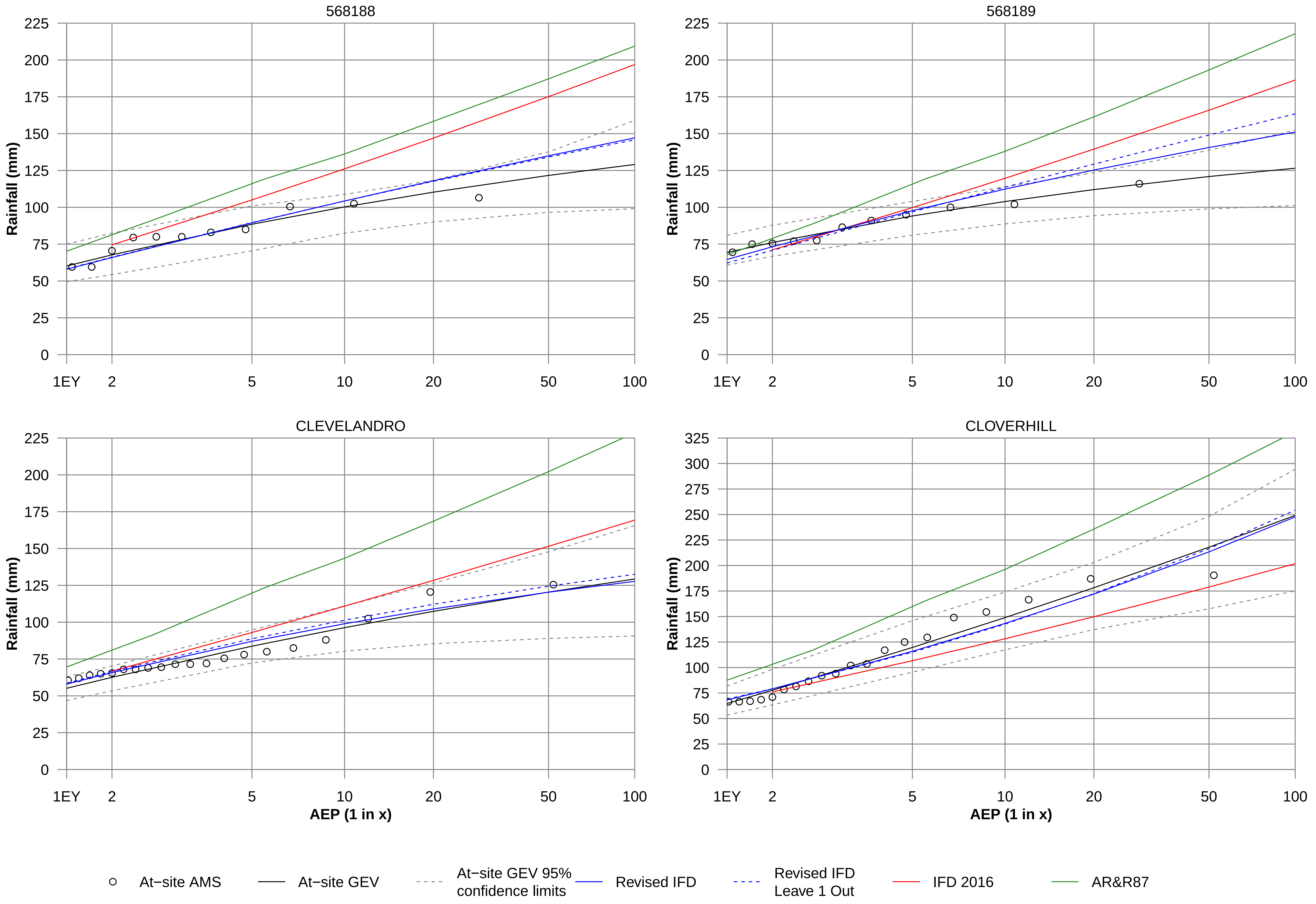


FIGURE A54
WOLLONGONG AREA STATIONS
6 HOUR IFD COMPARISON

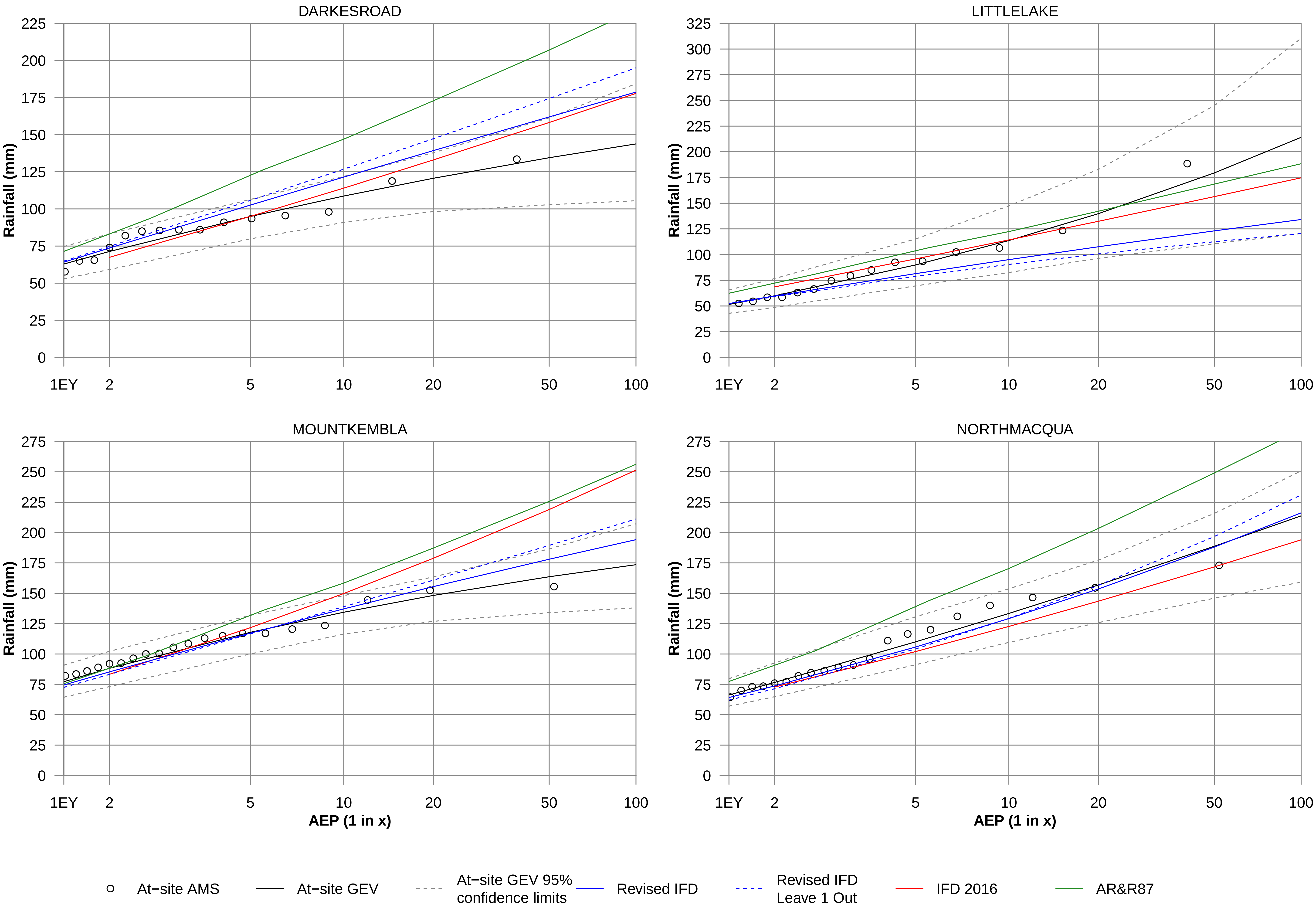


FIGURE A55
WOLLONGONG AREA STATIONS
6 HOUR IFD COMPARISON

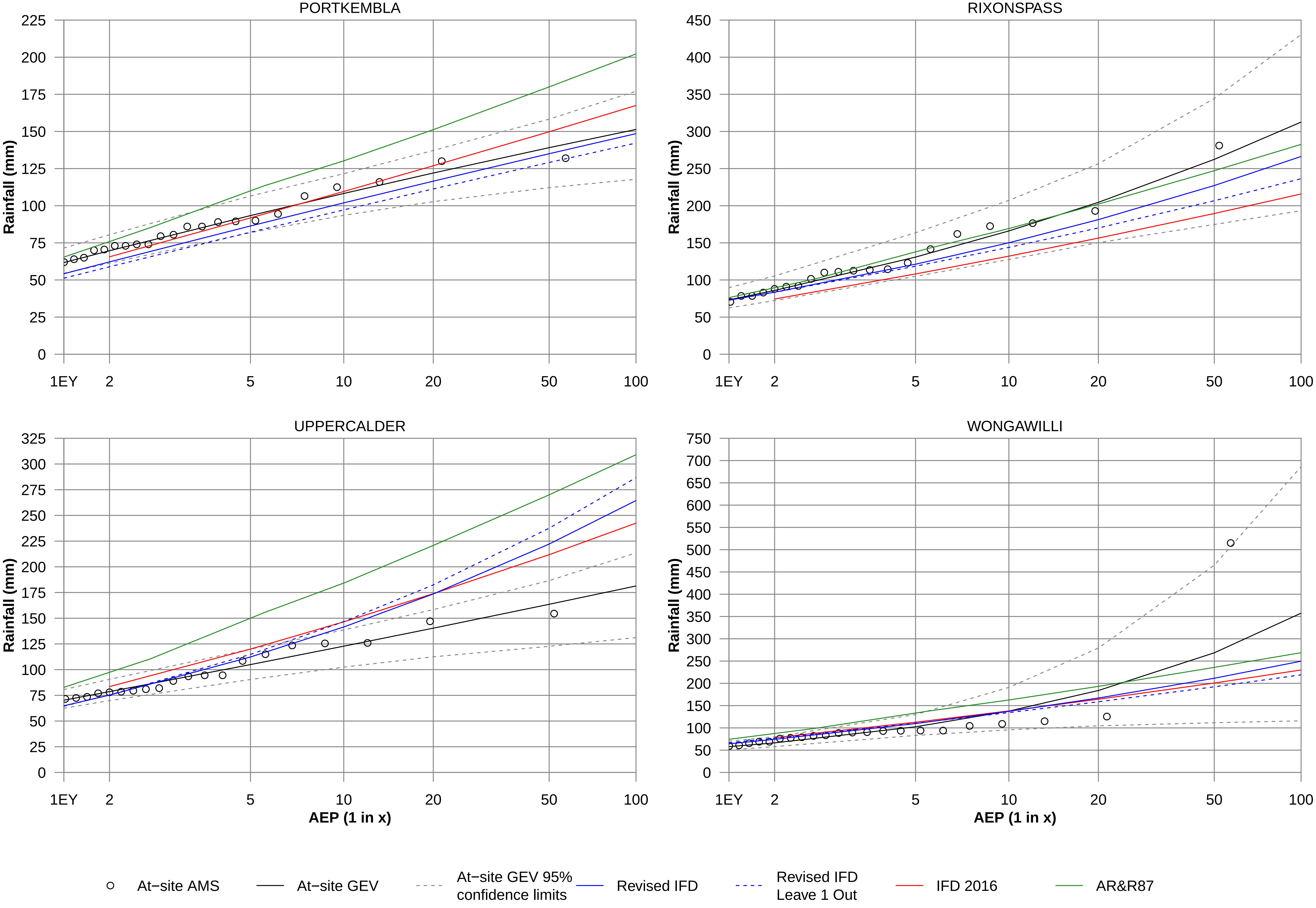


FIGURE A56
WOLLONGONG AREA STATIONS
6 HOUR IFD COMPARISON

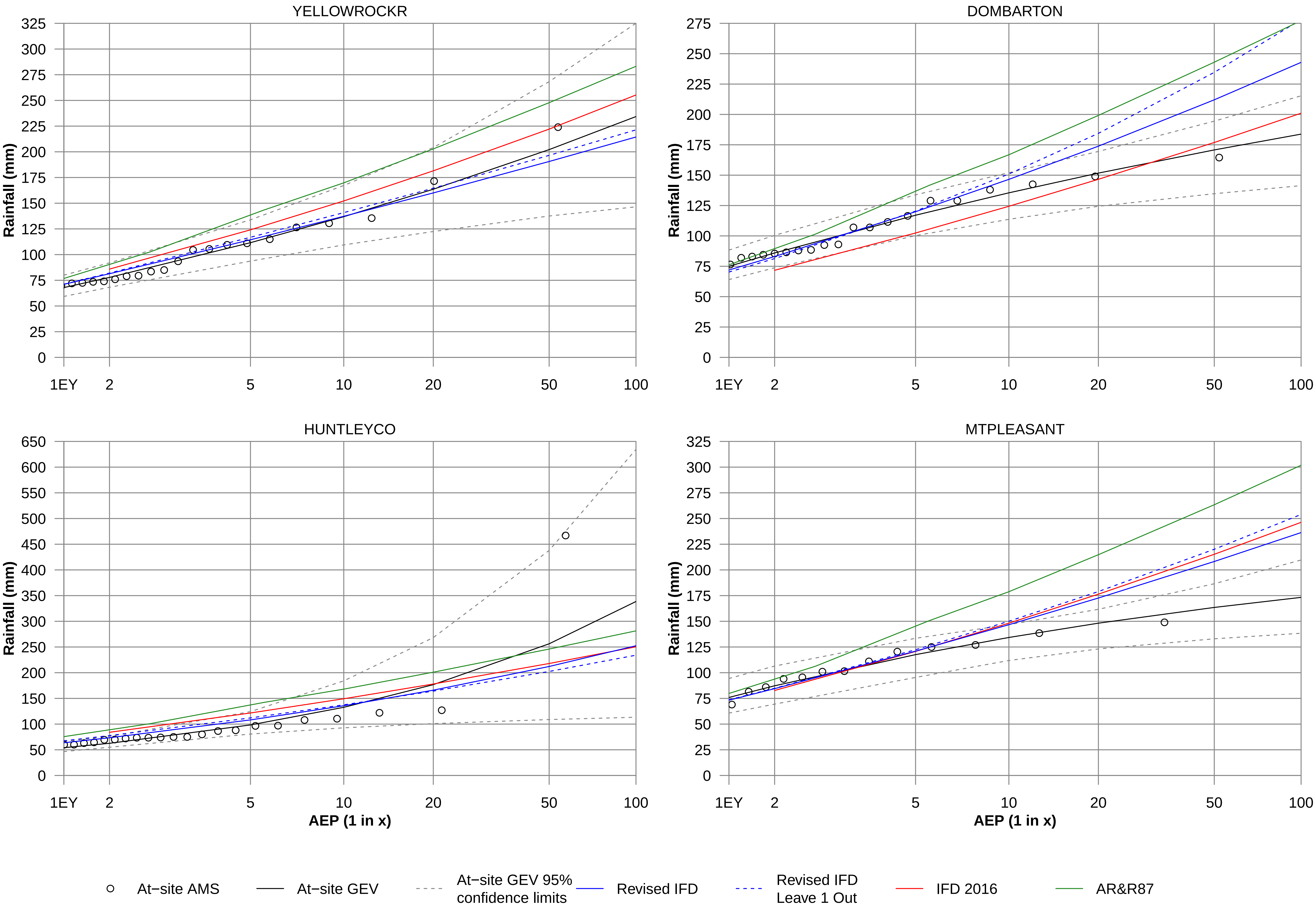


FIGURE A57
WOLLONGONG AREA STATIONS
6 HOUR IFD COMPARISON

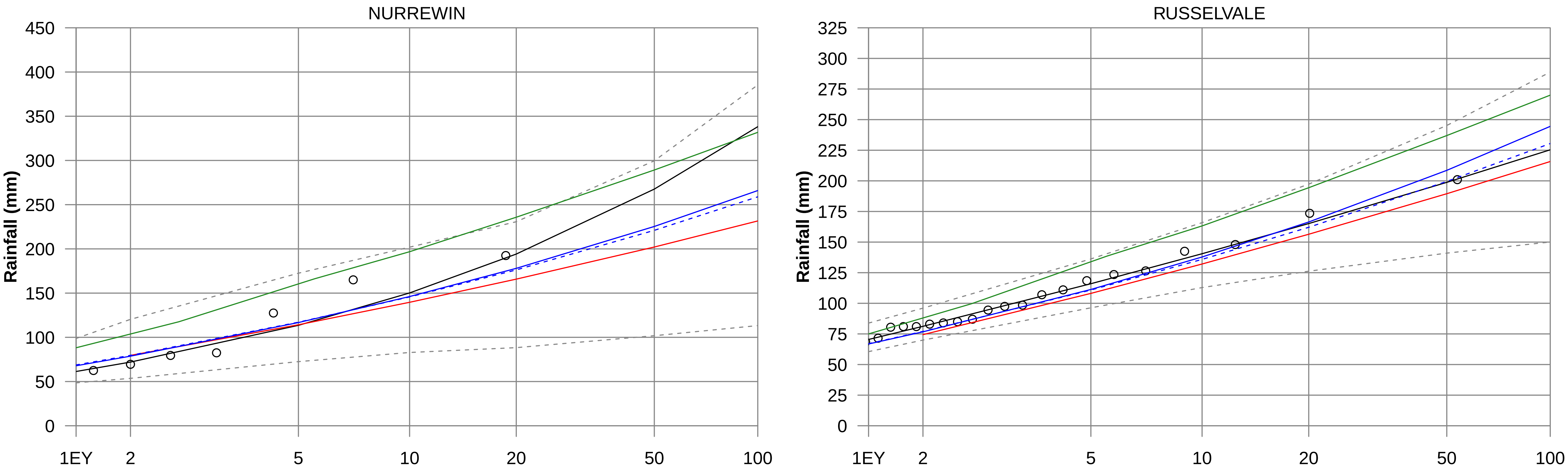
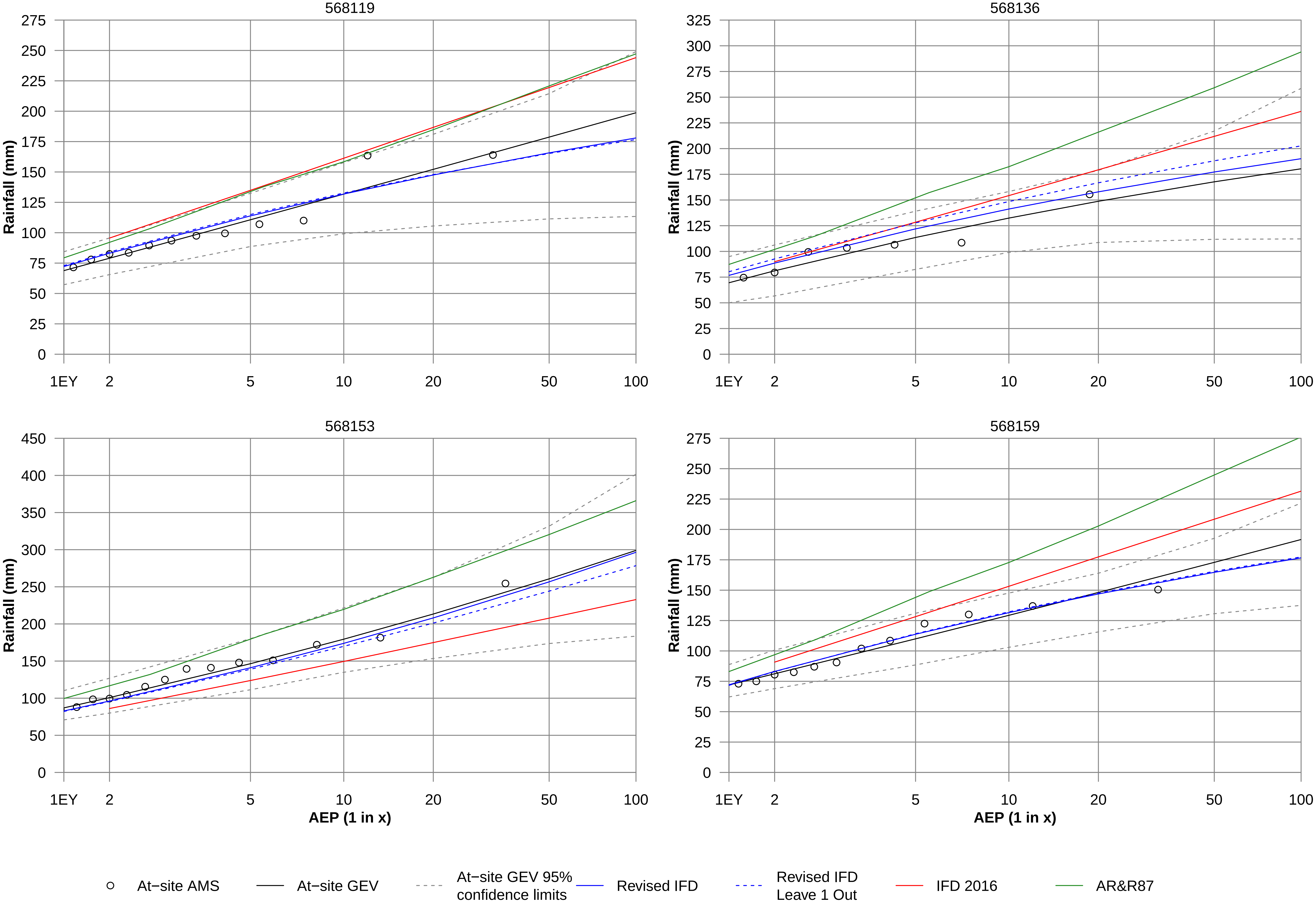
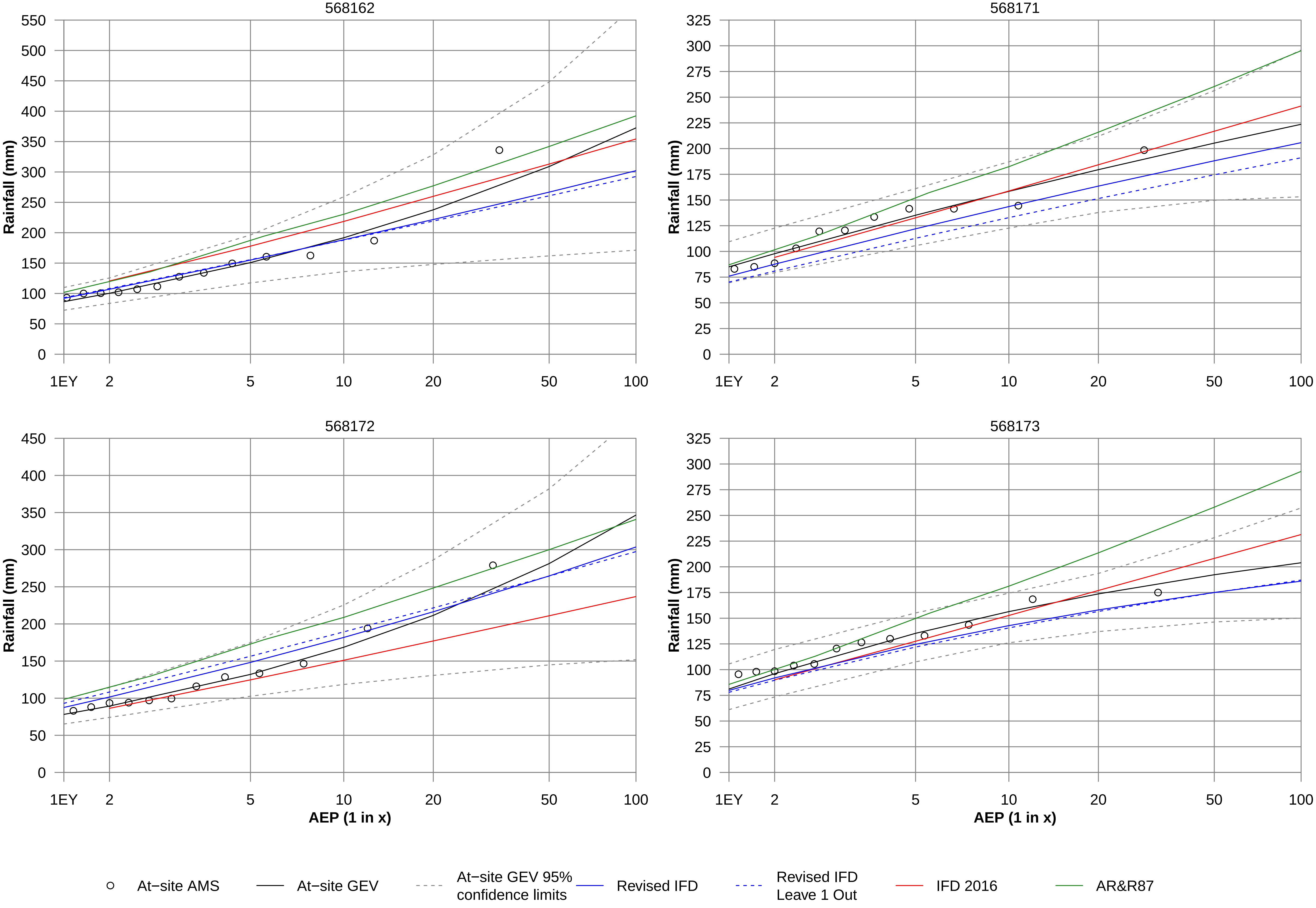


FIGURE A58
WOLLONGONG AREA STATIONS
12 HOUR IFD COMPARISON



WOLLONGONG AREA STATIONS
12 HOUR IFD COMPARISON



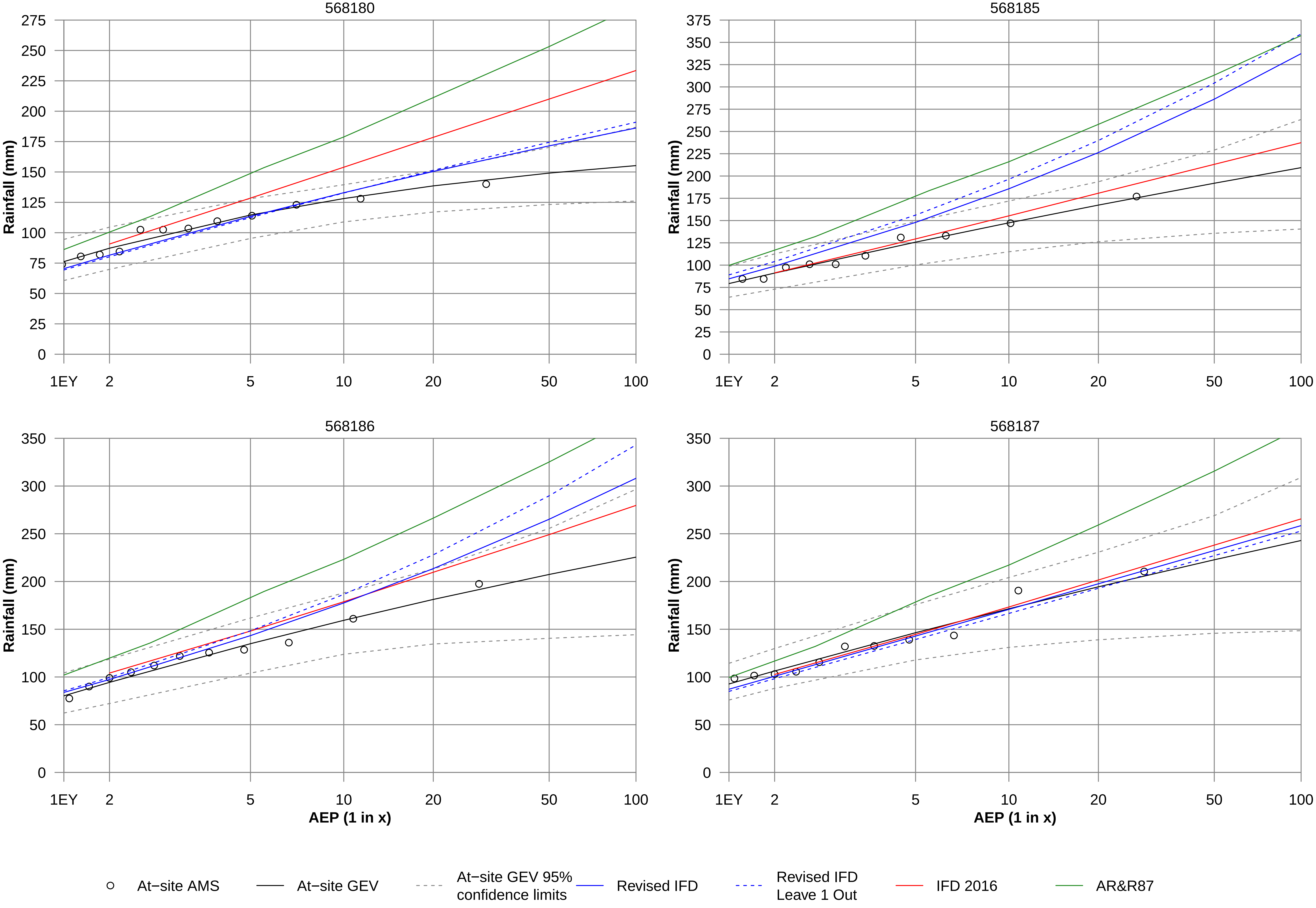

568180
568185
568186
568187
Rainfall (mm)
AEP (1 in x)
1EY
2
5
10
20
50
100
At−site AMS
At−site GEV
At−site GEV 95% confidence limits
Revised IFD
Revised IFD Leave 1 Out
IFD 2016
AR&R87

FIGURE A61
WOLLONGONG AREA STATIONS
12 HOUR IFD COMPARISON

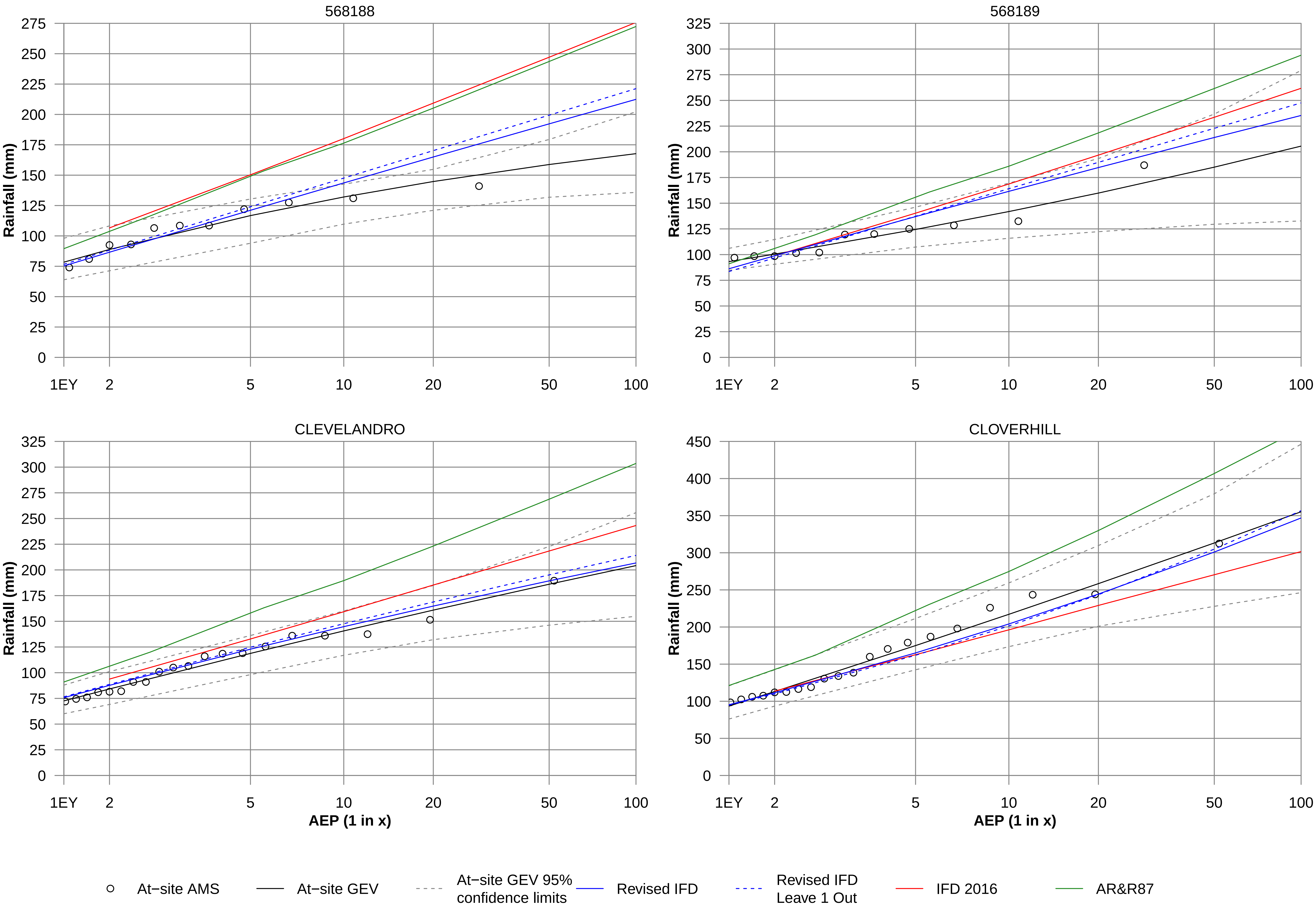


FIGURE A62
WOLLONGONG AREA STATIONS
12 HOUR IFD COMPARISON

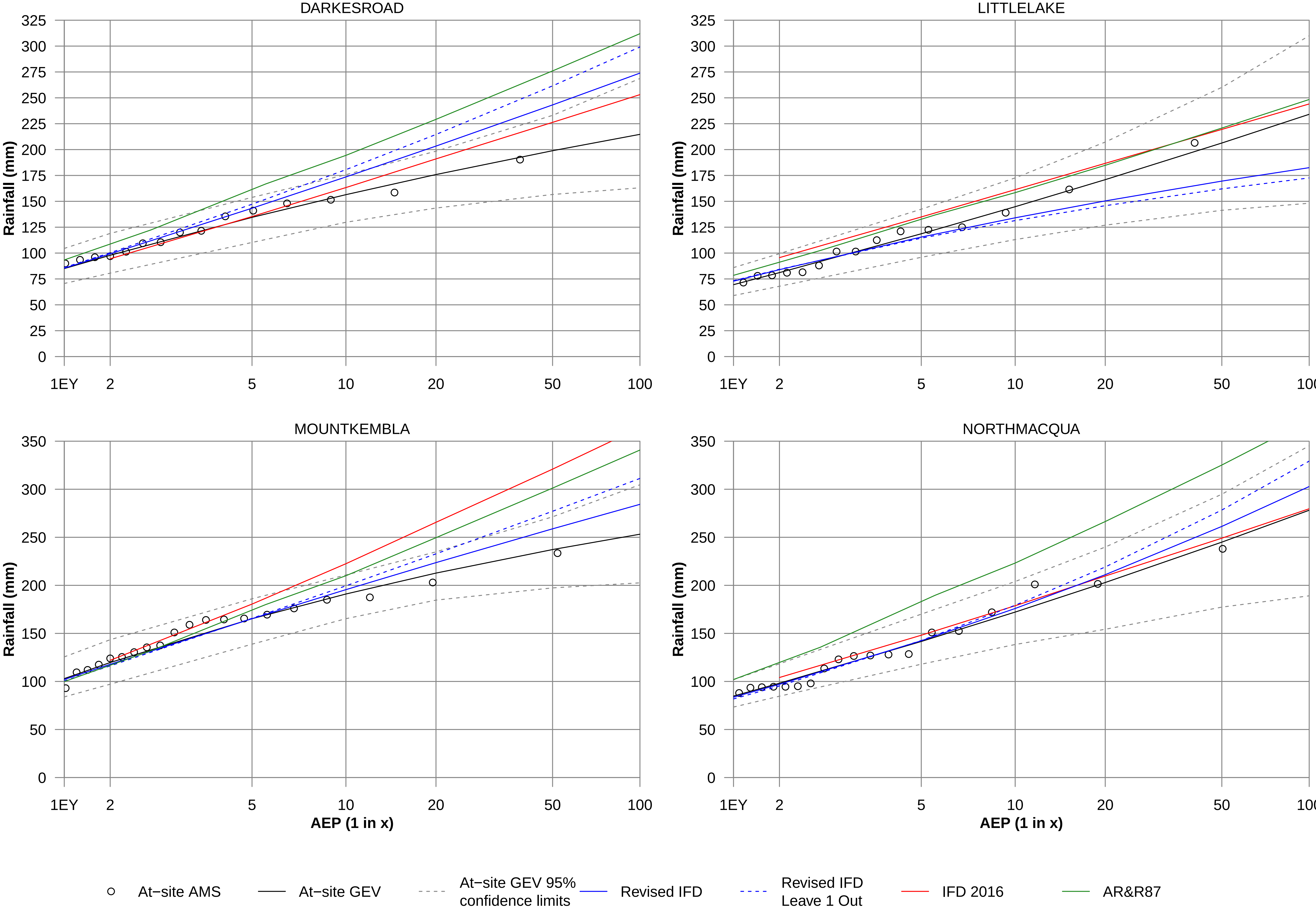
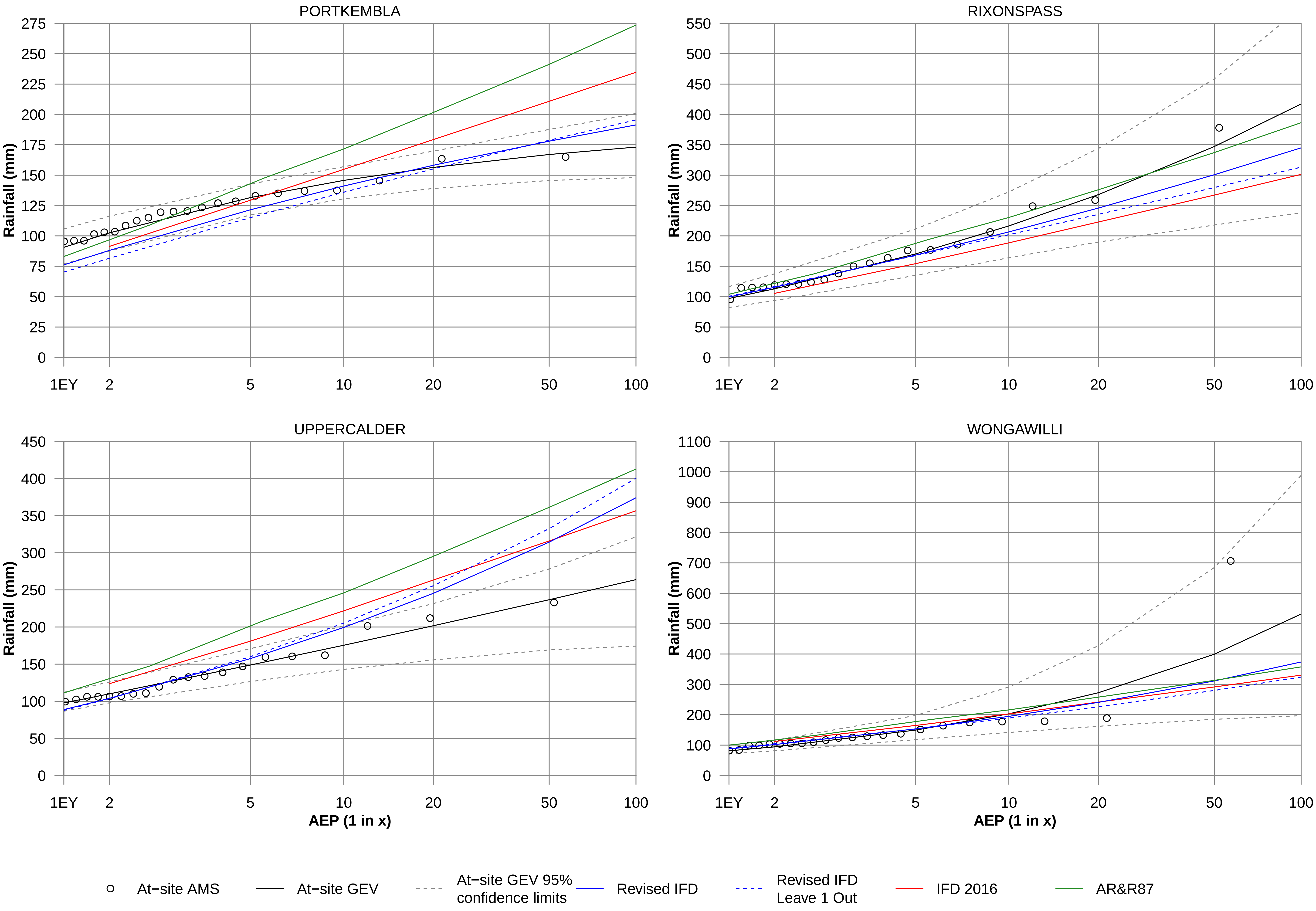


FIGURE A63
WOLLONGONG AREA STATIONS
12 HOUR IFD COMPARISON



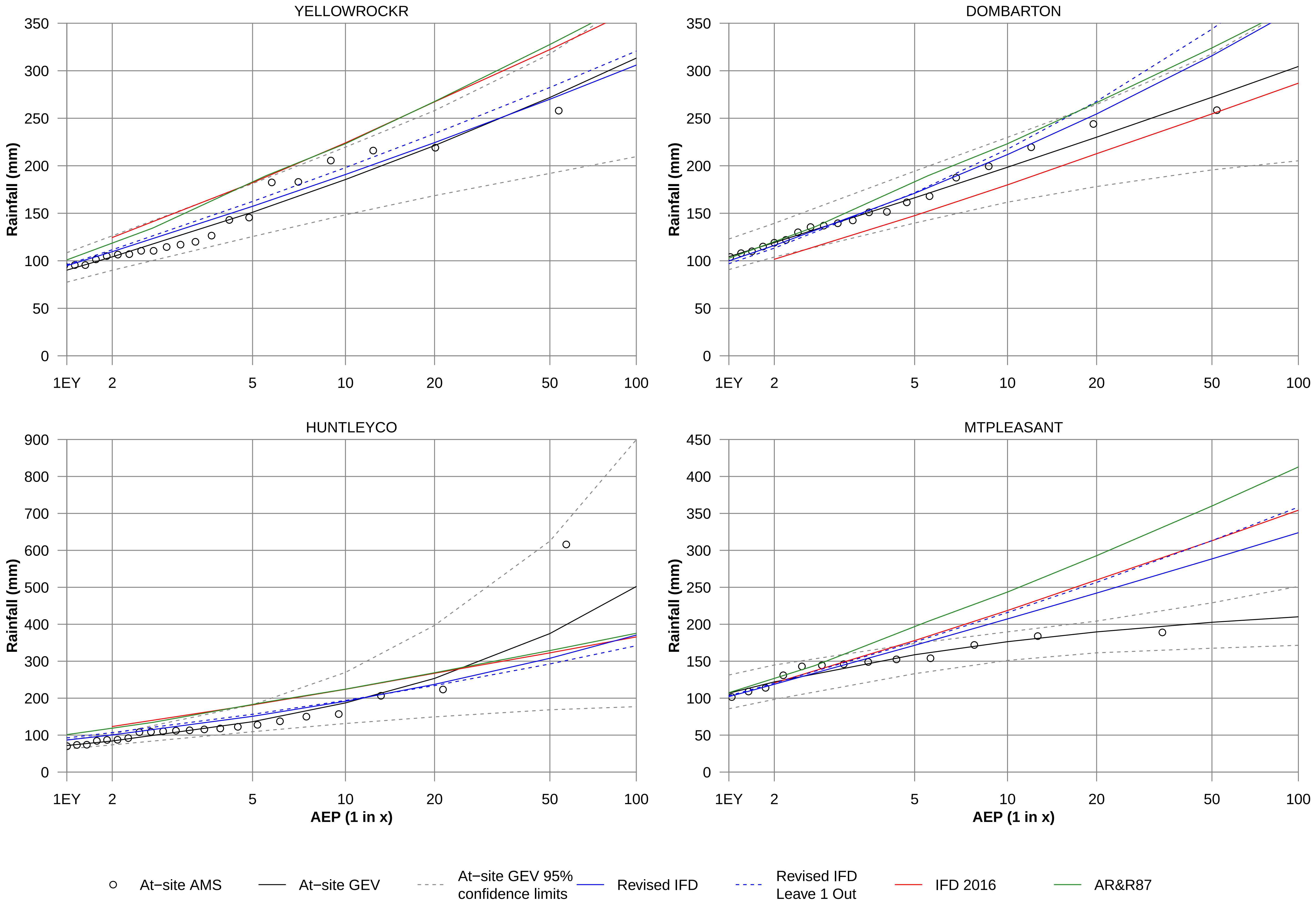
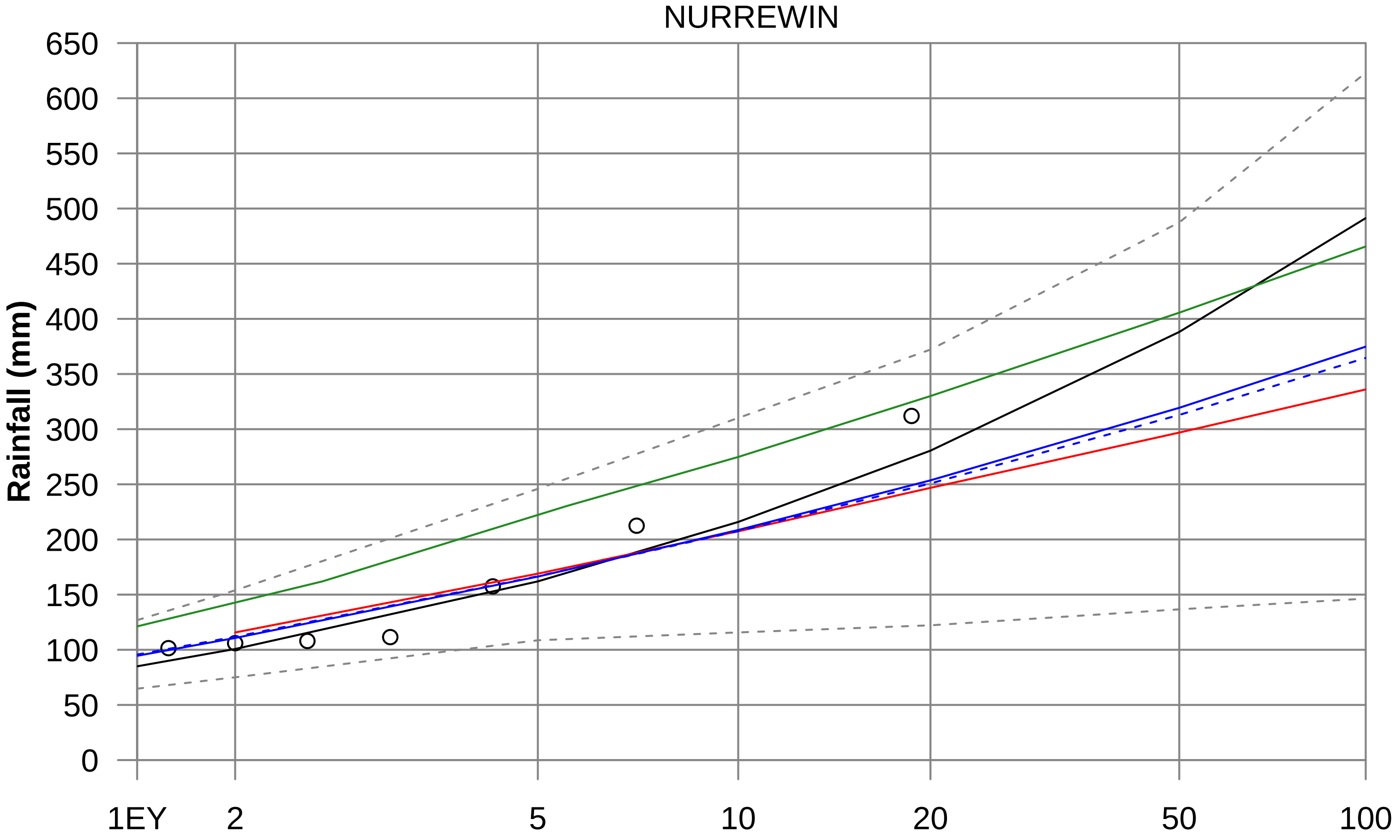
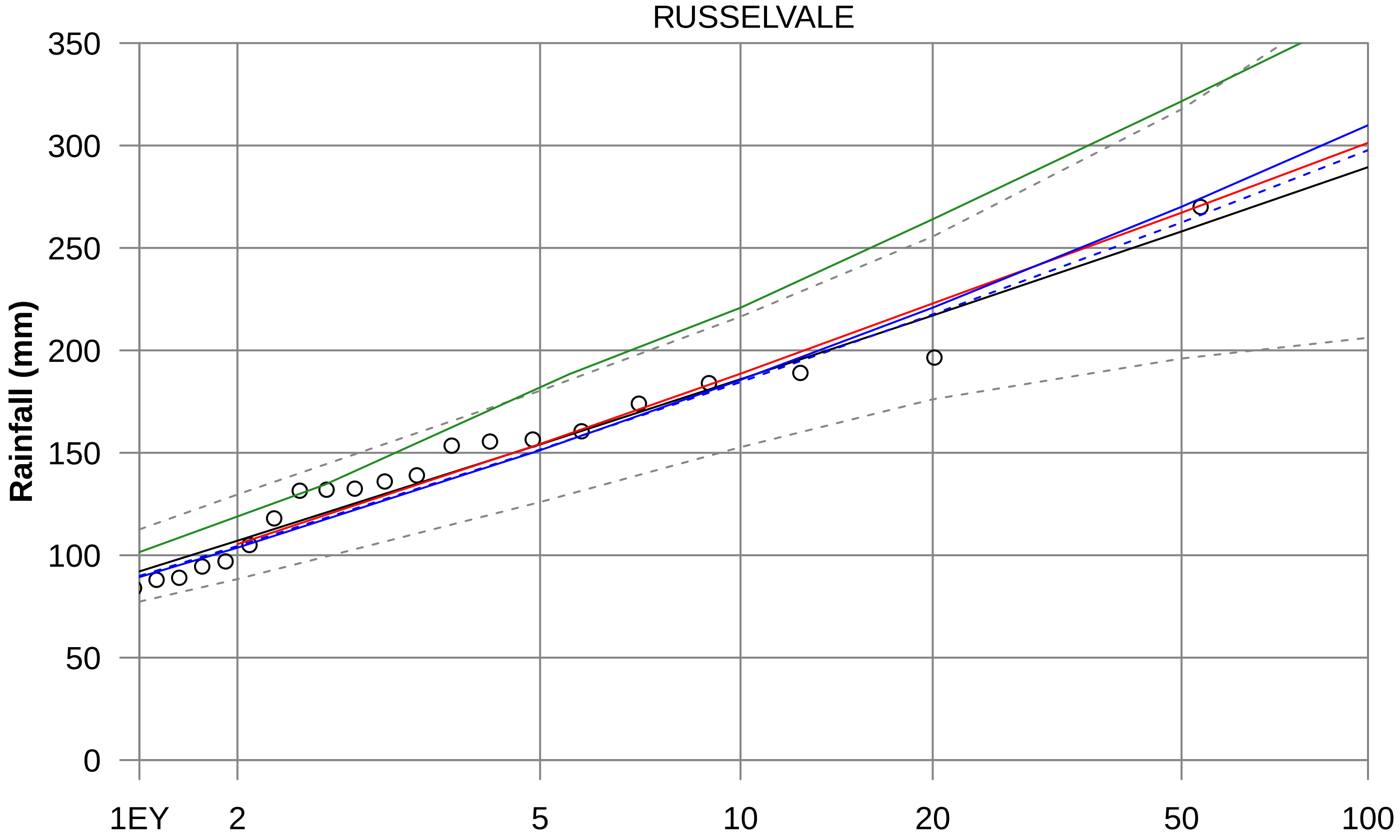

YELLOWROCKR
DOMBARTON
HUNTLEYCO
MTPLEASANT
Rainfall (mm)
AEP (1 in x)
1EY
2
5
10
20
50
100
At−site AMS
At−site GEV
At−site GEV 95% confidence limits
Revised IFD
Revised IFD Leave 1 Out
IFD 2016
AR&R87

FIGURE A65
WOLLONGONG AREA STATIONS
12 HOUR IFD COMPARISON





WOLLONGONG AREA STATIONS
24 HOUR IFD COMPARISON

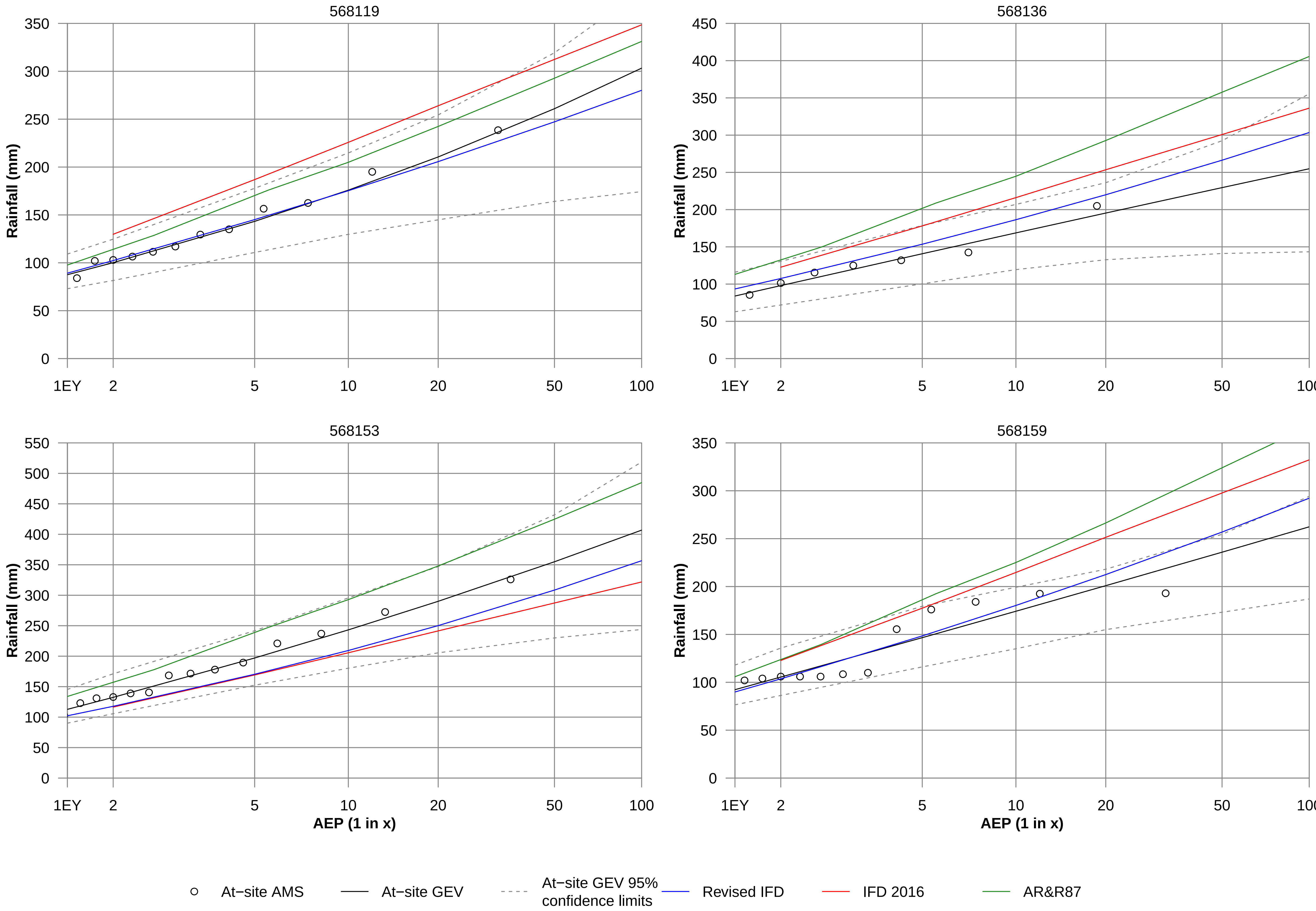


FIGURE A67

WOLLONGONG AREA STATIONS

24 HOUR IFD COMPARISON

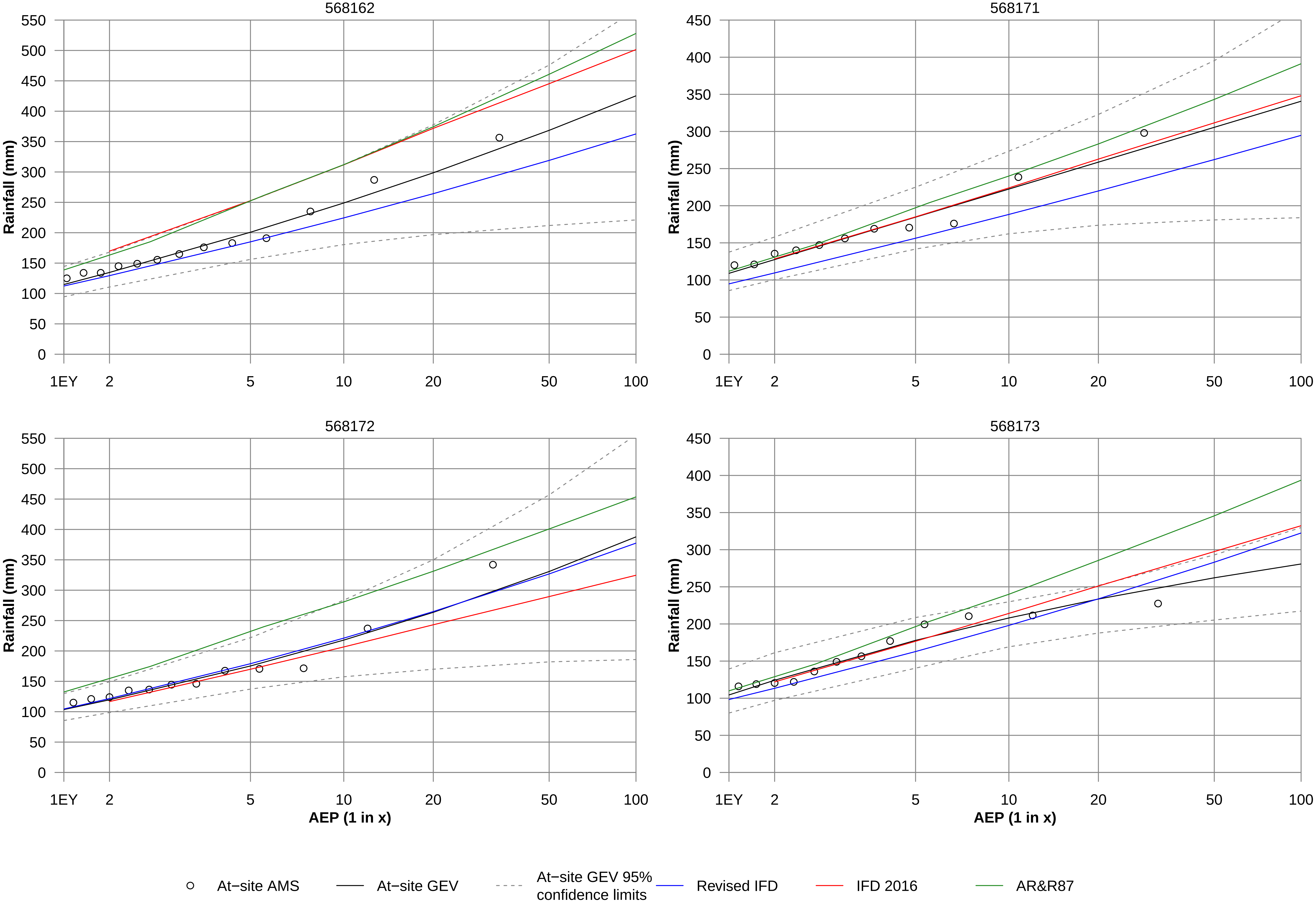


FIGURE A68

WOLLONGONG AREA STATIONS
24 HOUR IFD COMPARISON

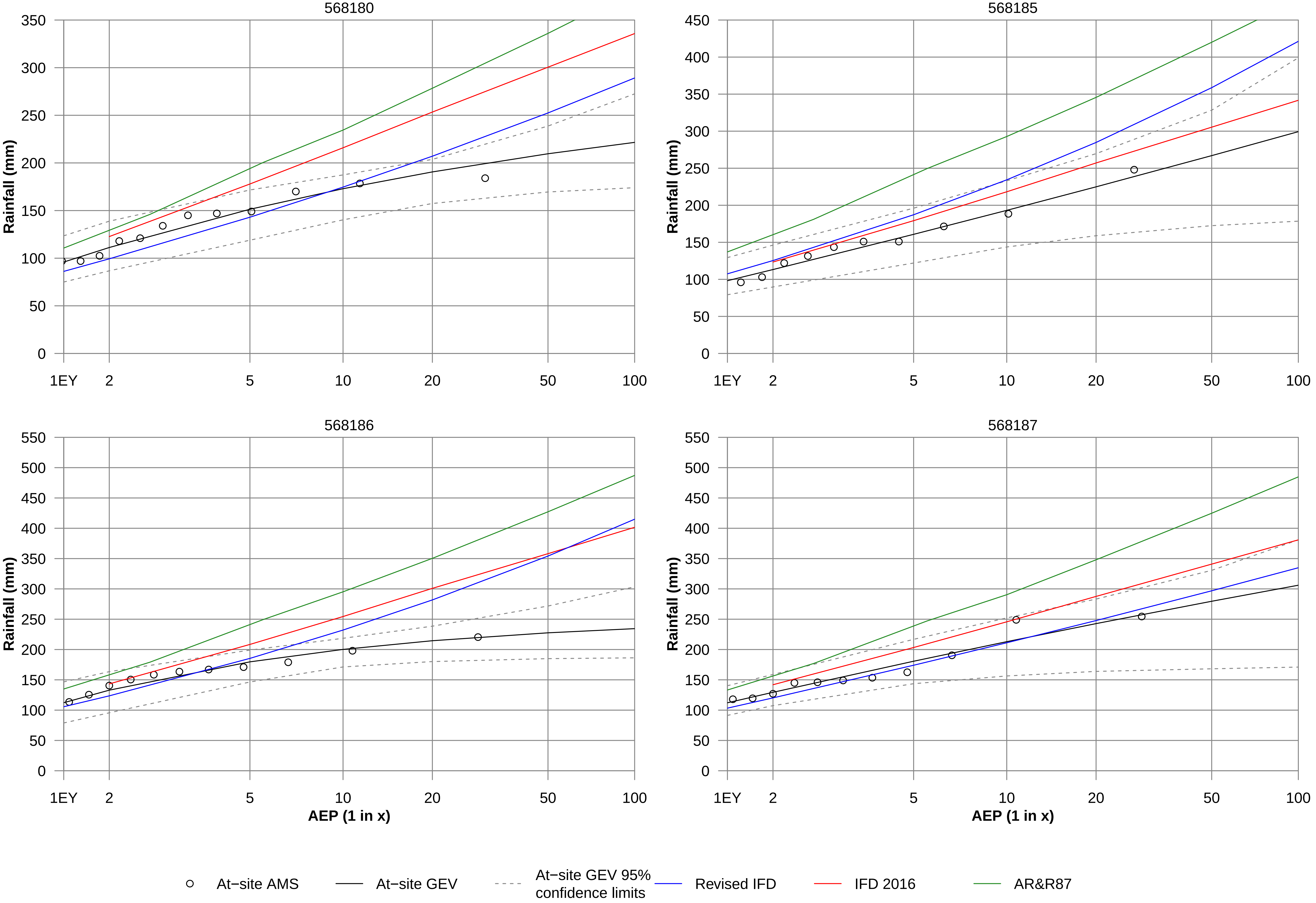


FIGURE A69
WOLLONGONG AREA STATIONS
24 HOUR IFD COMPARISON

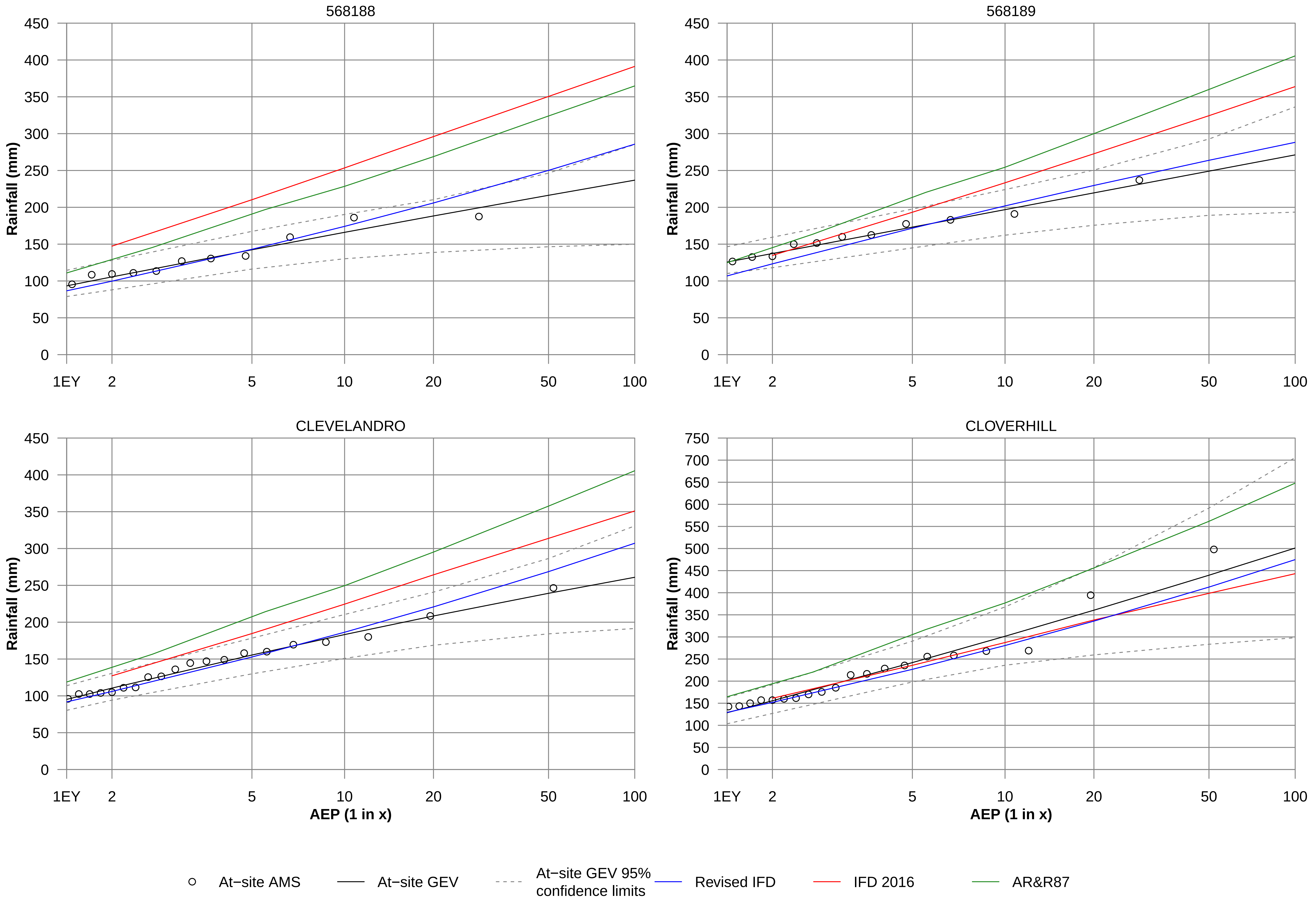


FIGURE A70
WOLLONGONG AREA STATIONS
24 HOUR IFD COMPARISON

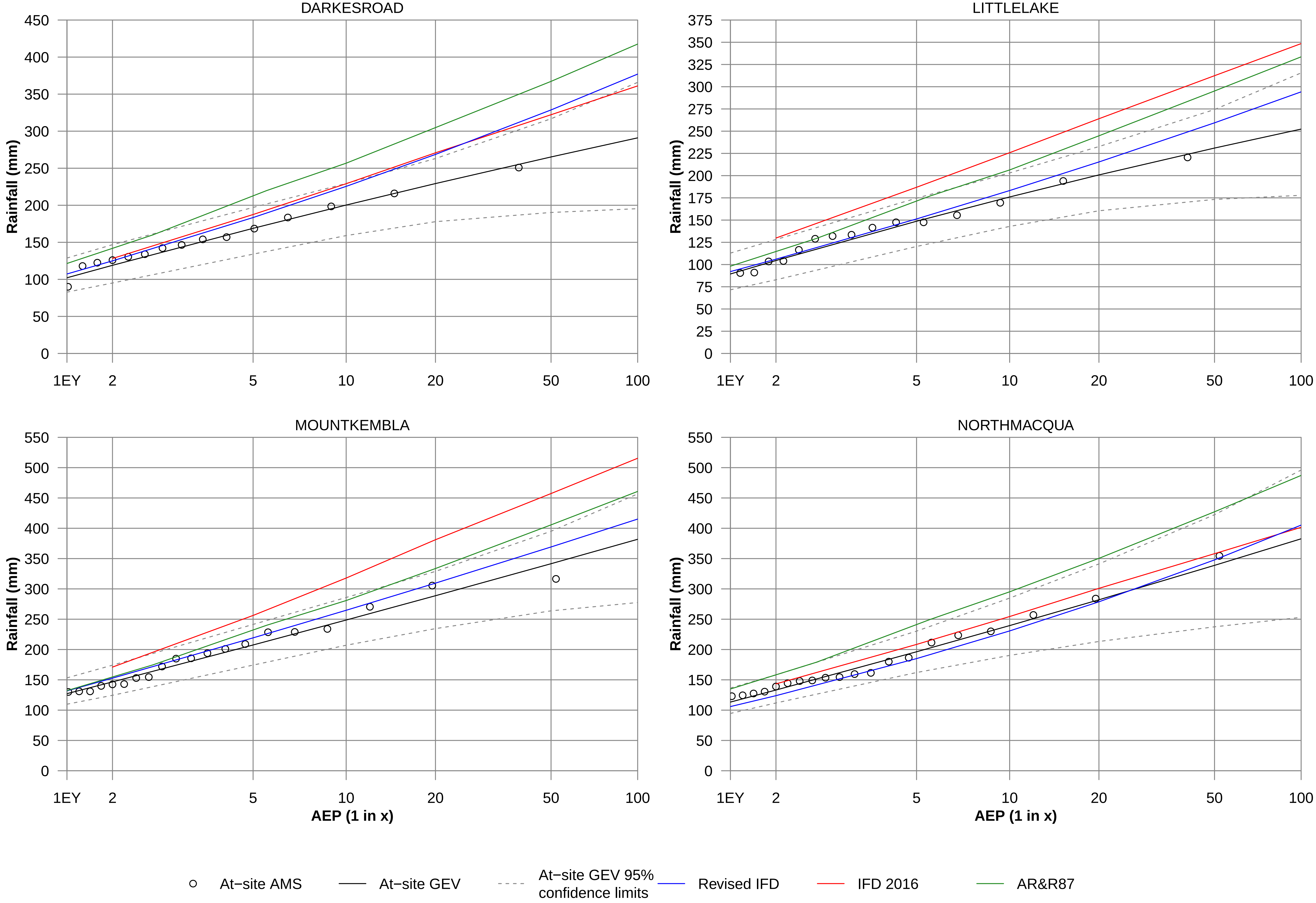
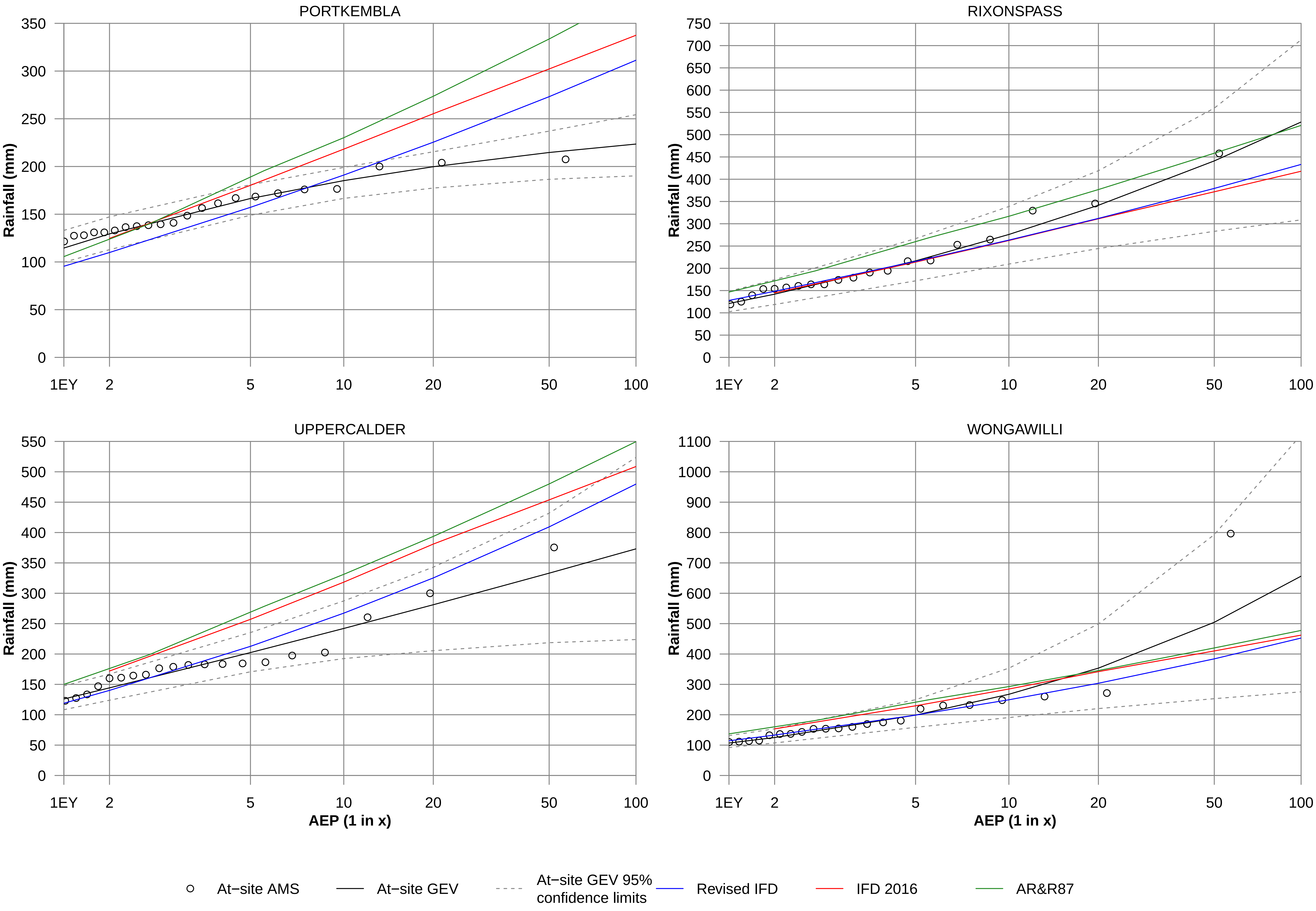


FIGURE A71
WOLLONGONG AREA STATIONS
24 HOUR IFD COMPARISON



WOLLONGONG AREA STATIONS
24 HOUR IFD COMPARISON

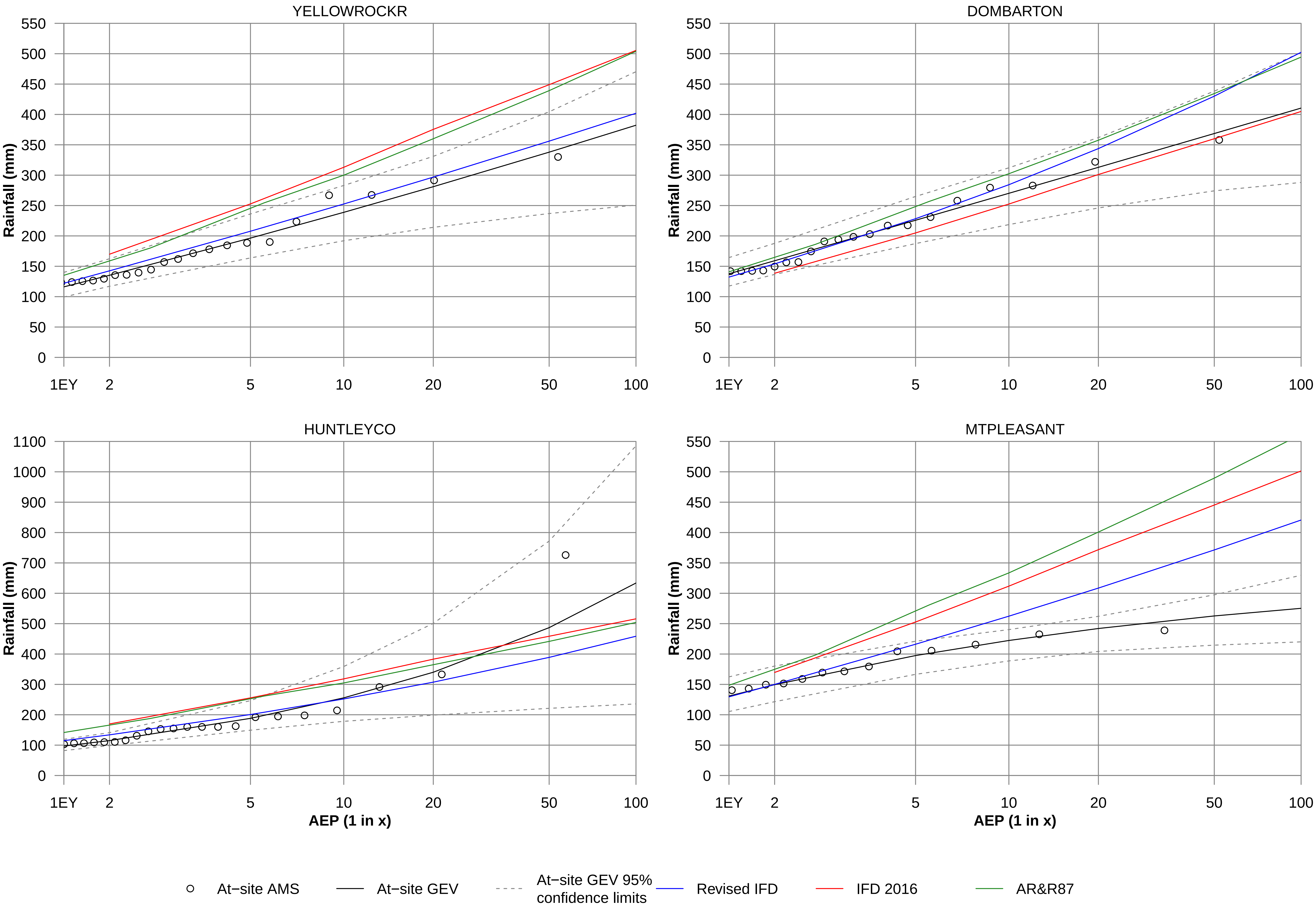
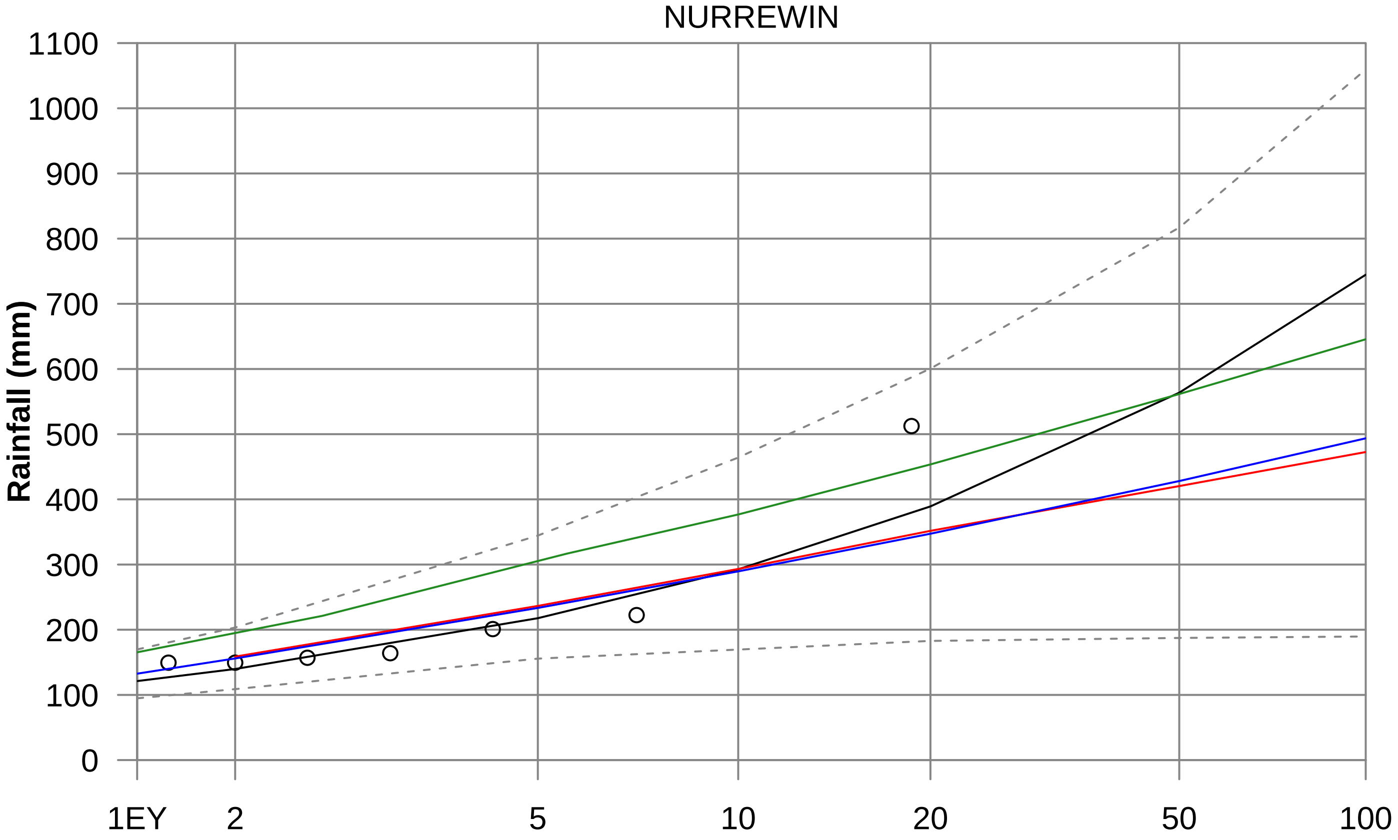


FIGURE A73
WOLLONGONG AREA STATIONS
24 HOUR IFD COMPARISON



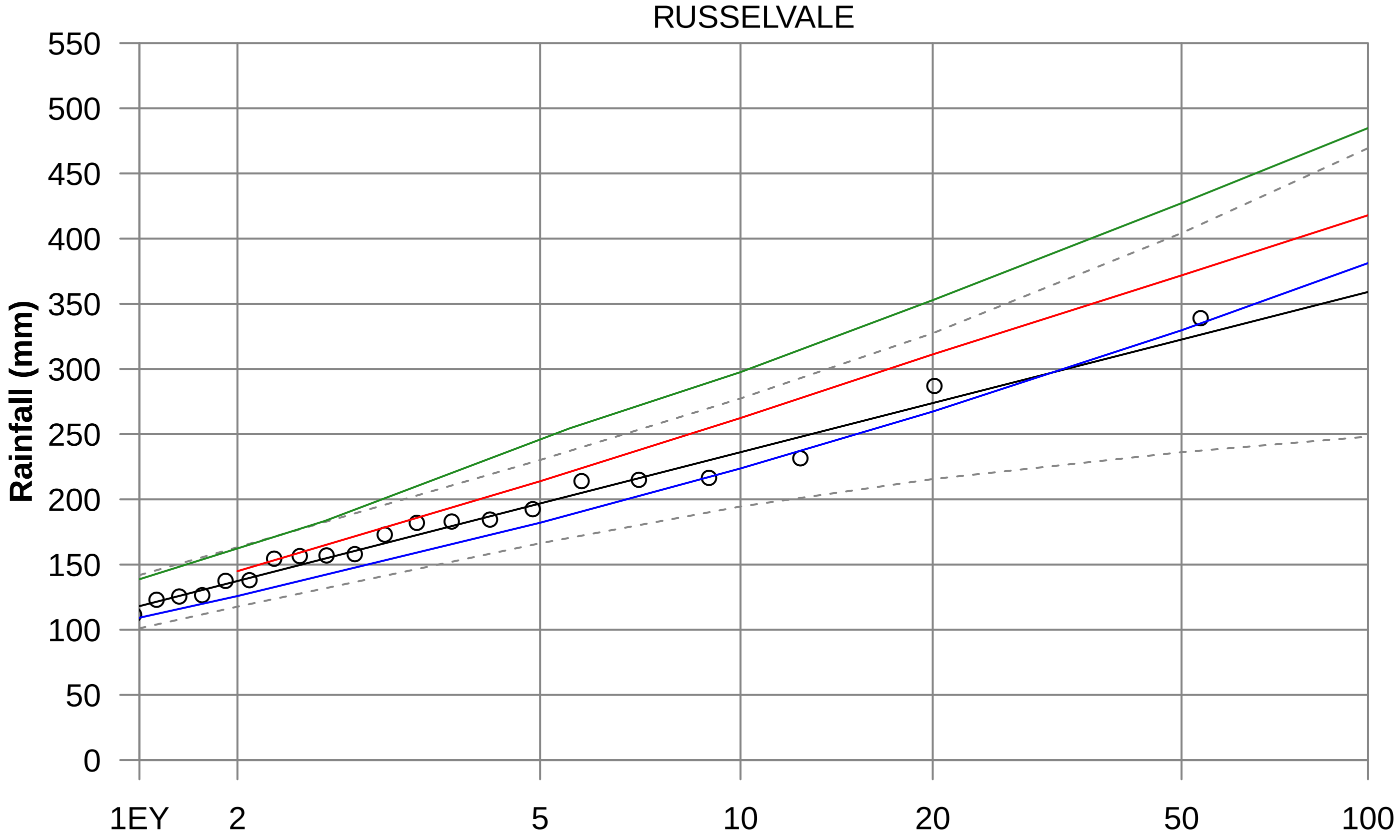


FIGURE A74
WOLLONGONG AREA STATIONS
48 HOUR IFD COMPARISON

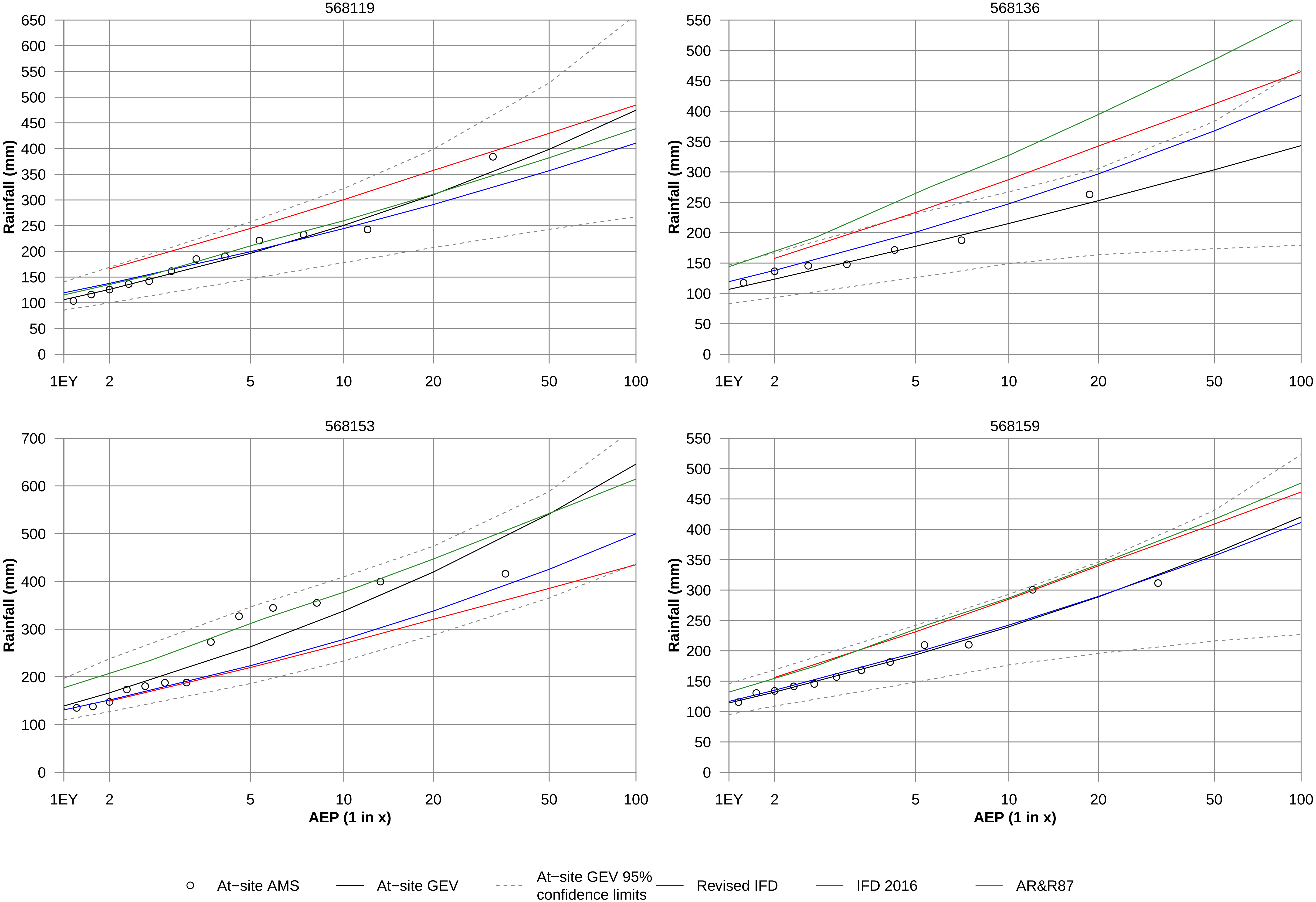


FIGURE A75
WOLLONGONG AREA STATIONS
48 HOUR IFD COMPARISON

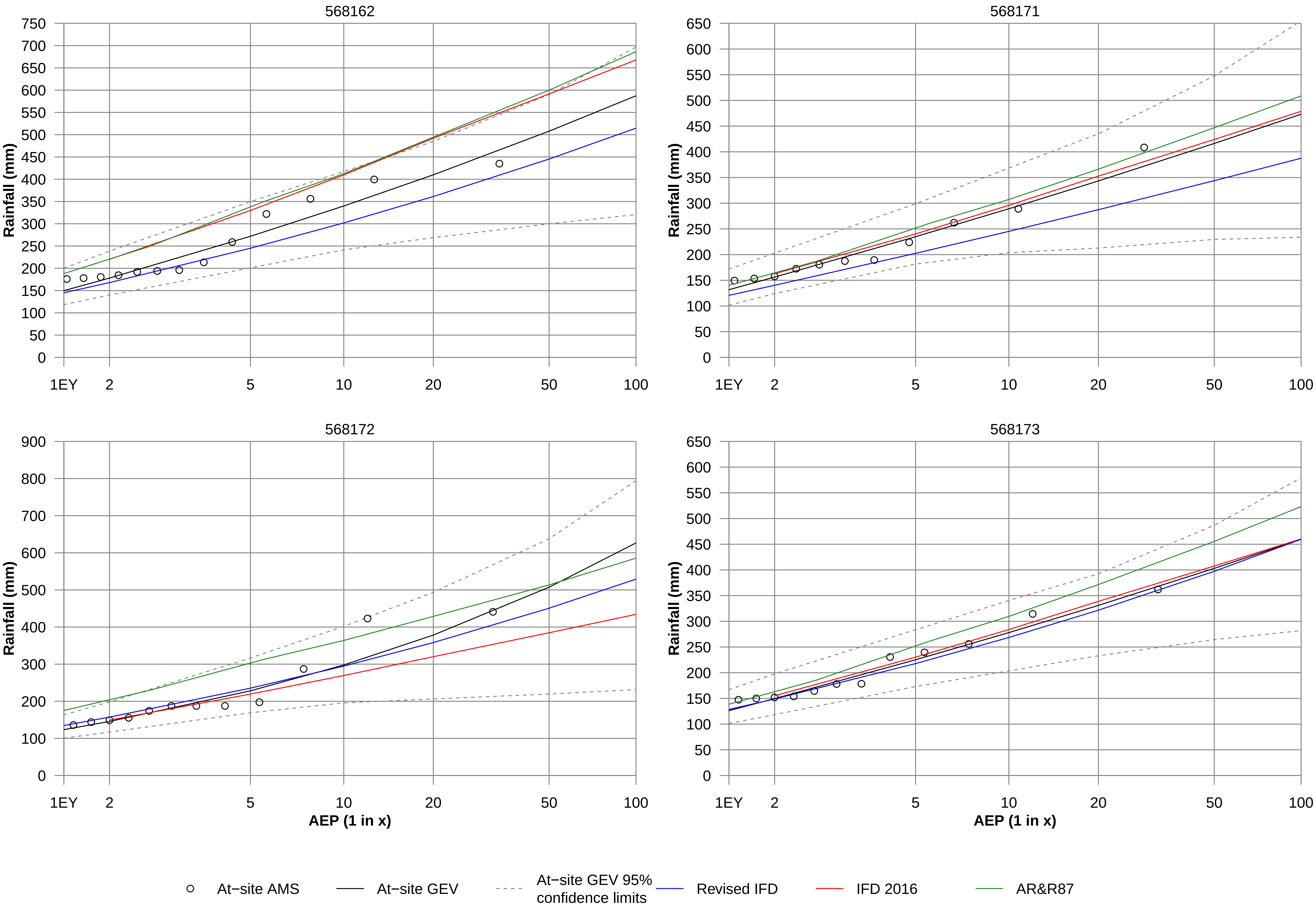


FIGURE A76

WOLLONGONG AREA STATIONS

48 HOUR IFD COMPARISON

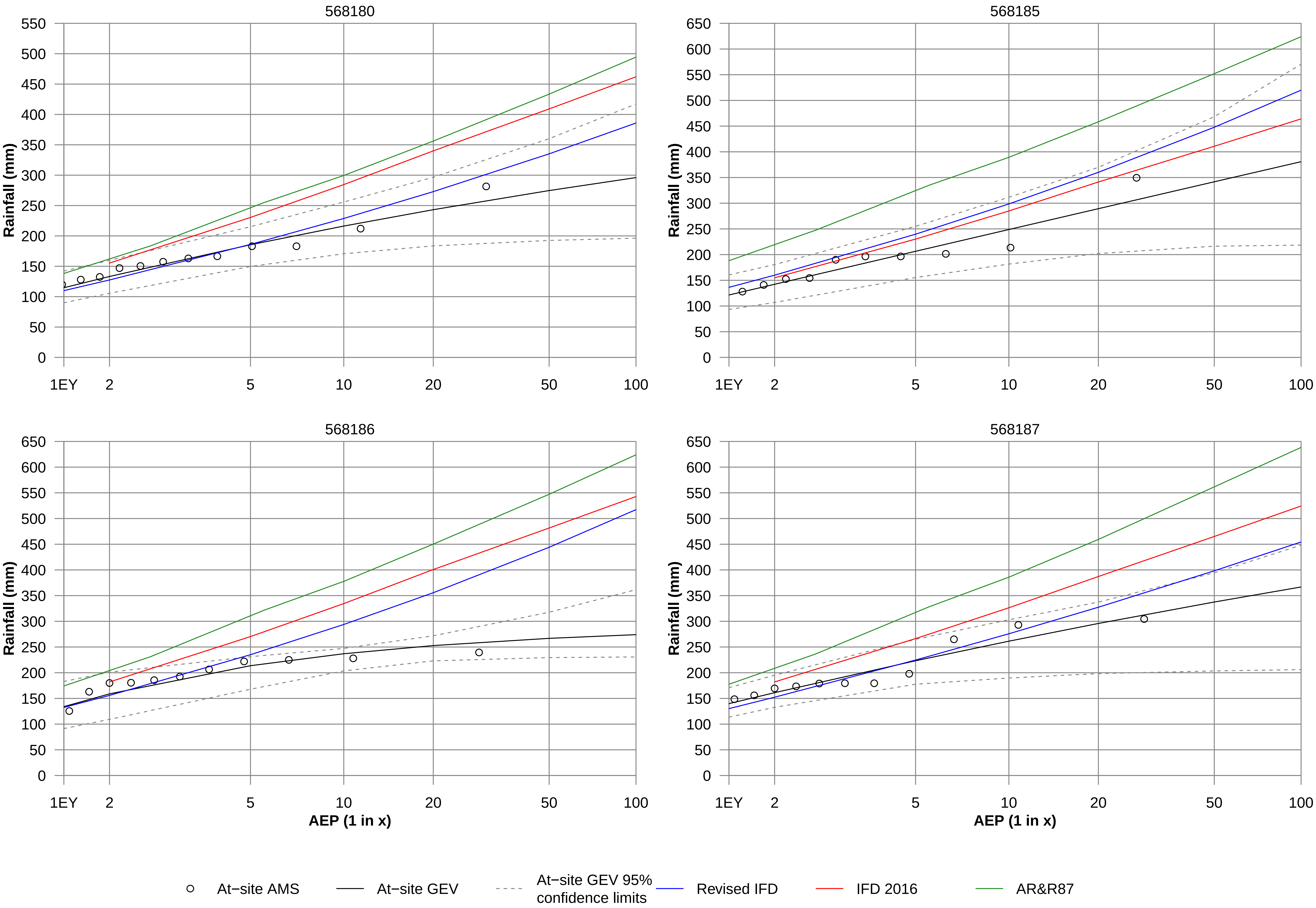


FIGURE A77
WOLLONGONG AREA STATIONS
48 HOUR IFD COMPARISON

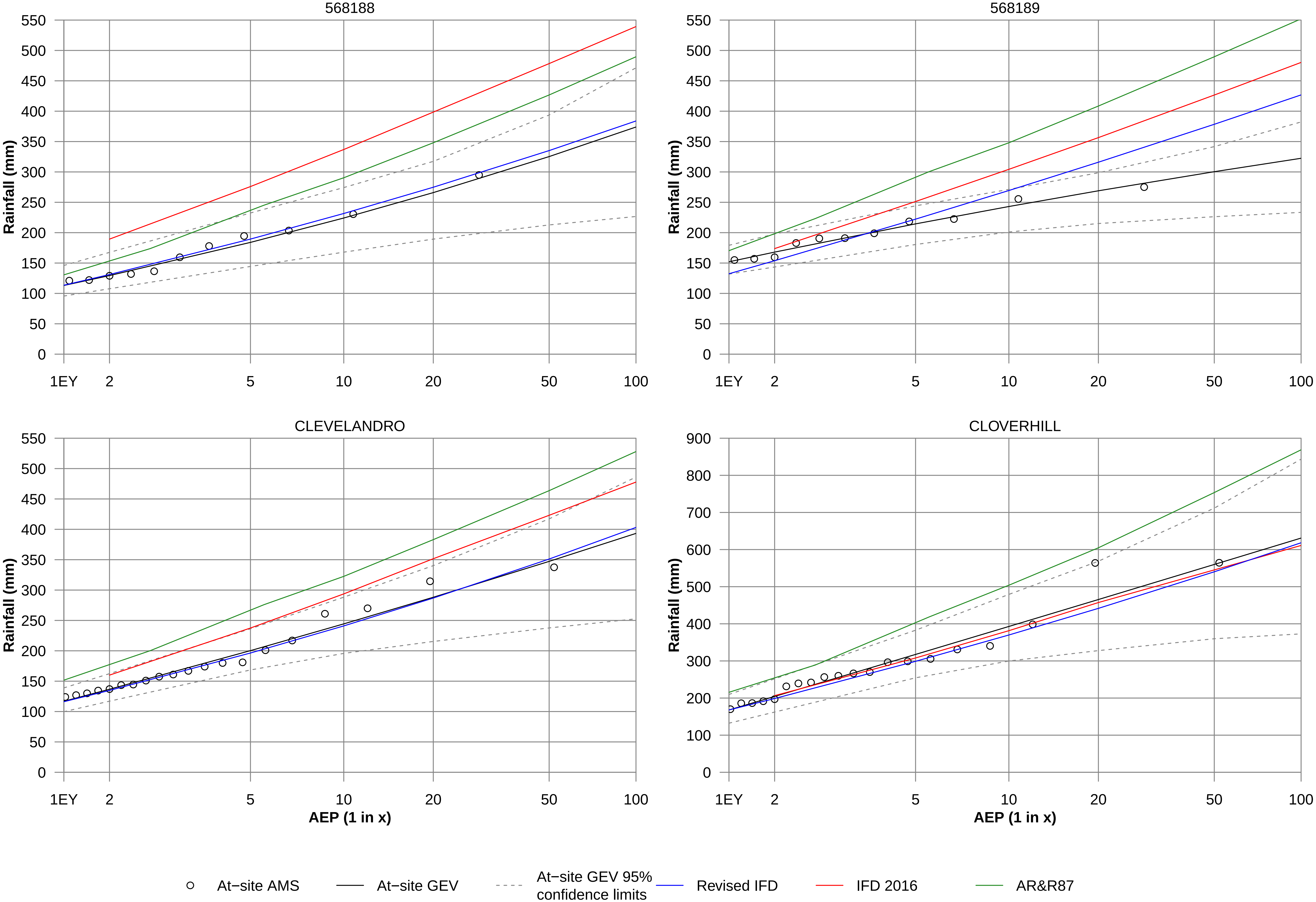
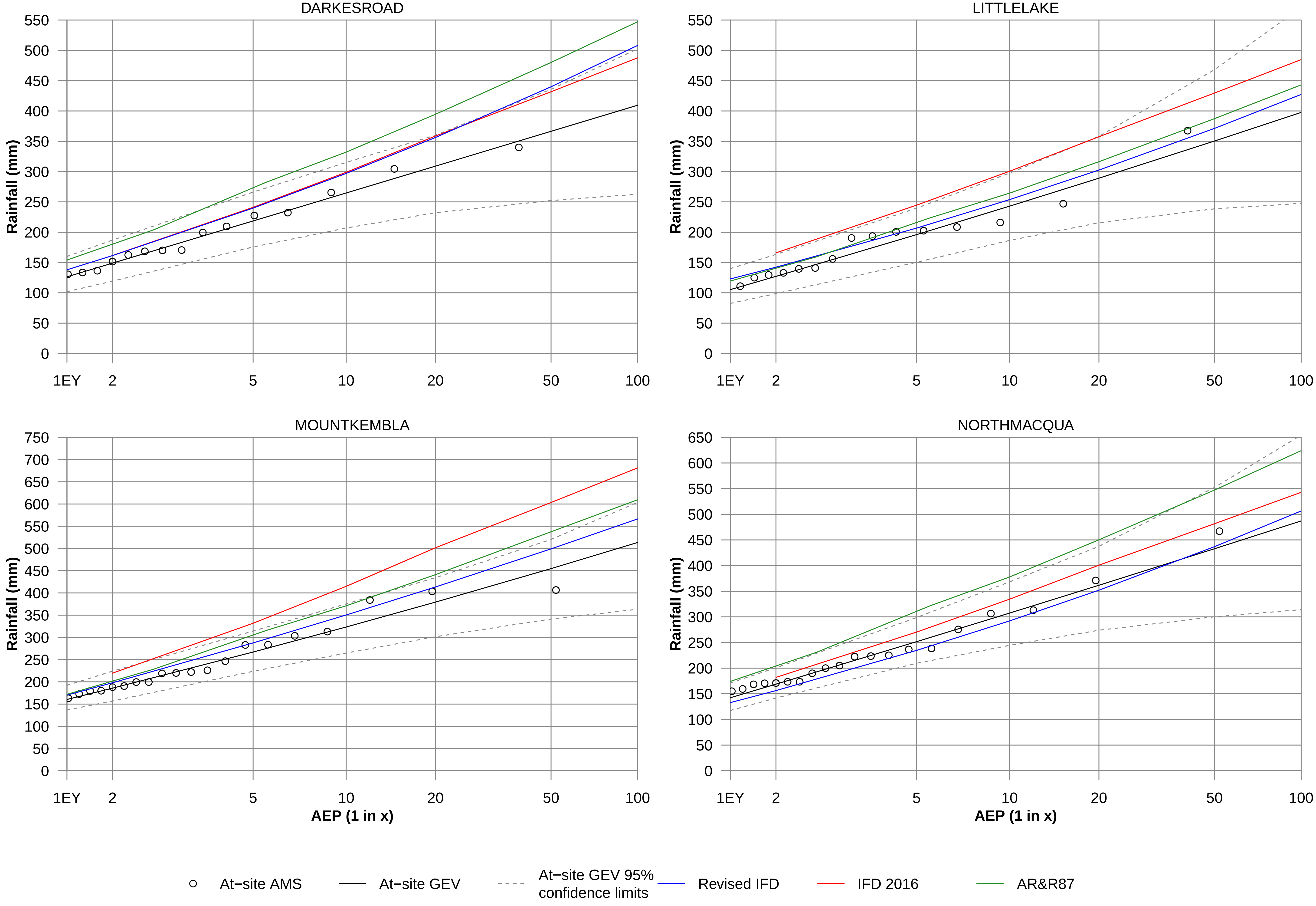
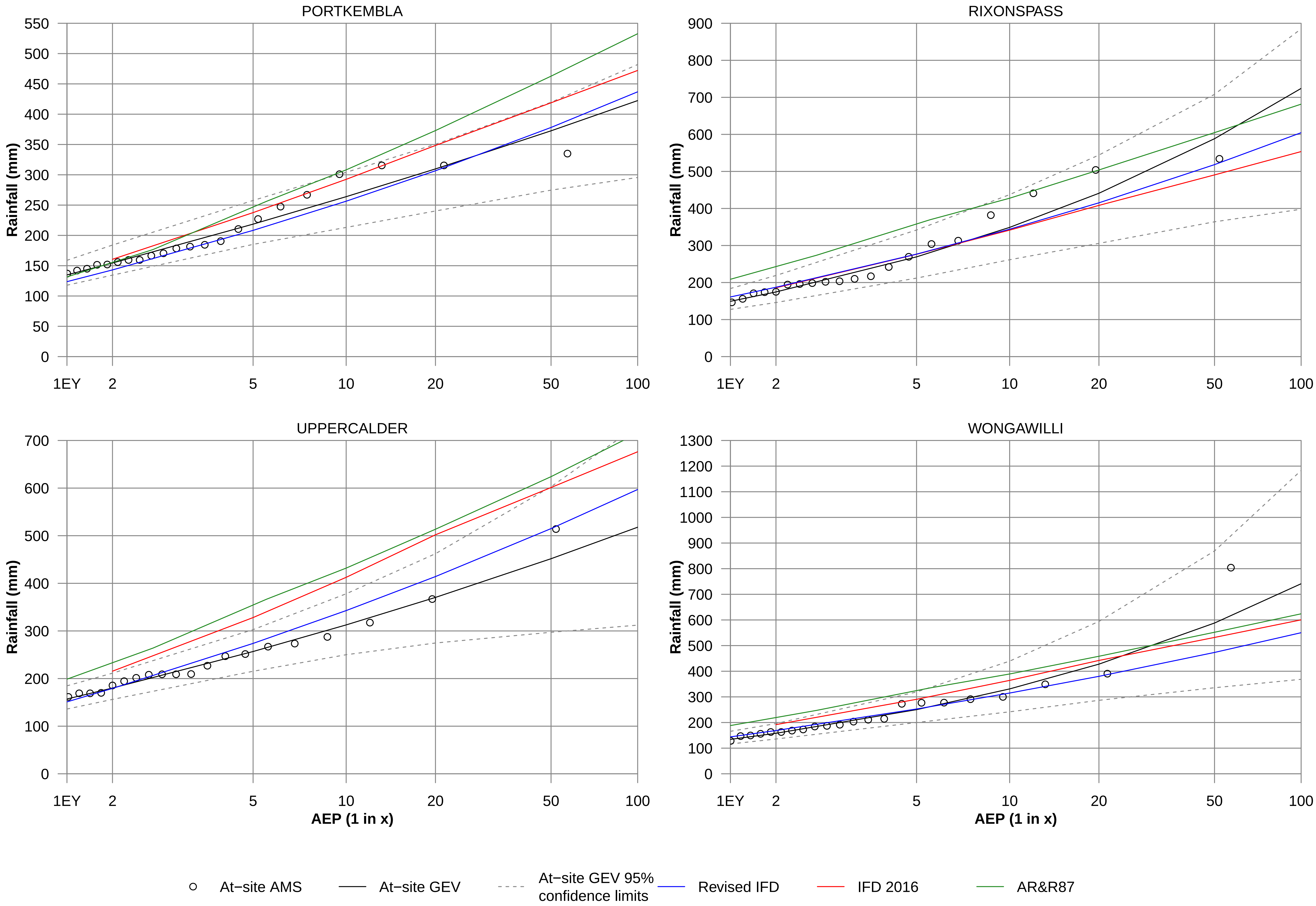


FIGURE A78
WOLLONGONG AREA STATIONS
48 HOUR IFD COMPARISON




PORTKEMBLA
RIXONSPASS
UPPERCALDER
WONGAWILLI
Rainfall (mm)
AEP (1 in x)
1EY
2
5
10
20
50
100
At−site AMS
At−site GEV
At−site GEV 95% confidence limits
Revised IFD
IFD 2016
AR&R87

WOLLONGONG AREA STATIONS
48 HOUR IFD COMPARISON

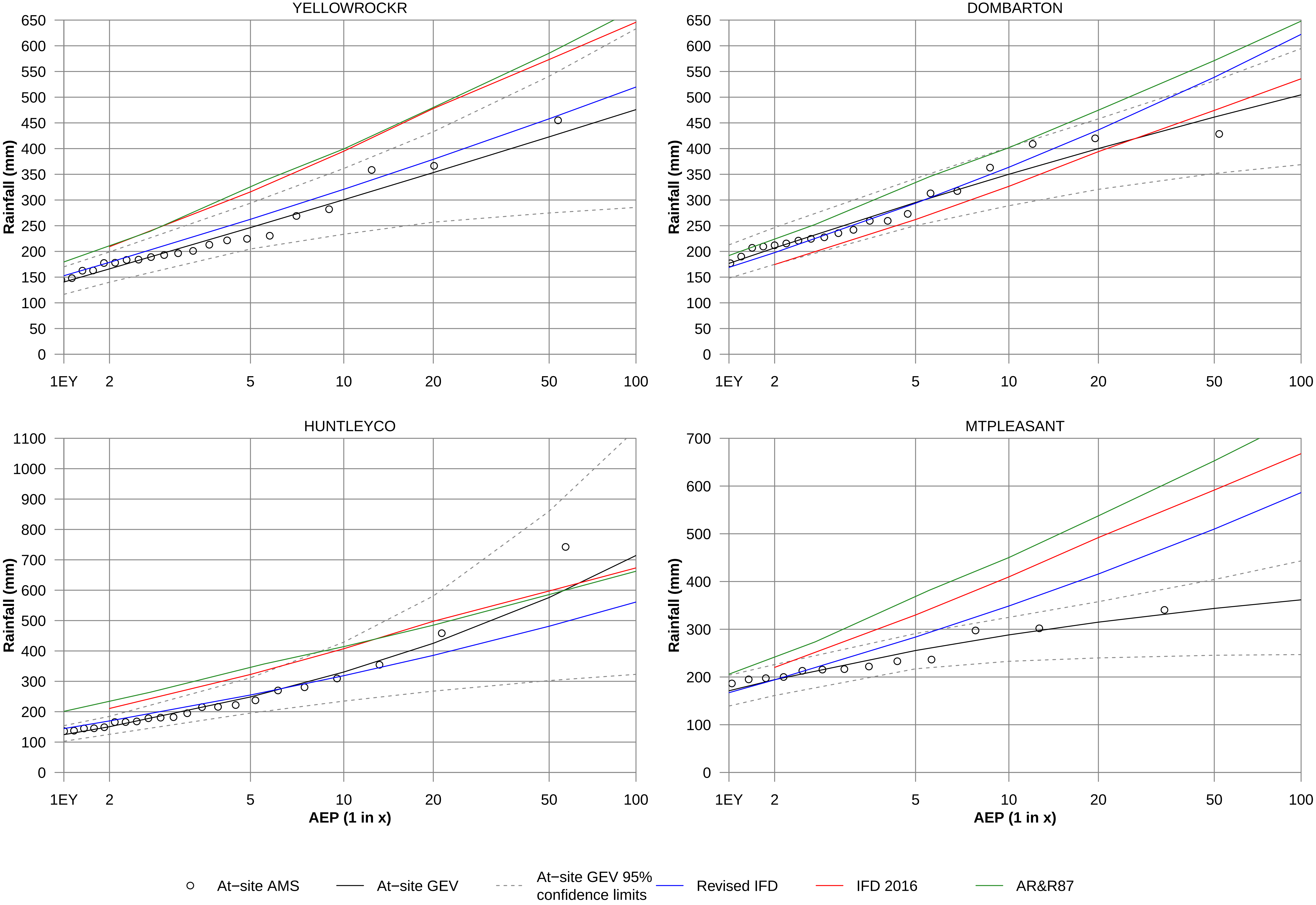
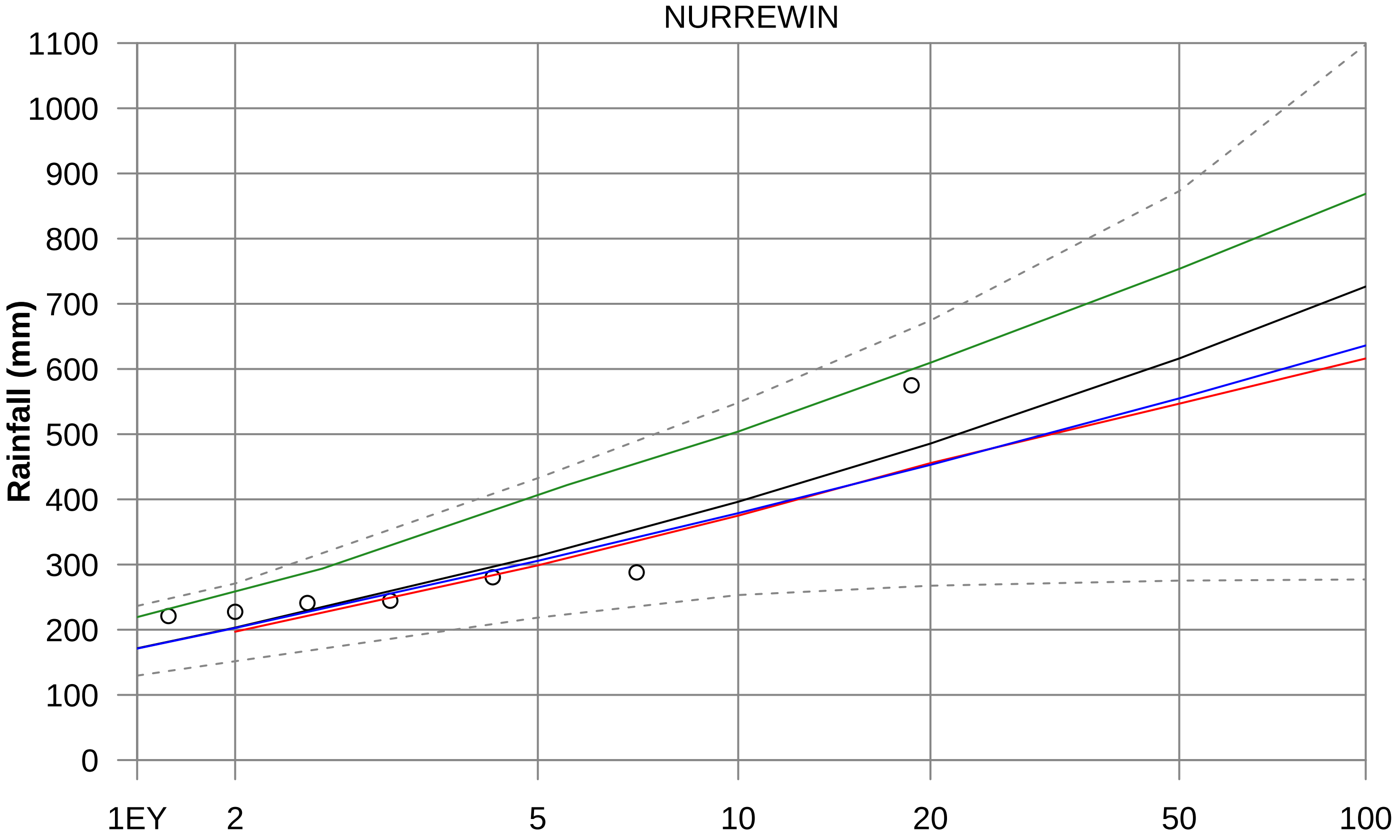


FIGURE A81
WOLLONGONG AREA STATIONS
48 HOUR IFD COMPARISON



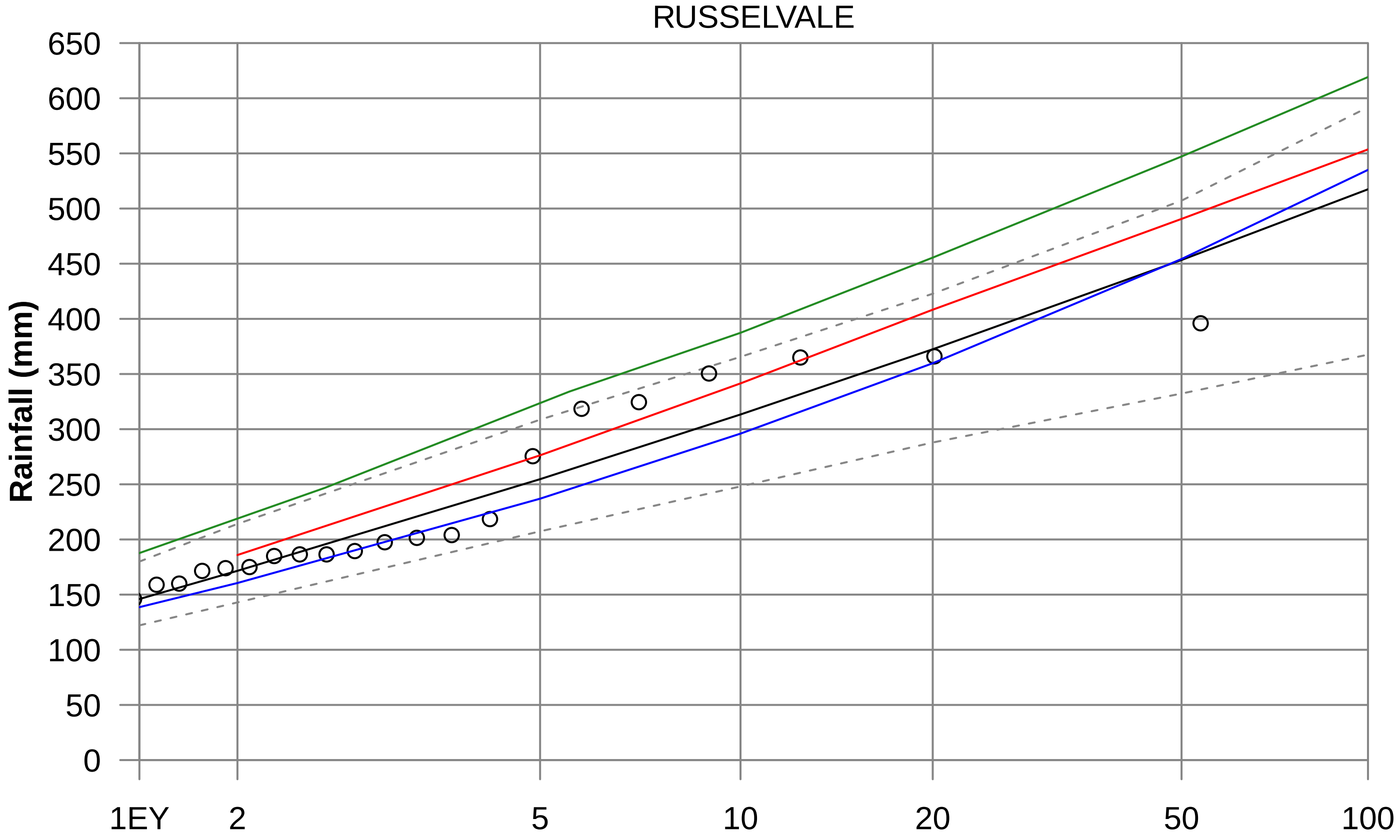


FIGURE A82
WOLLONGONG AREA STATIONS
72 HOUR IFD COMPARISON

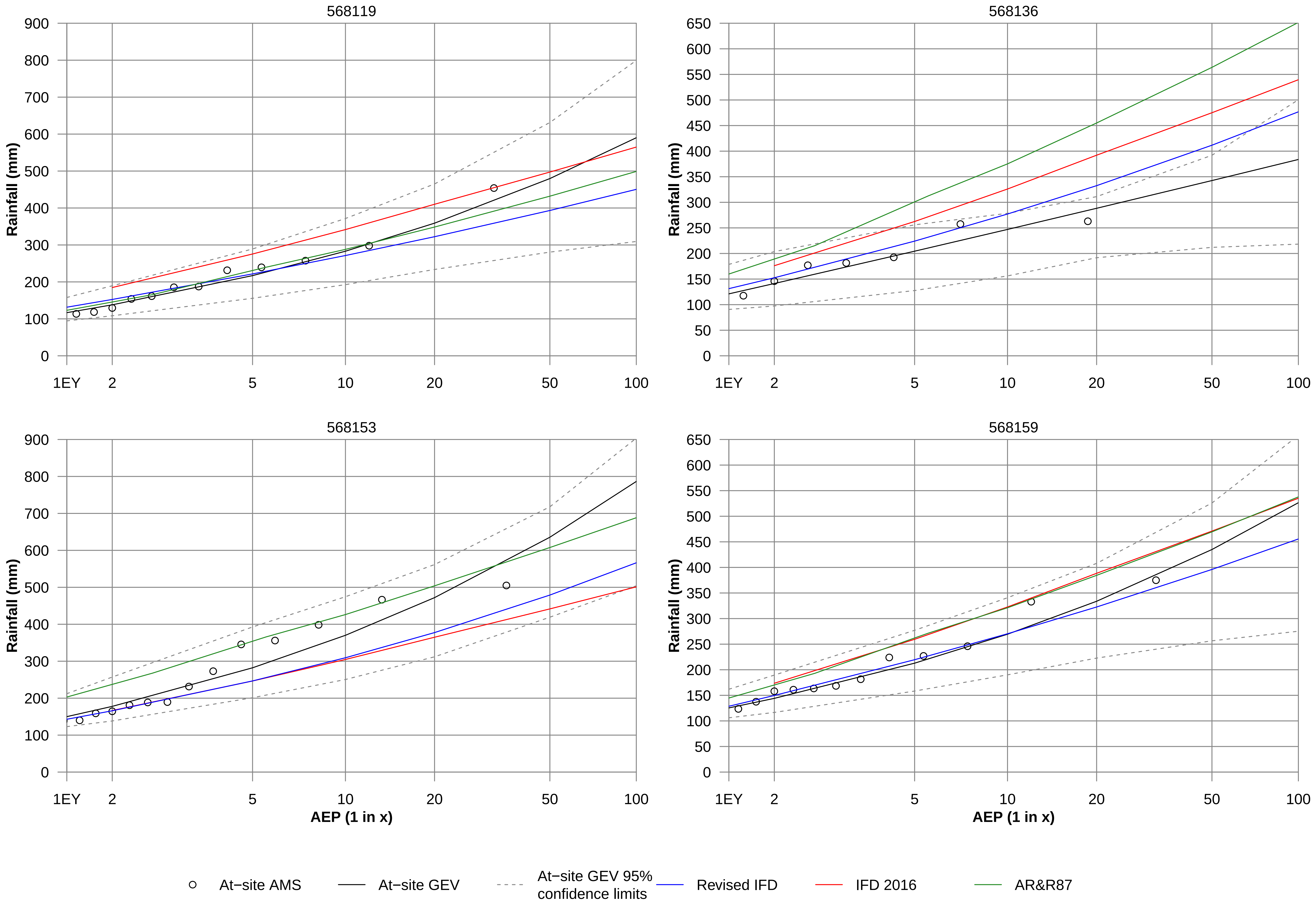


FIGURE A83
WOLLONGONG AREA STATIONS
72 HOUR IFD COMPARISON

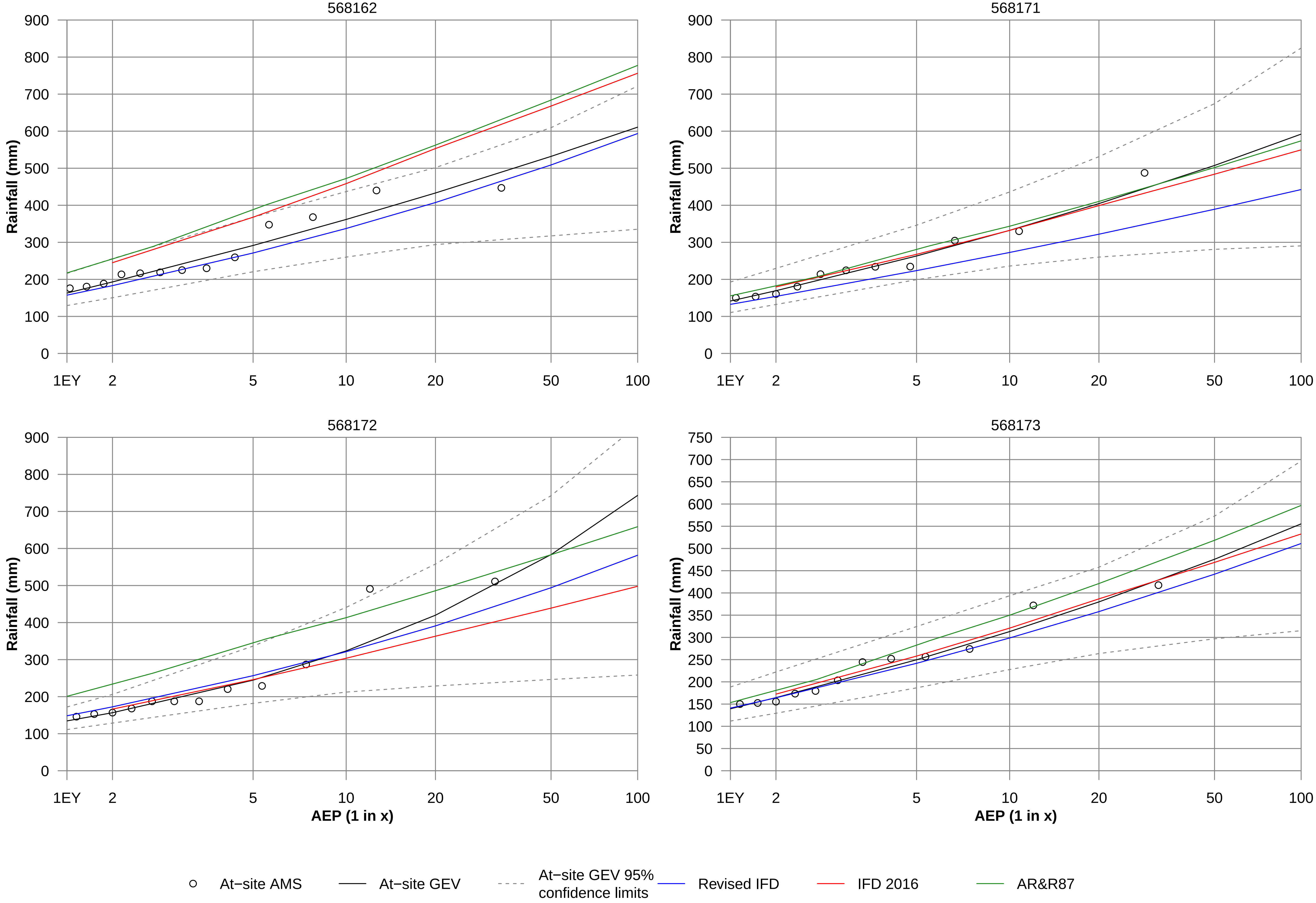
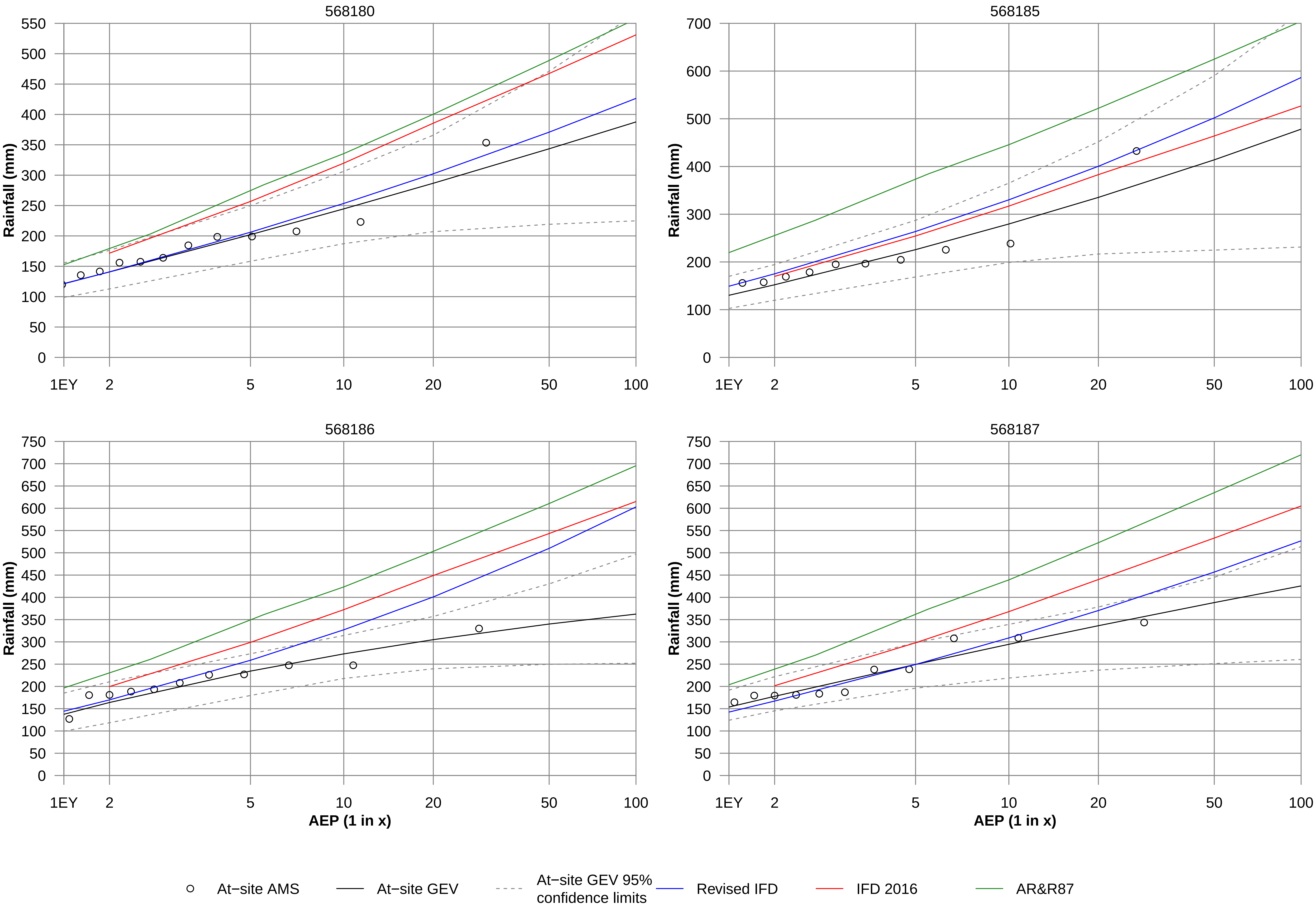


FIGURE A84
WOLLONGONG AREA STATIONS
72 HOUR IFD COMPARISON



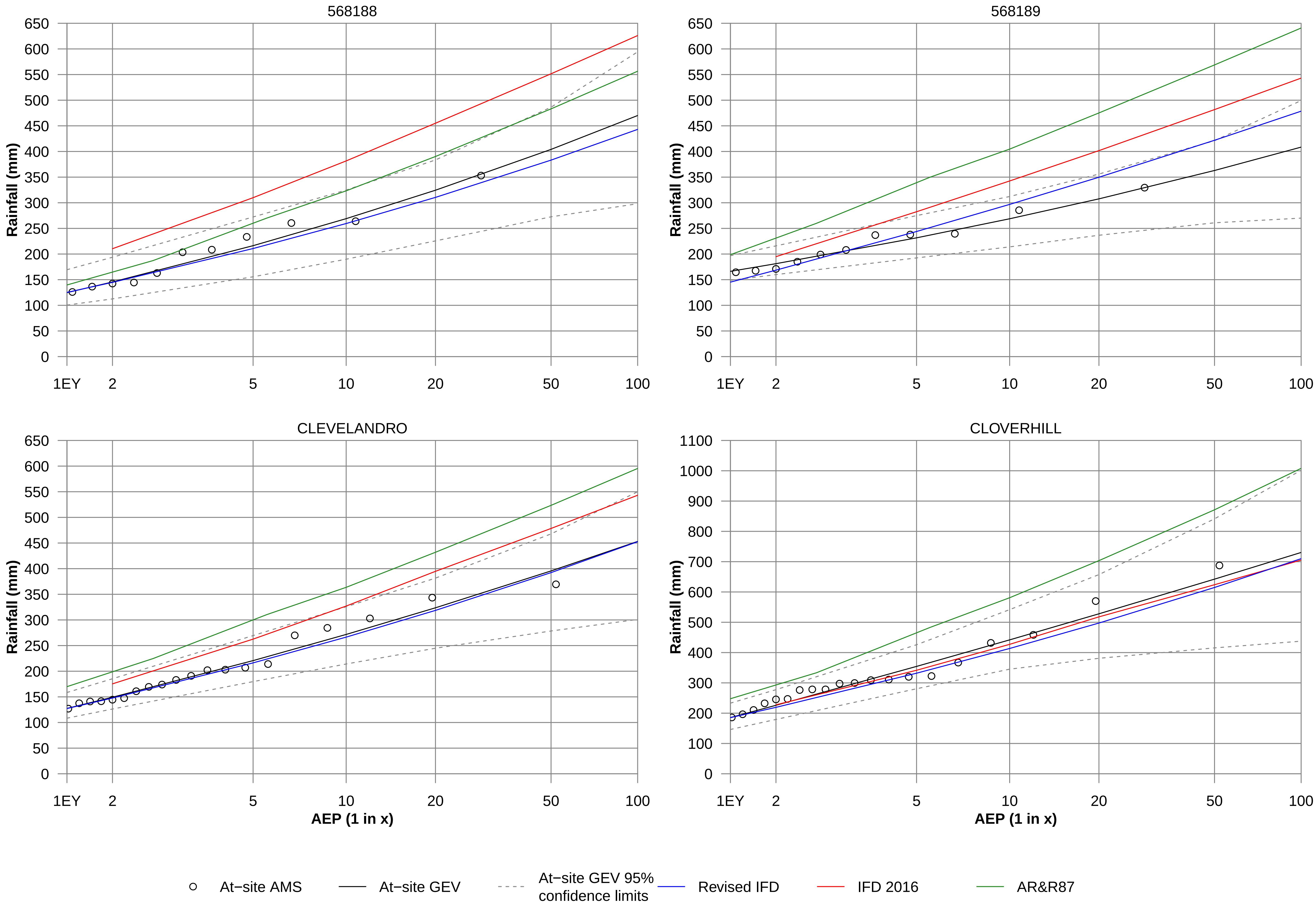

568188
568189
CLEVELANDRO
CLOVERHILL
Rainfall (mm)
AEP (1 in x)
1EY
2
5
10
20
50
100
At−site AMS
At−site GEV
At−site GEV 95% confidence limits
Revised IFD
IFD 2016
AR&R87

FIGURE A86
WOLLONGONG AREA STATIONS
72 HOUR IFD COMPARISON

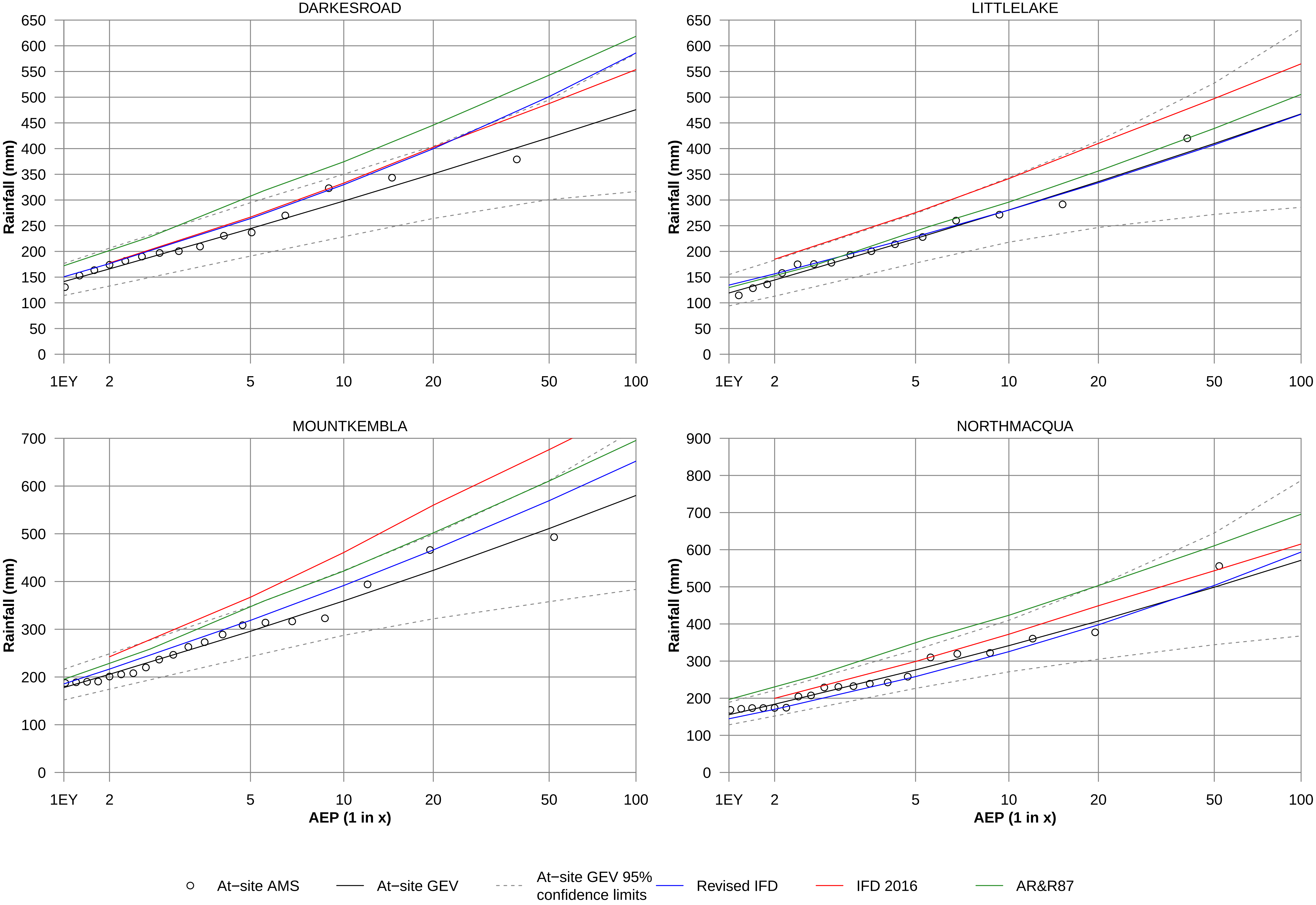


FIGURE A87
WOLLONGONG AREA STATIONS
72 HOUR IFD COMPARISON

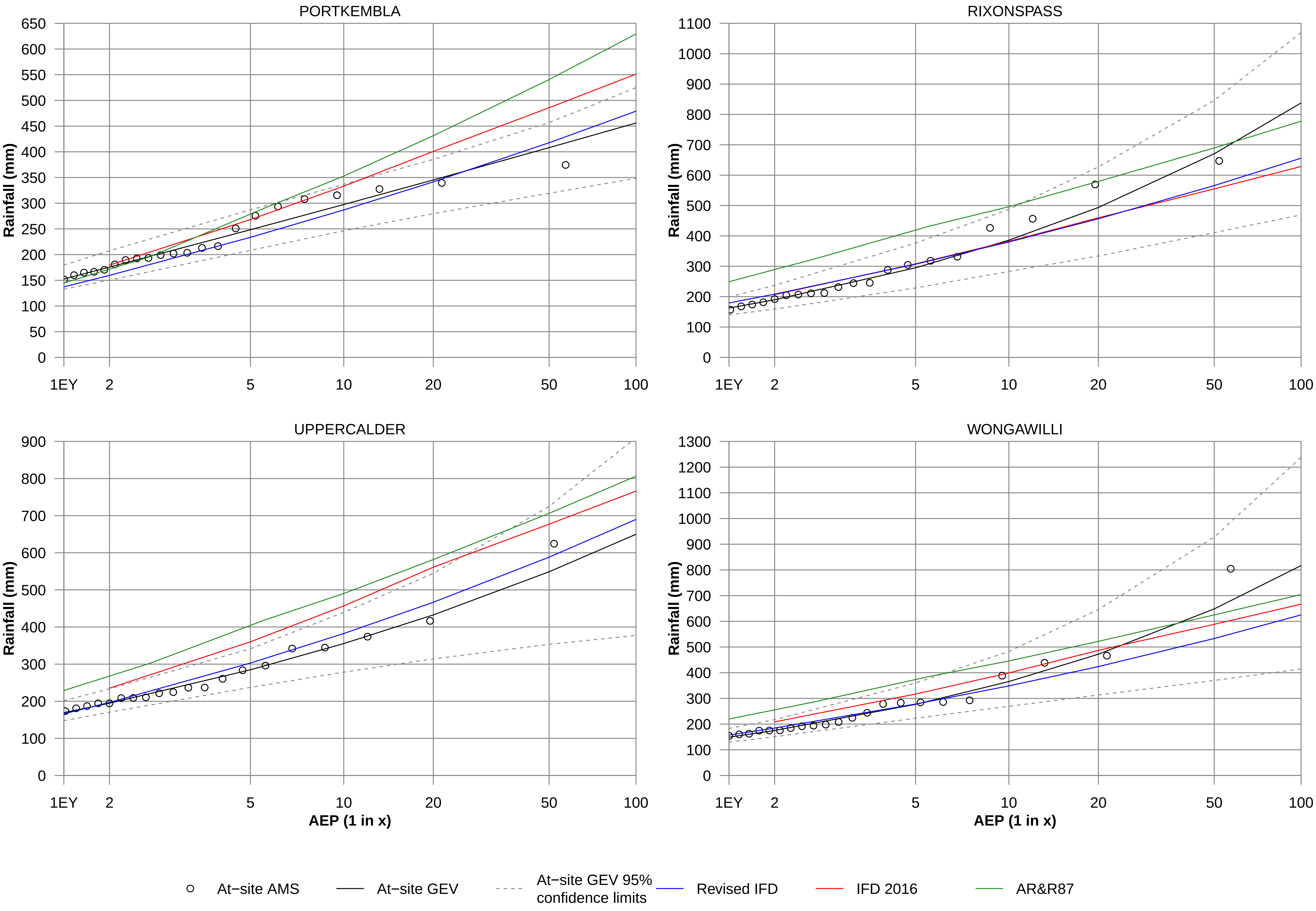


FIGURE A88

WOLLONGONG AREA STATIONS

72 HOUR IFD COMPARISON

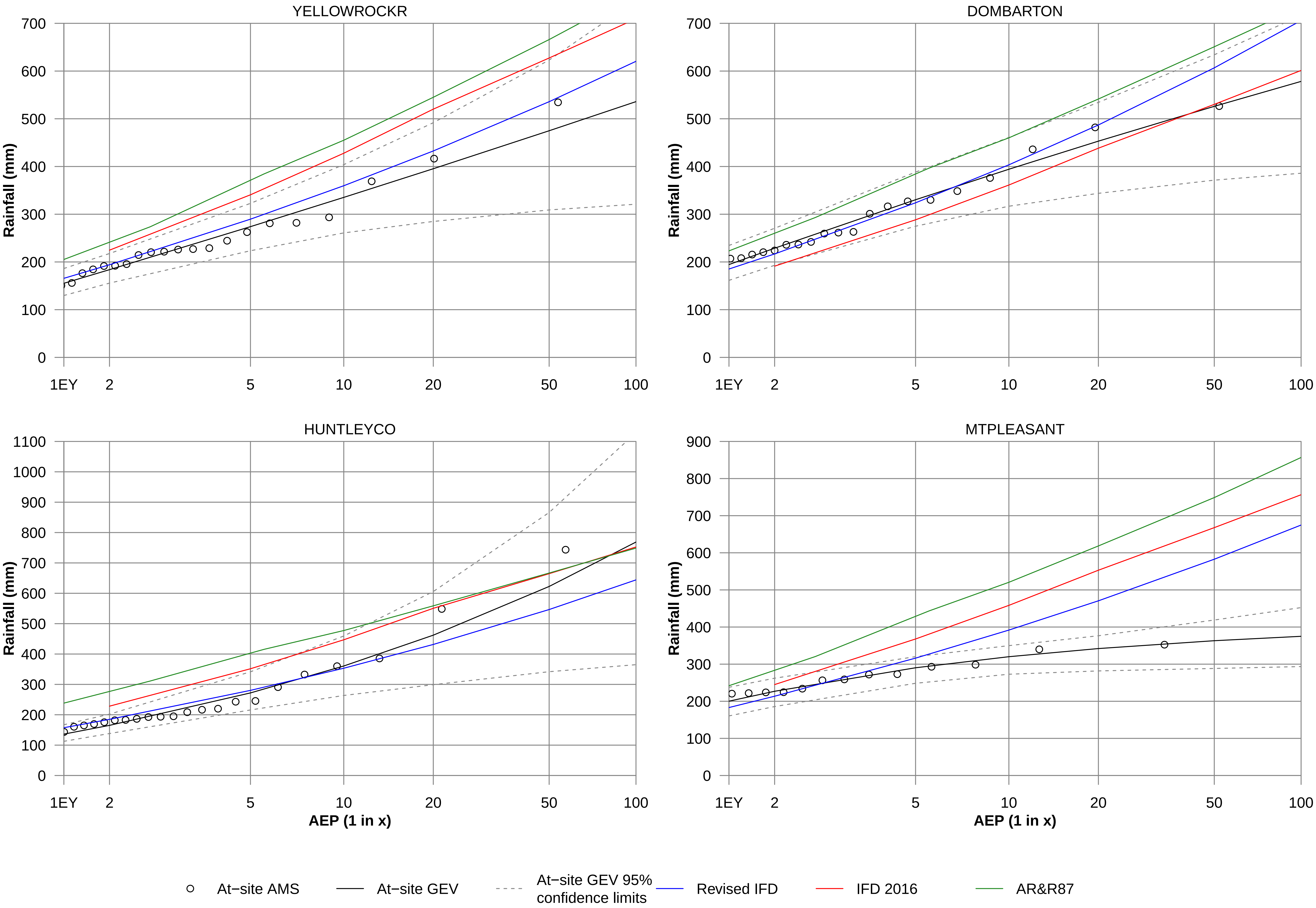
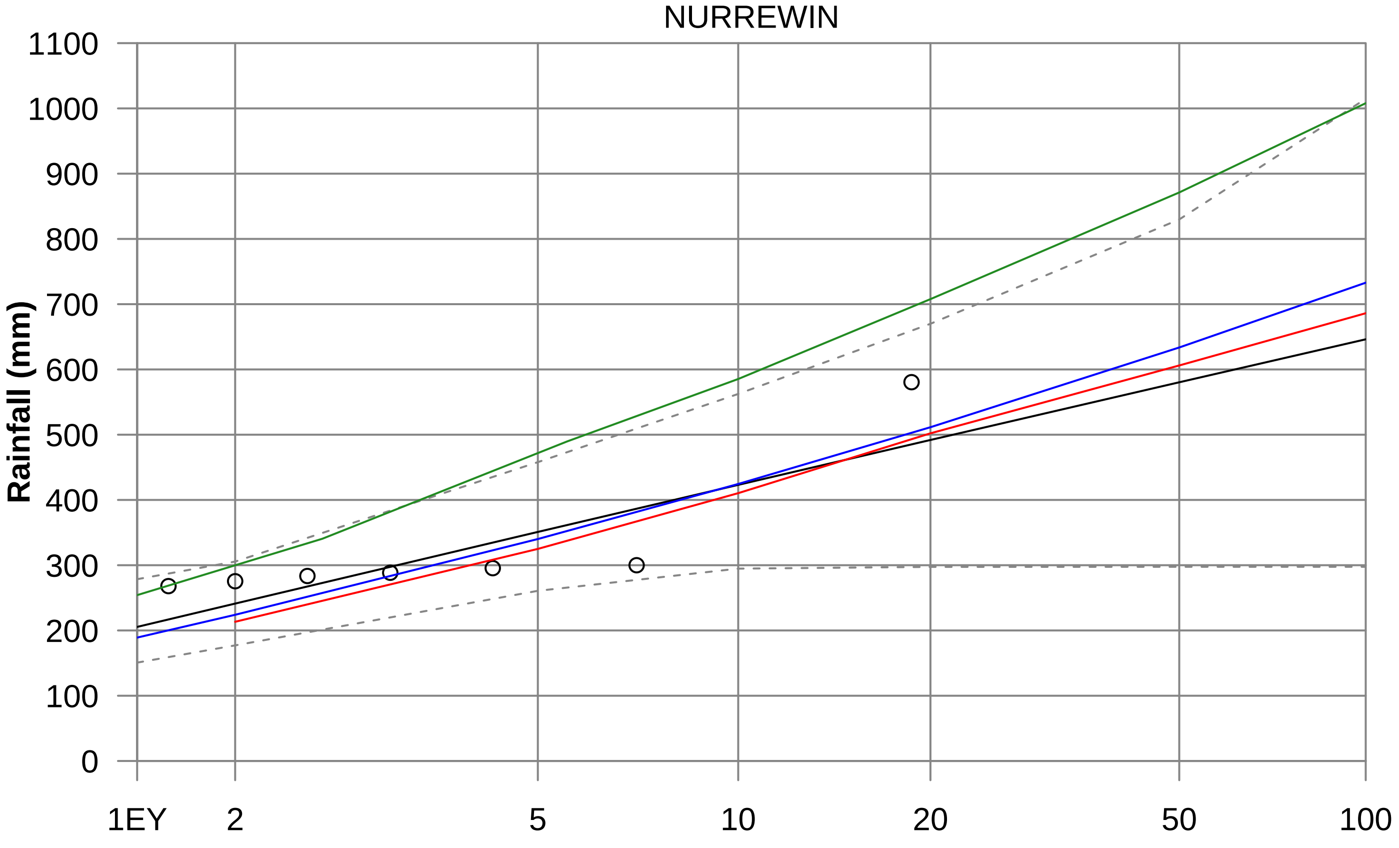
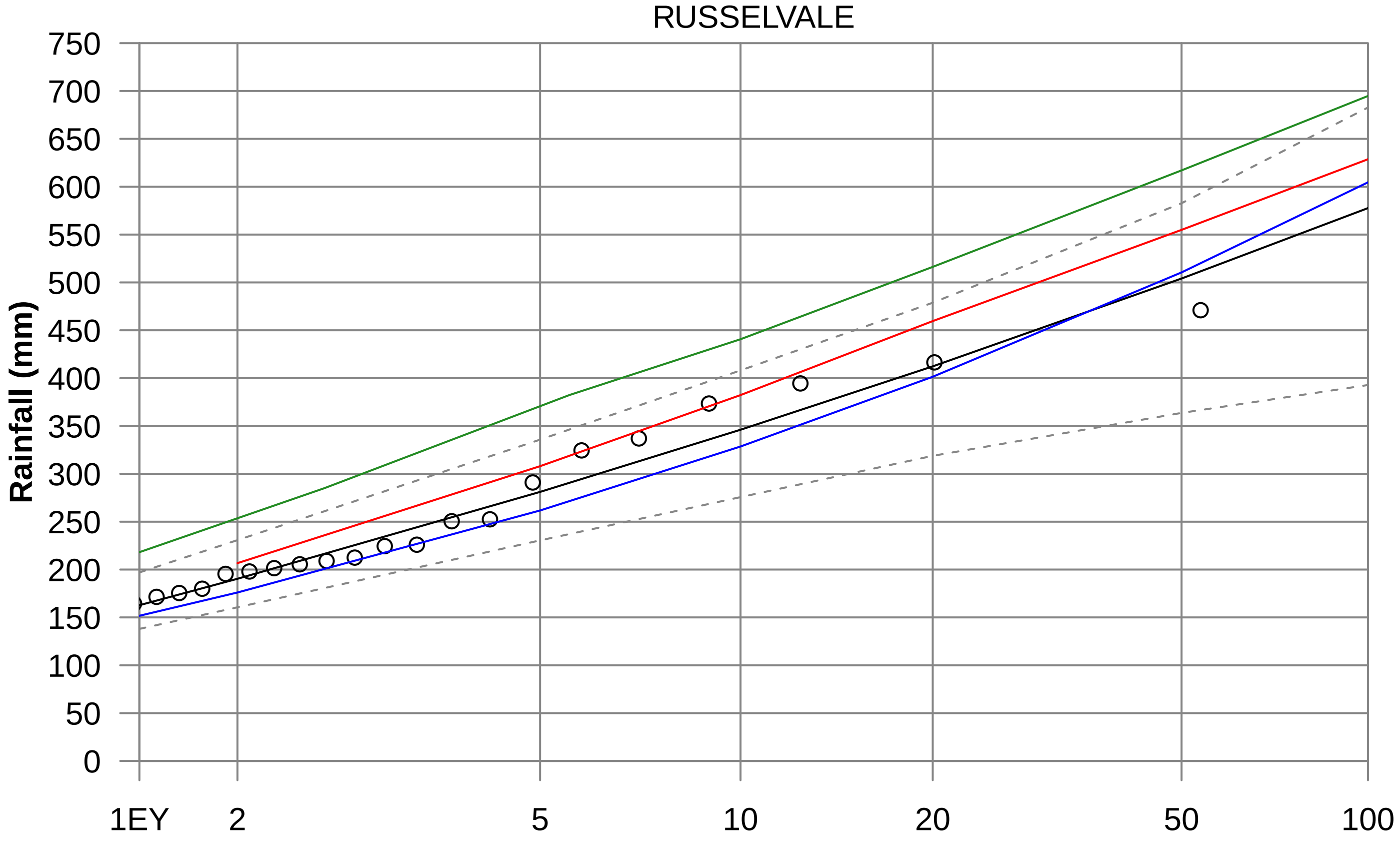


FIGURE A89
WOLLONGONG AREA STATIONS
72 HOUR IFD COMPARISON





Appendix B

FIGURE B1

5 MIN MEAN ESTIMATES

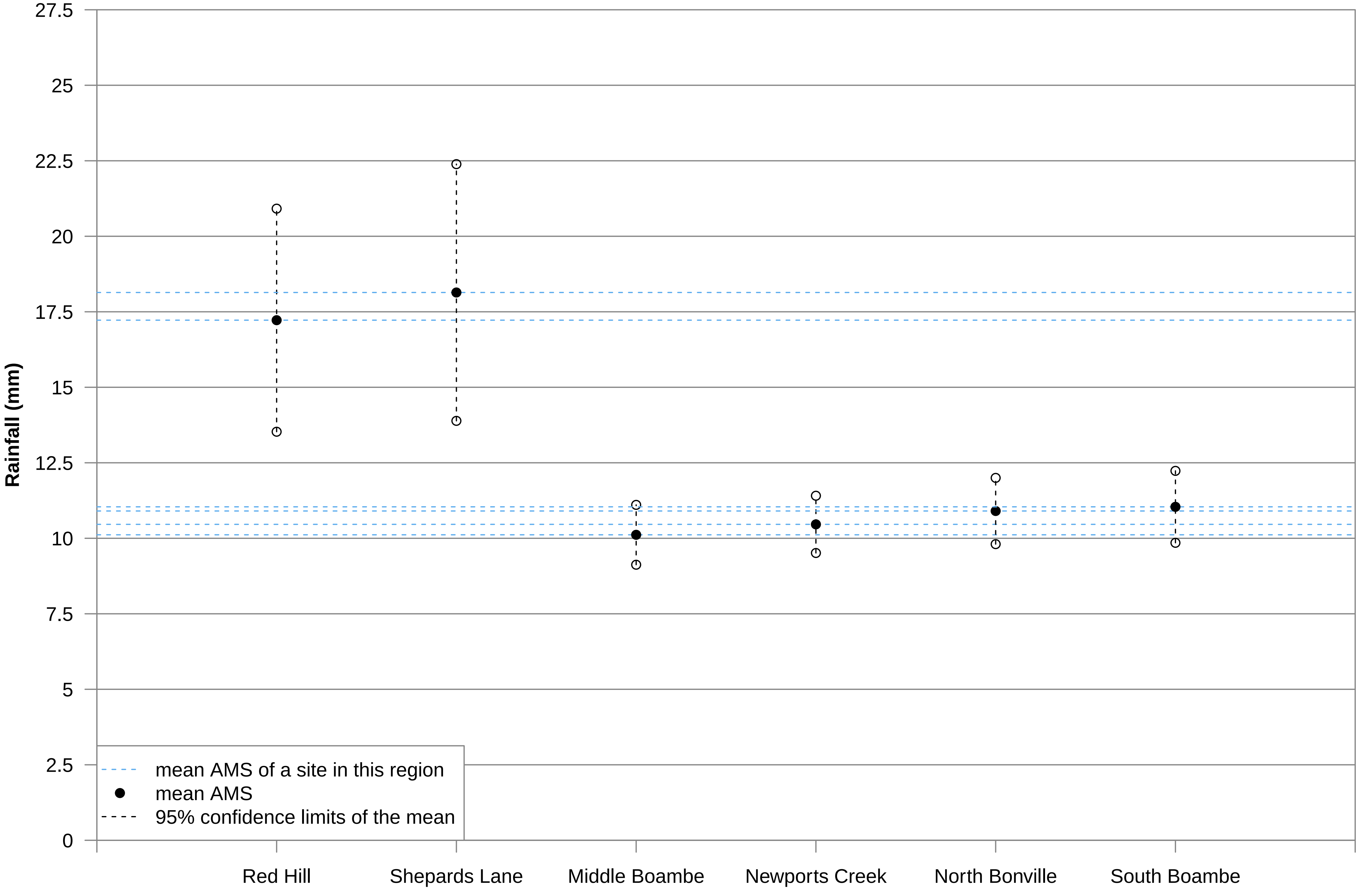


FIGURE B2

10 MIN MEAN ESTIMATES

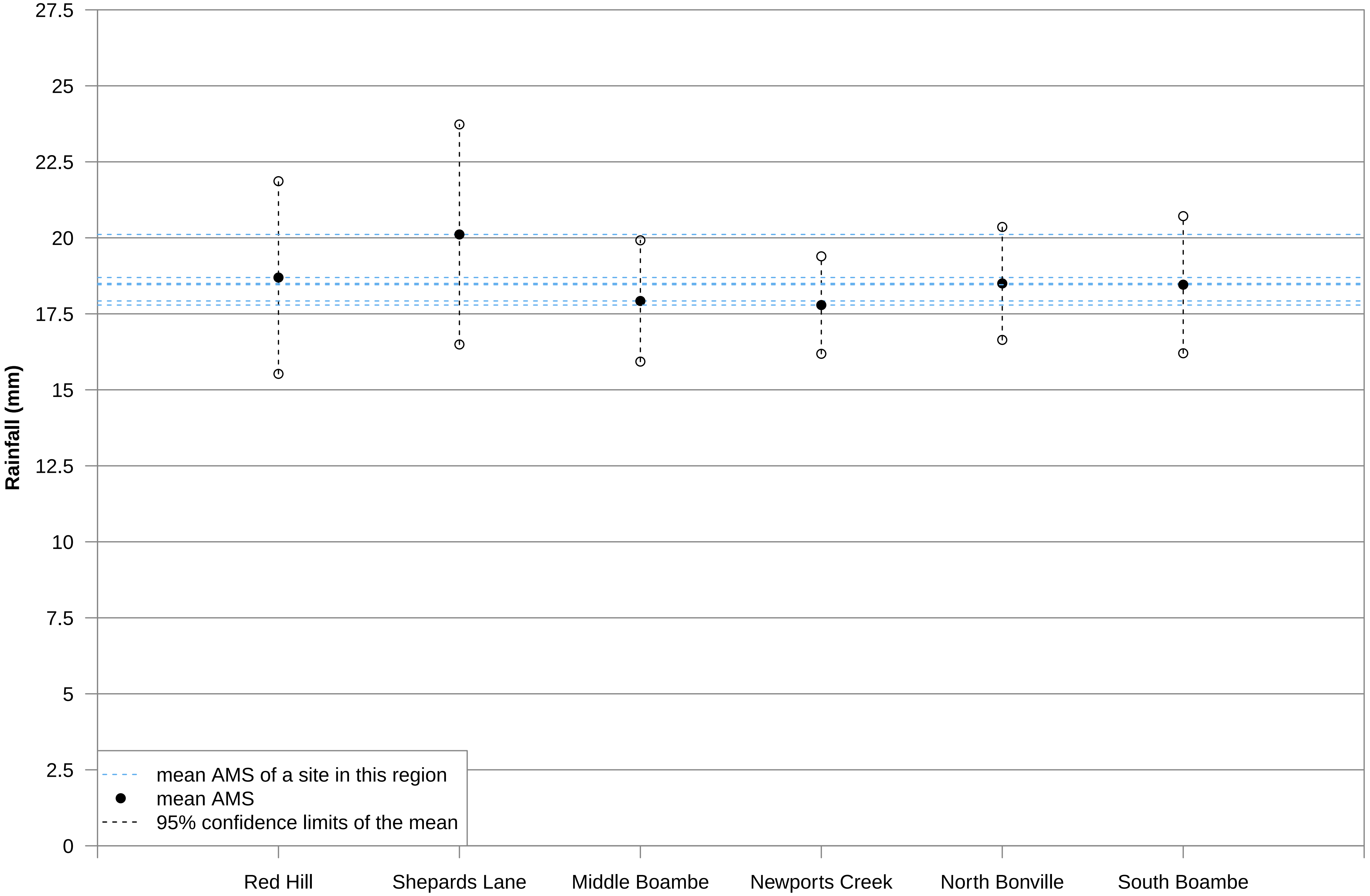


FIGURE B3
15 MIN MEAN ESTIMATES

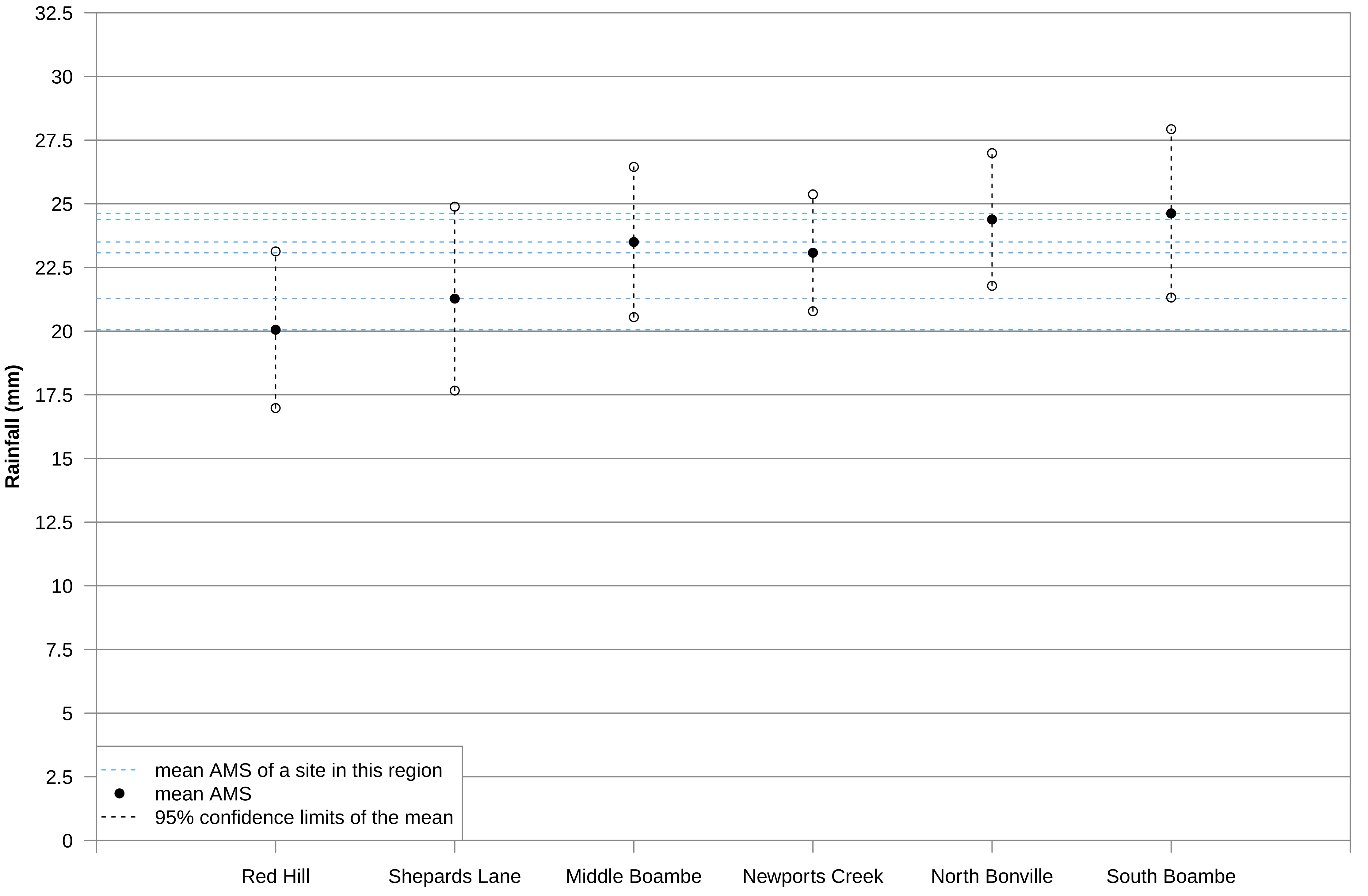


FIGURE B4
30 MIN MEAN ESTIMATES

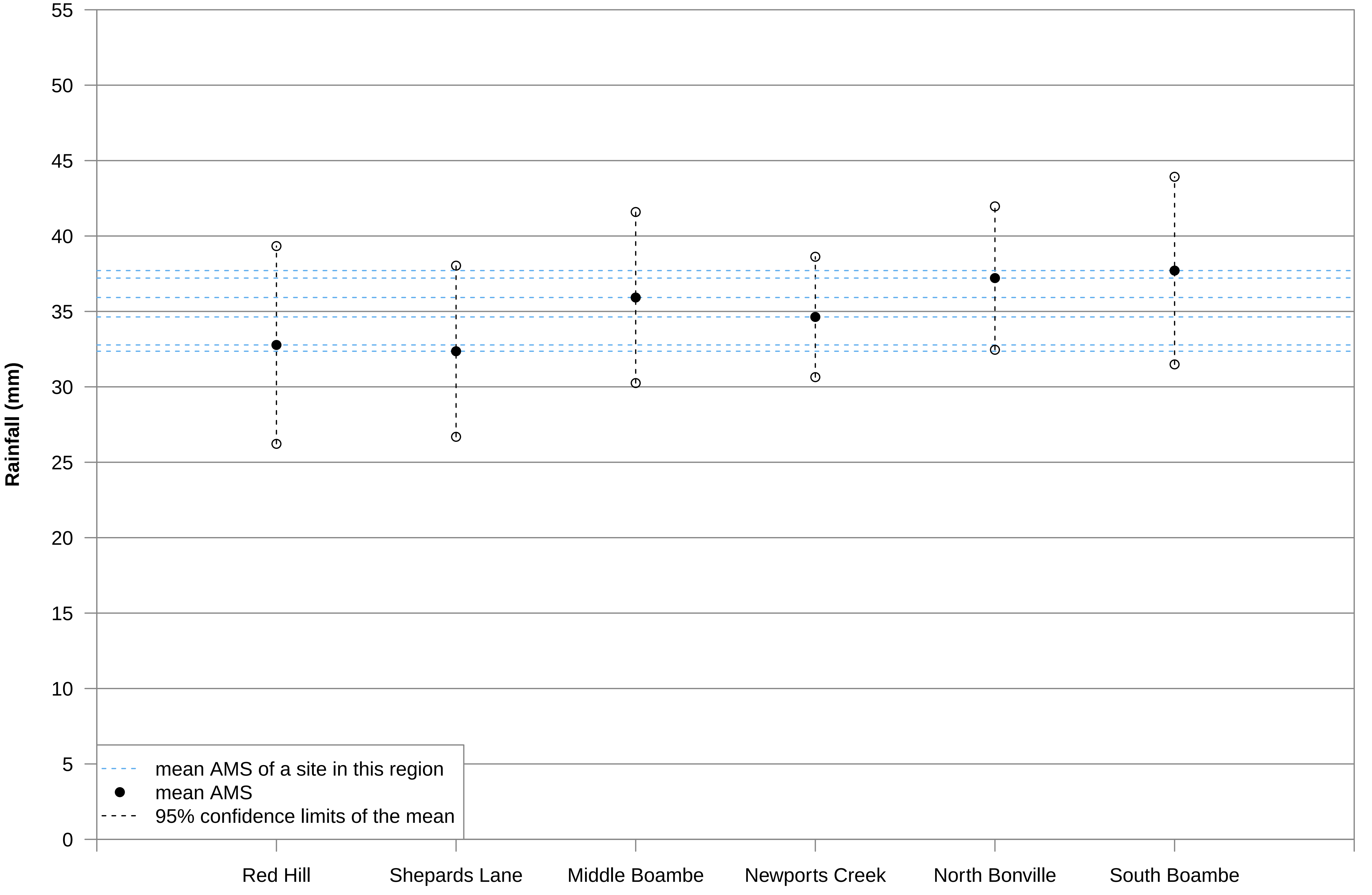
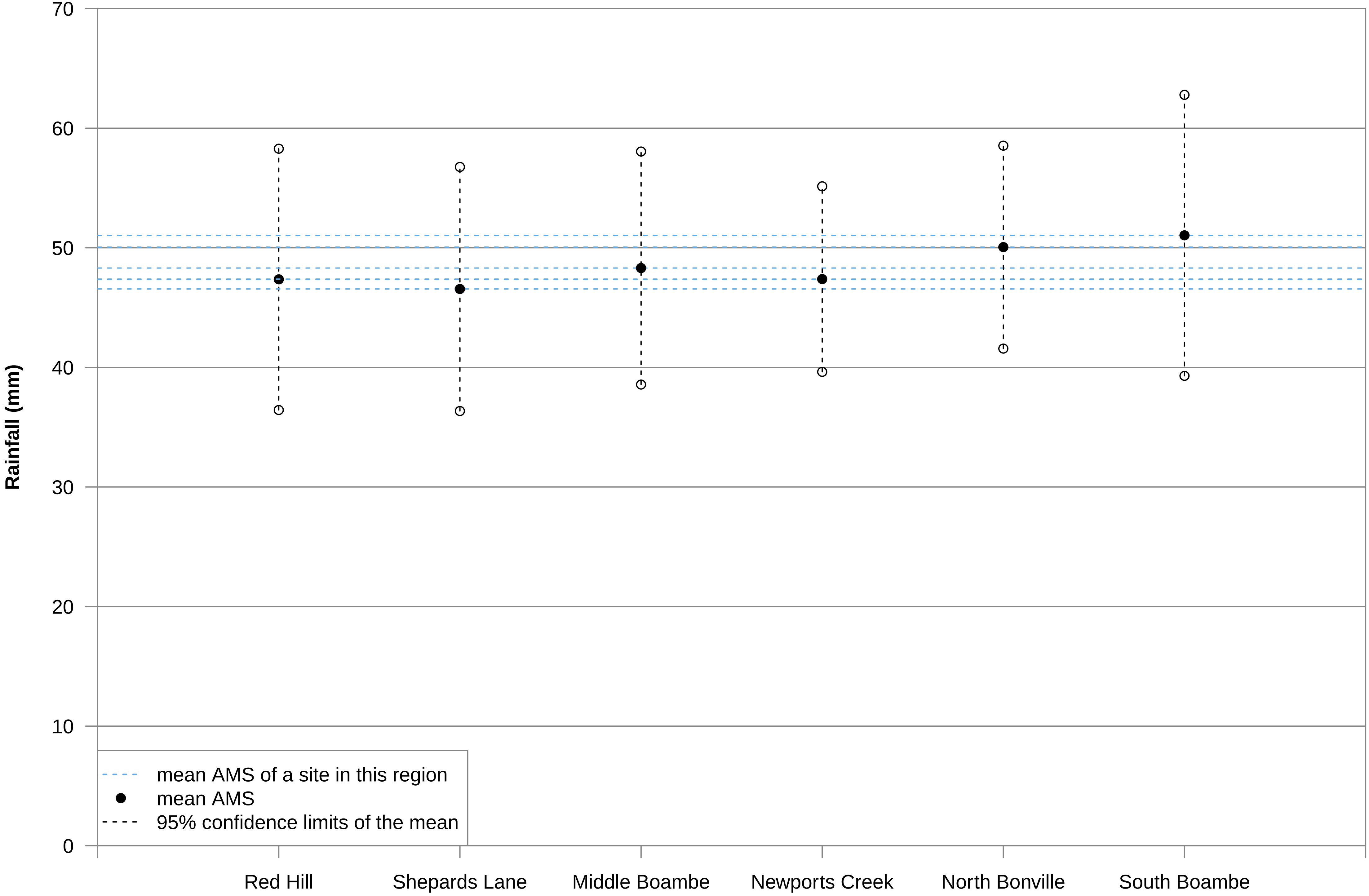
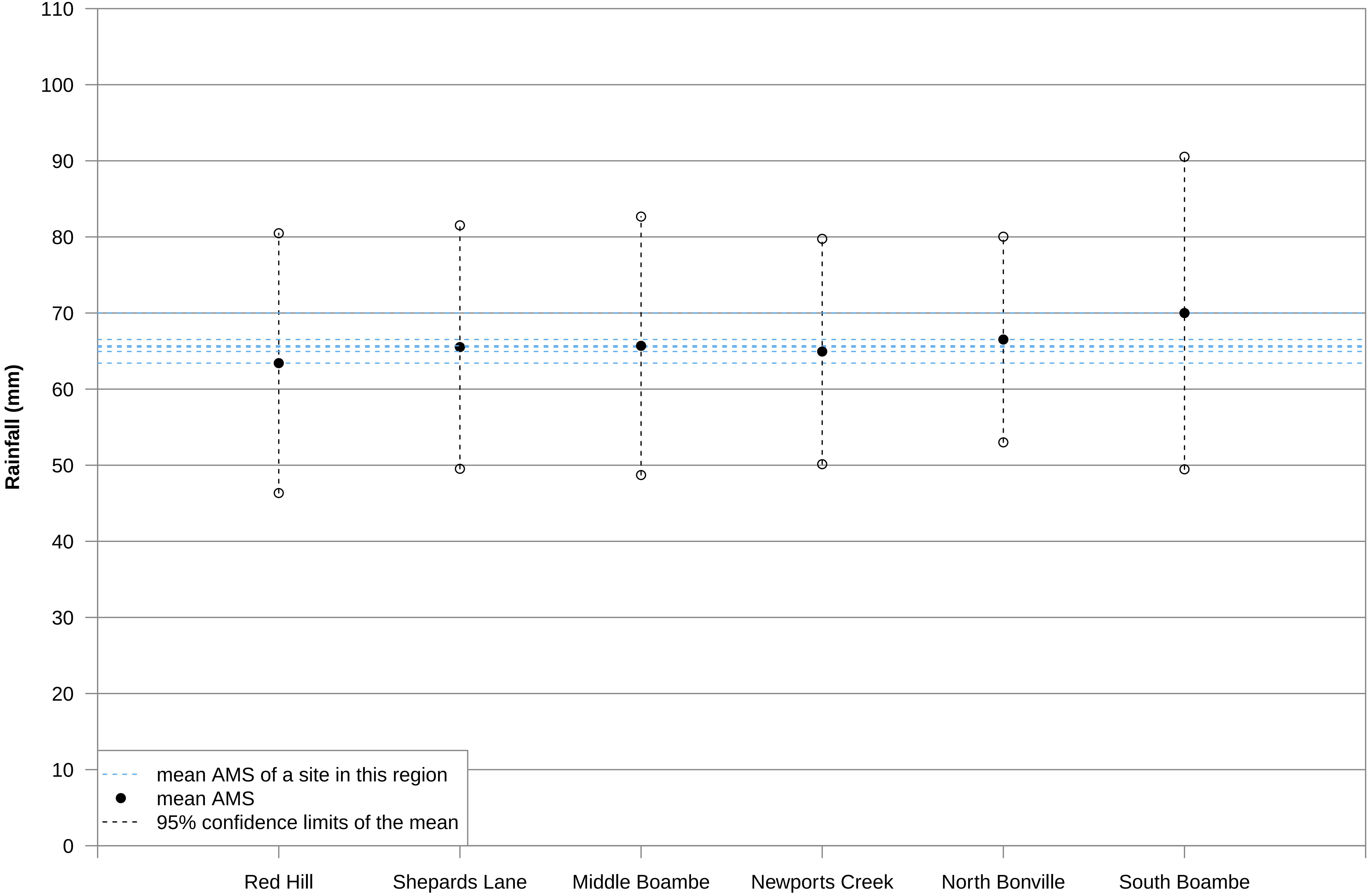


FIGURE B5
60 MIN MEAN ESTIMATES



120 MIN MEAN ESTIMATES



180 MIN MEAN ESTIMATES

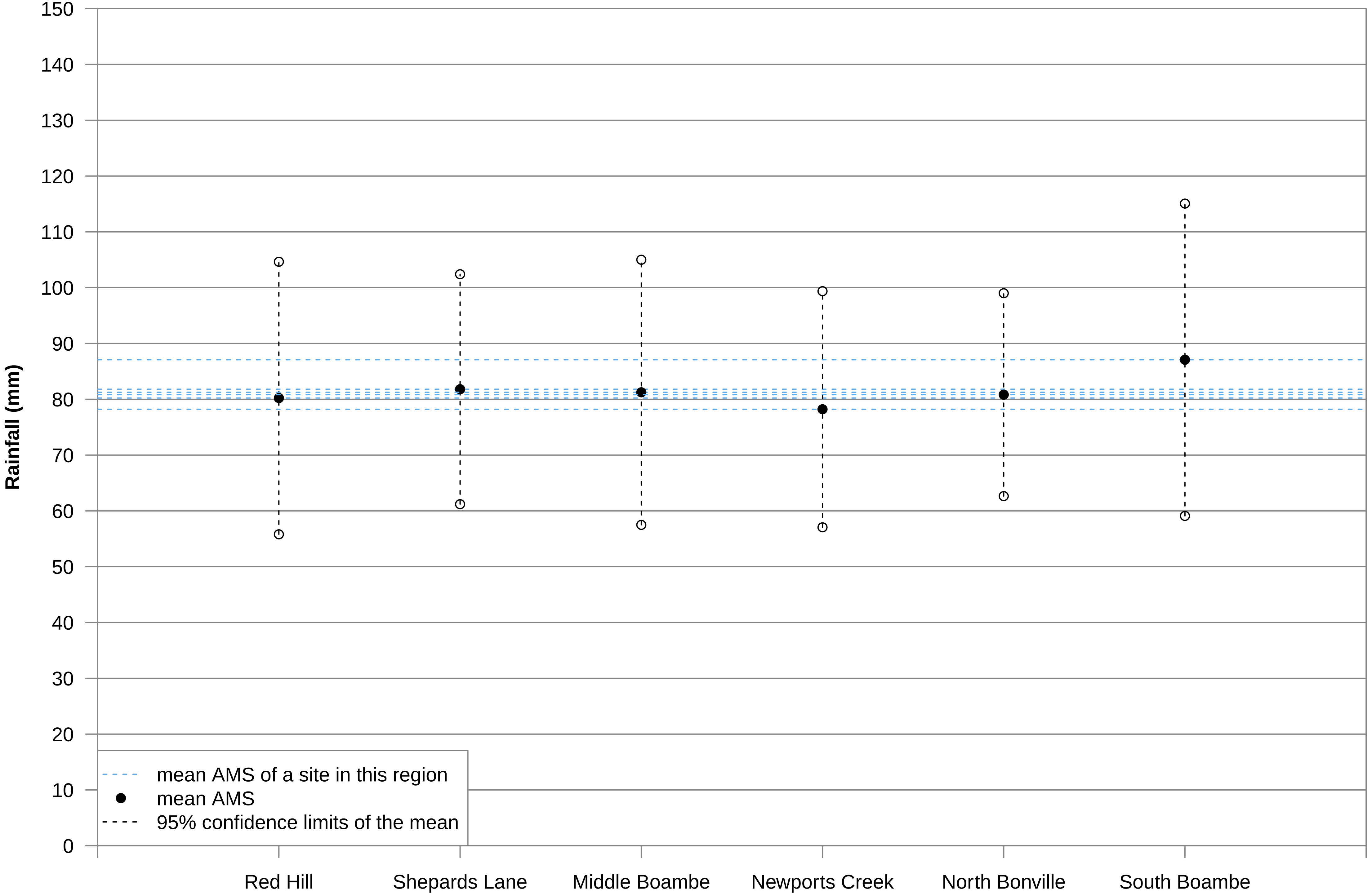


FIGURE B8
360 MIN MEAN ESTIMATES

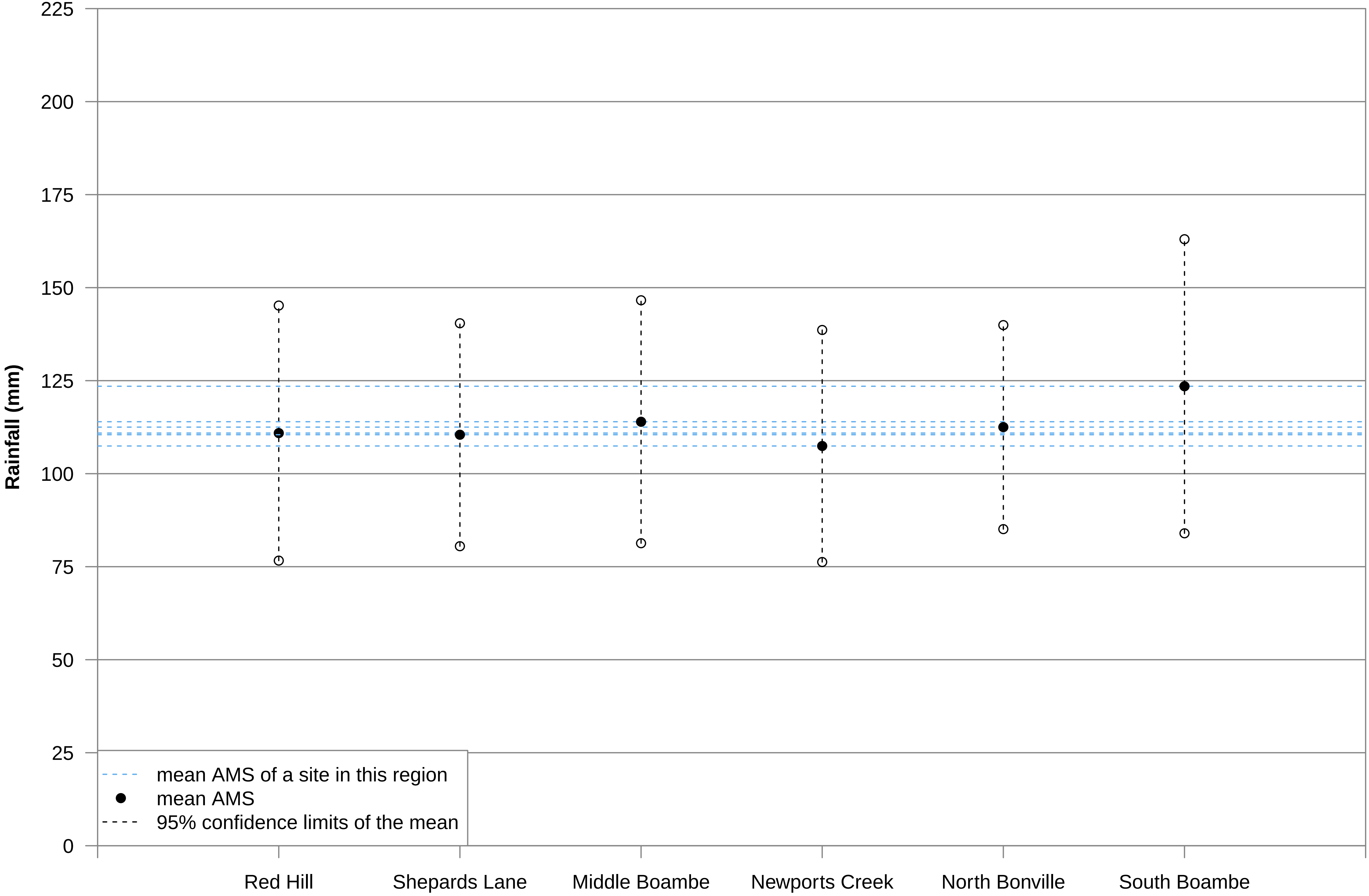


FIGURE B9

720 MIN MEAN ESTIMATES

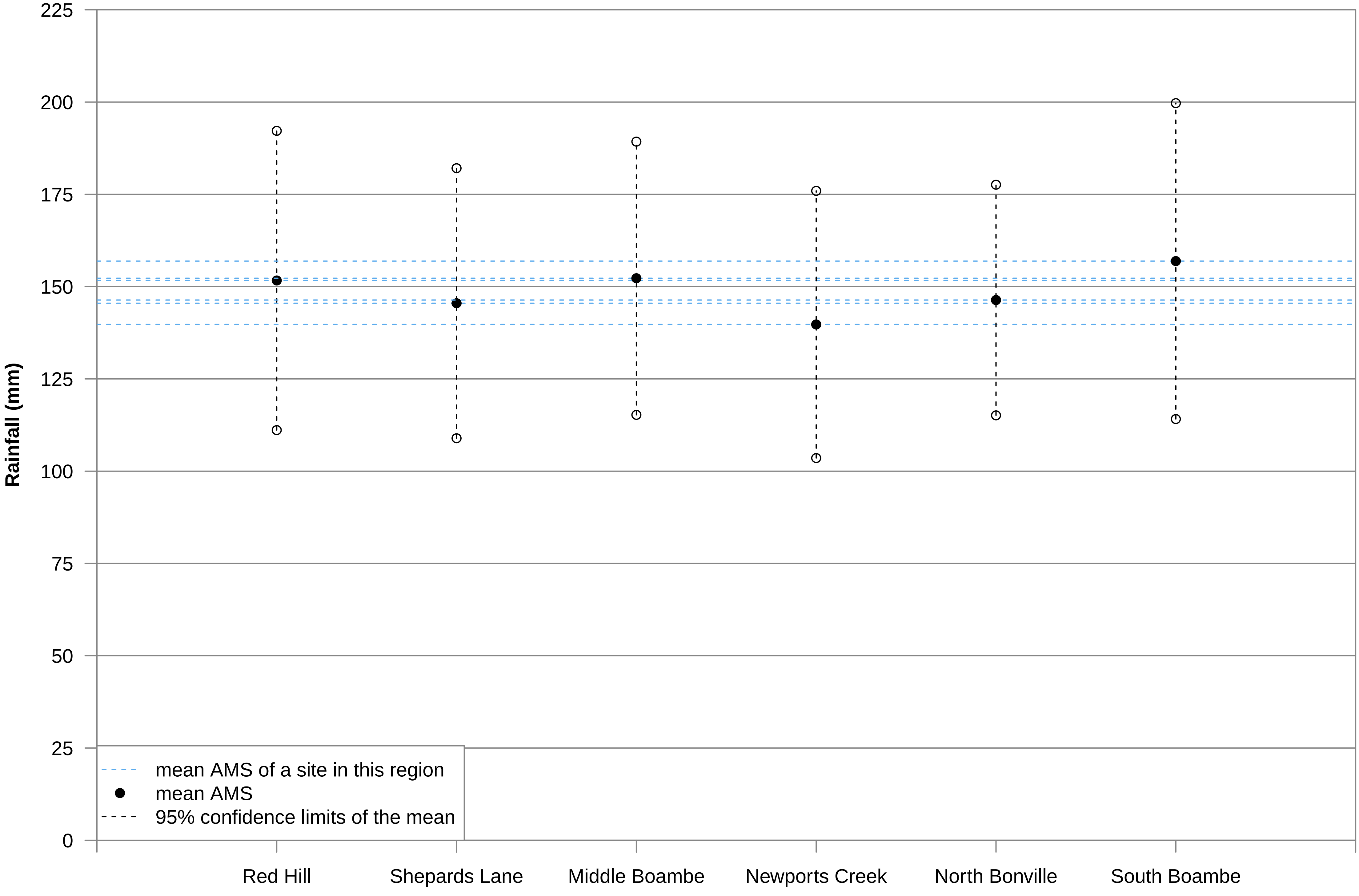


FIGURE B10
1440 MIN MEAN ESTIMATES

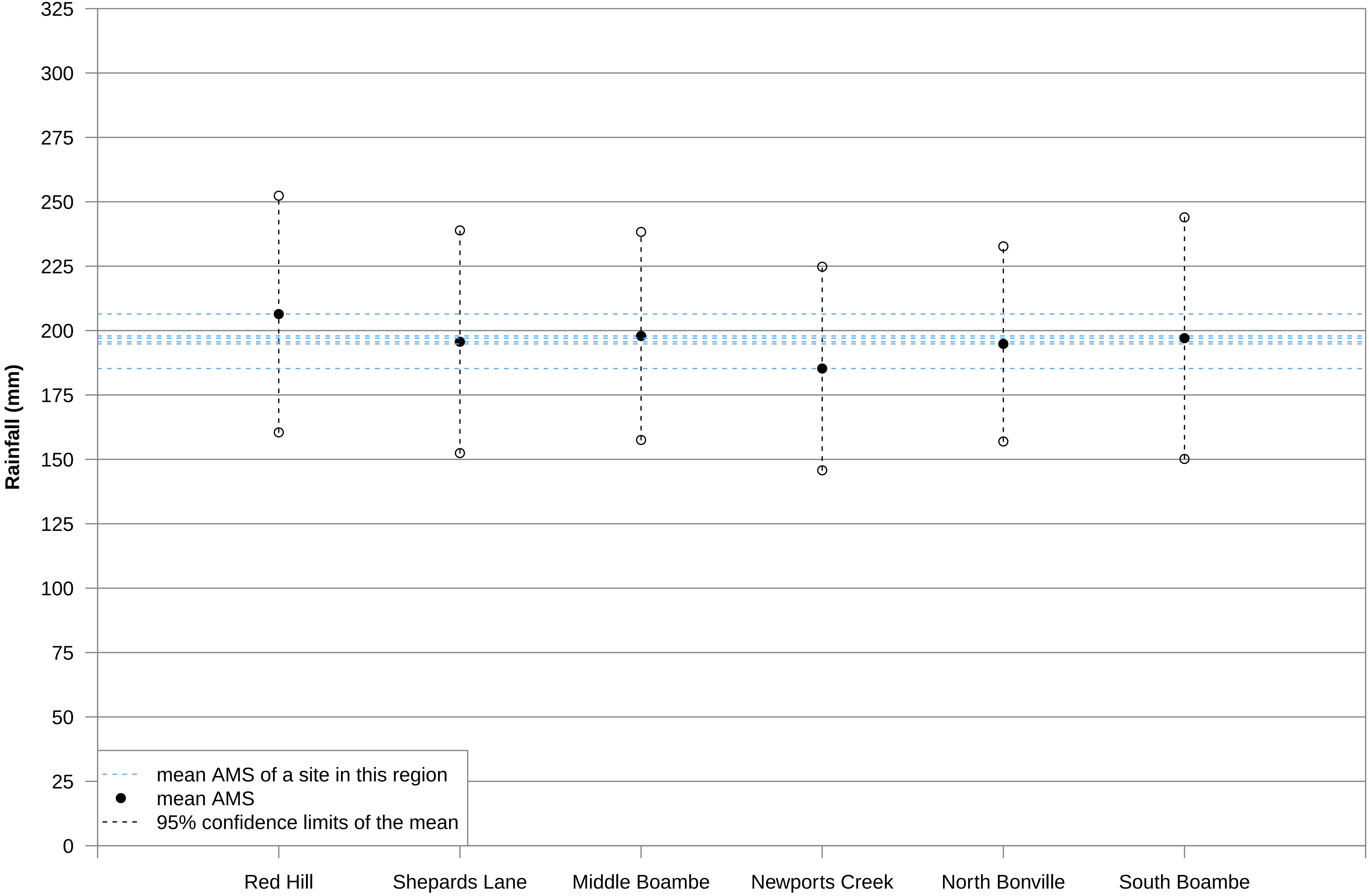


FIGURE B11

2880 MIN MEAN ESTIMATES

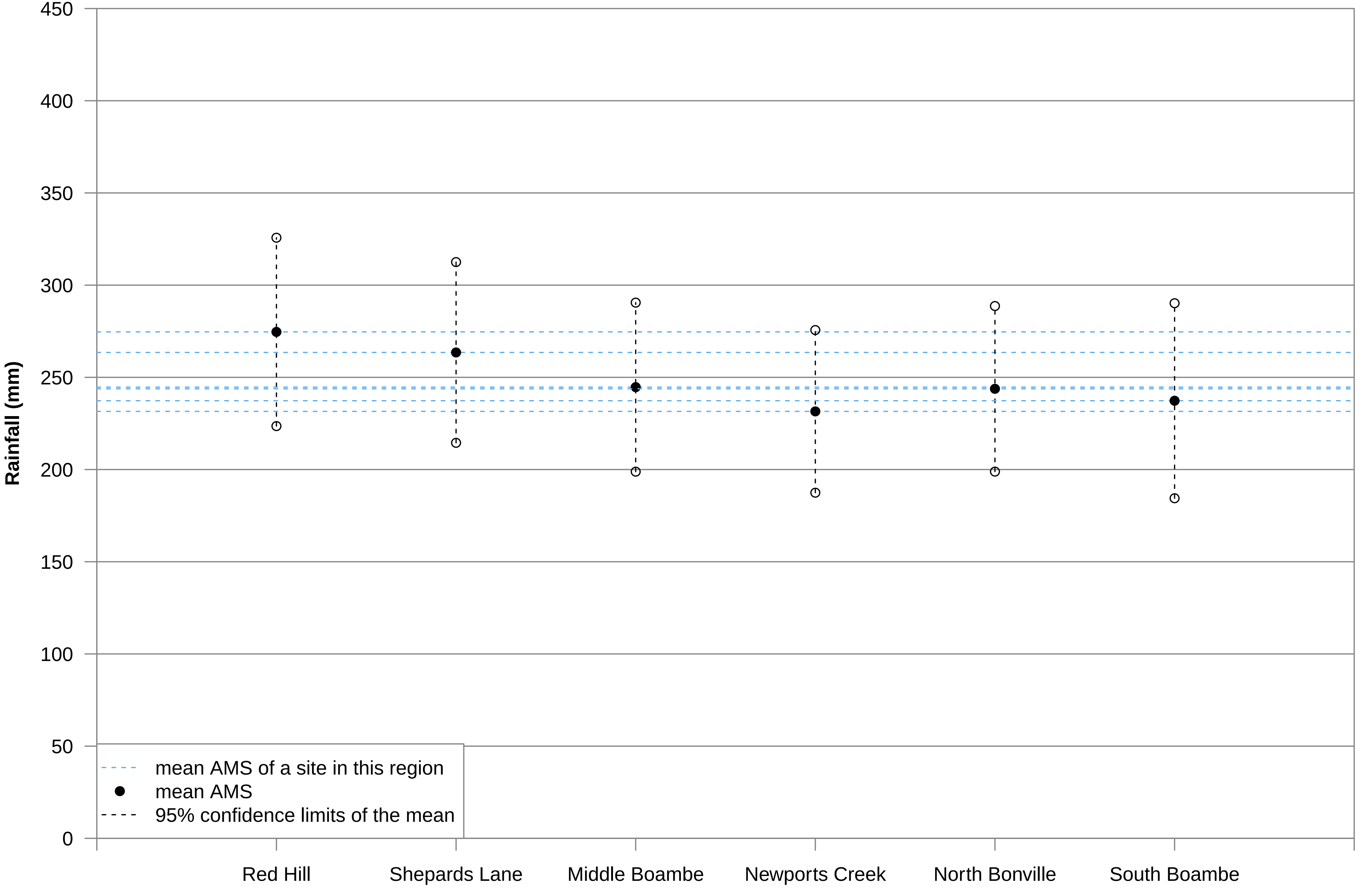
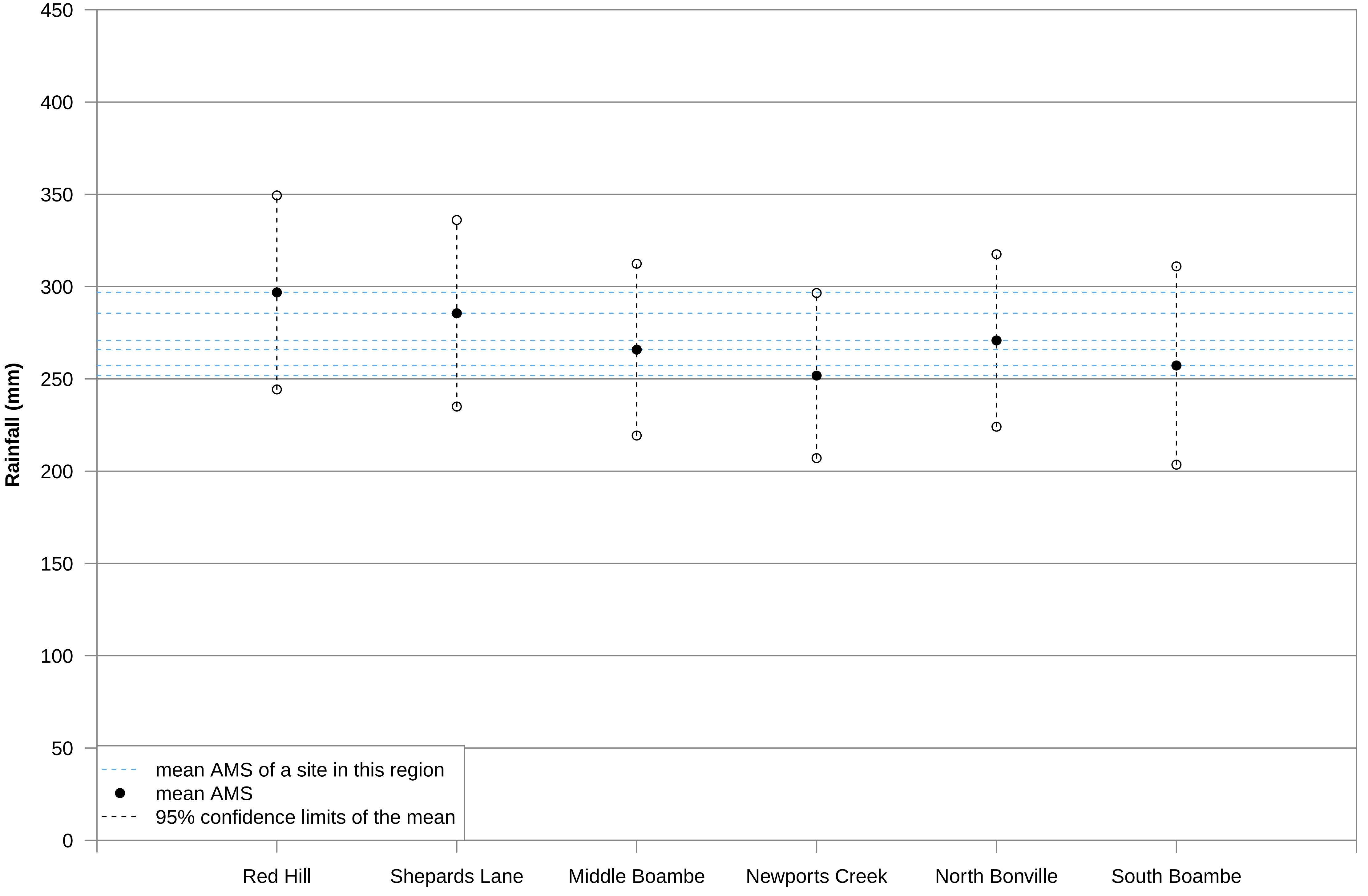


FIGURE B12

4320 MIN MEAN ESTIMATES



Appendix C

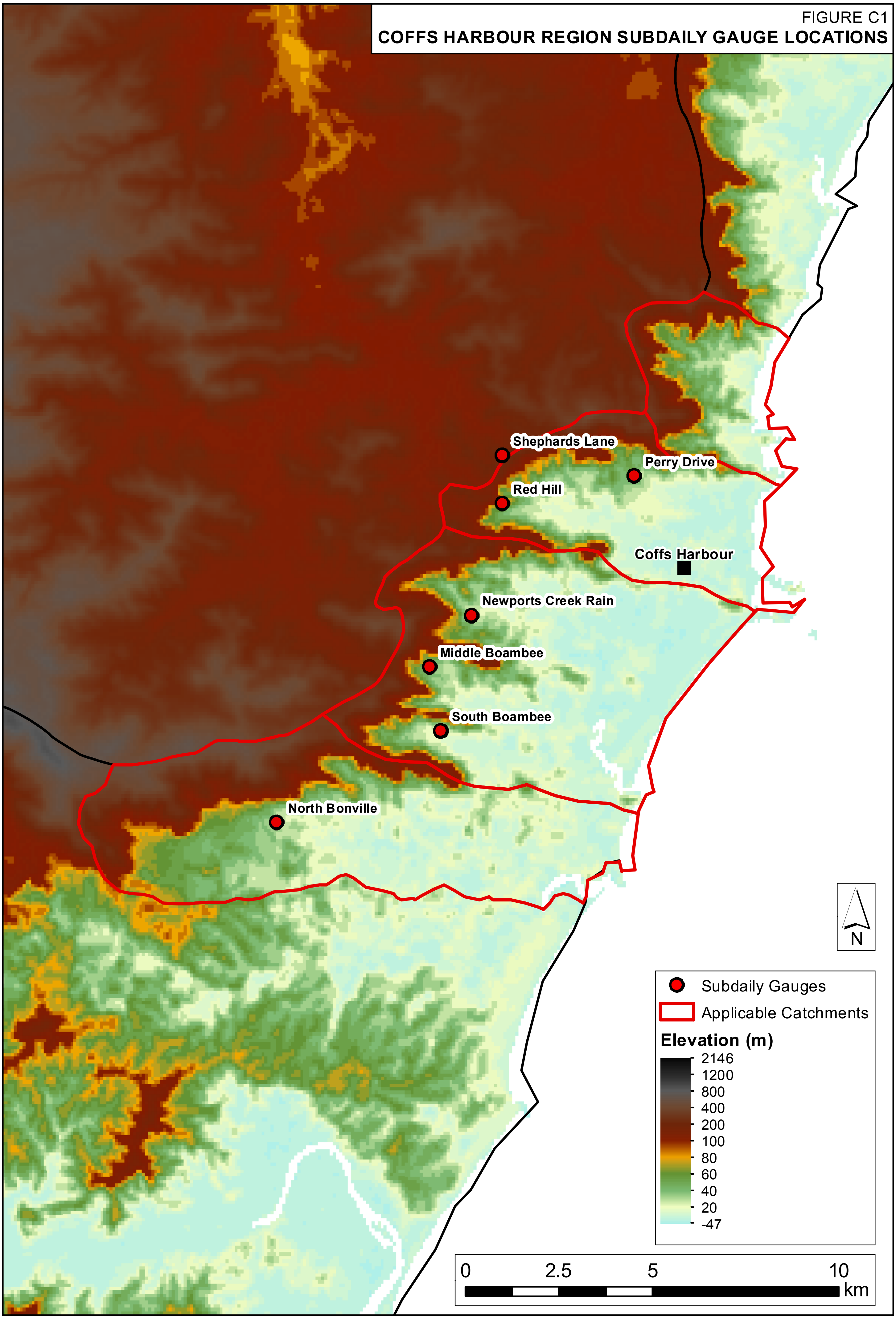
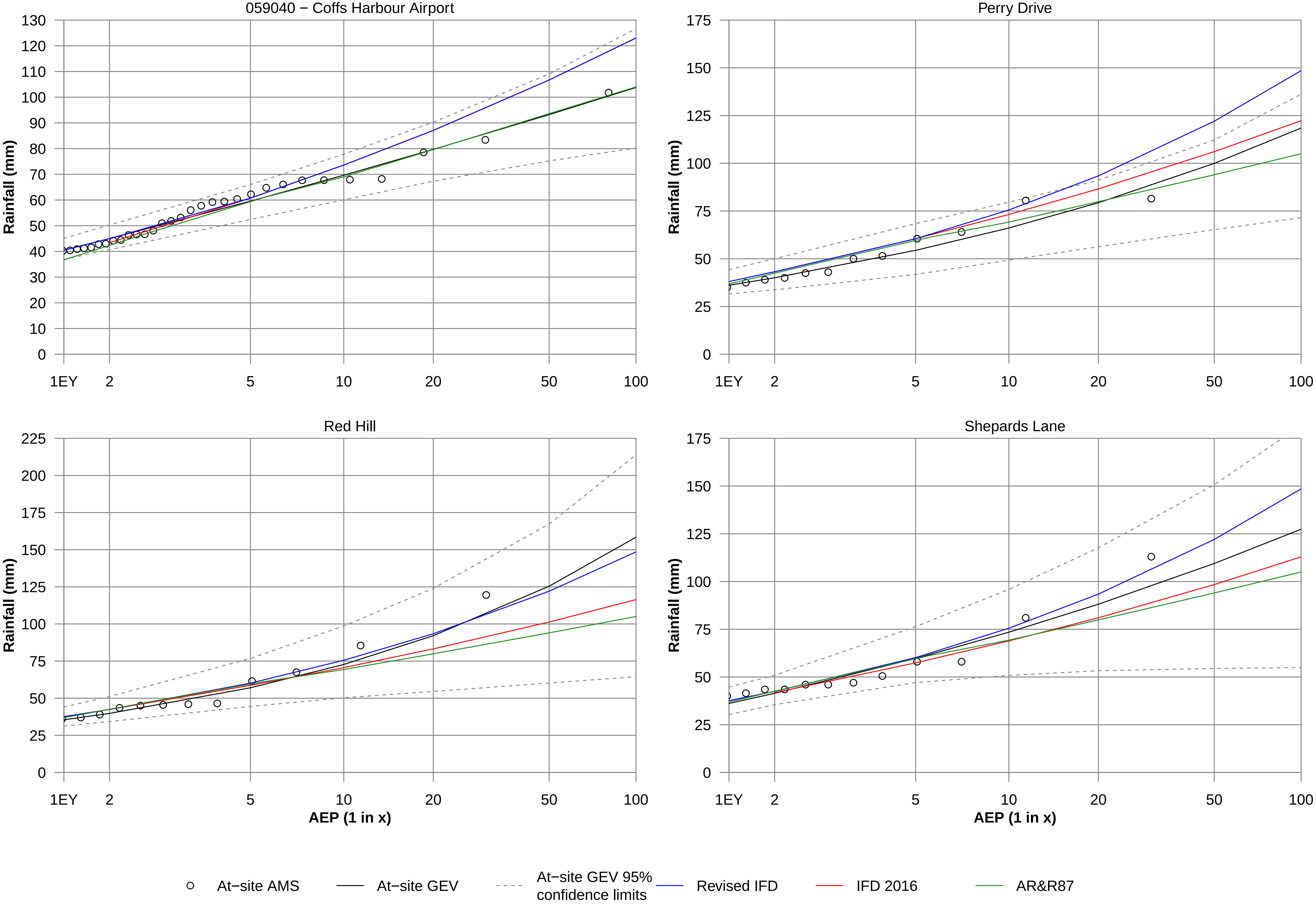
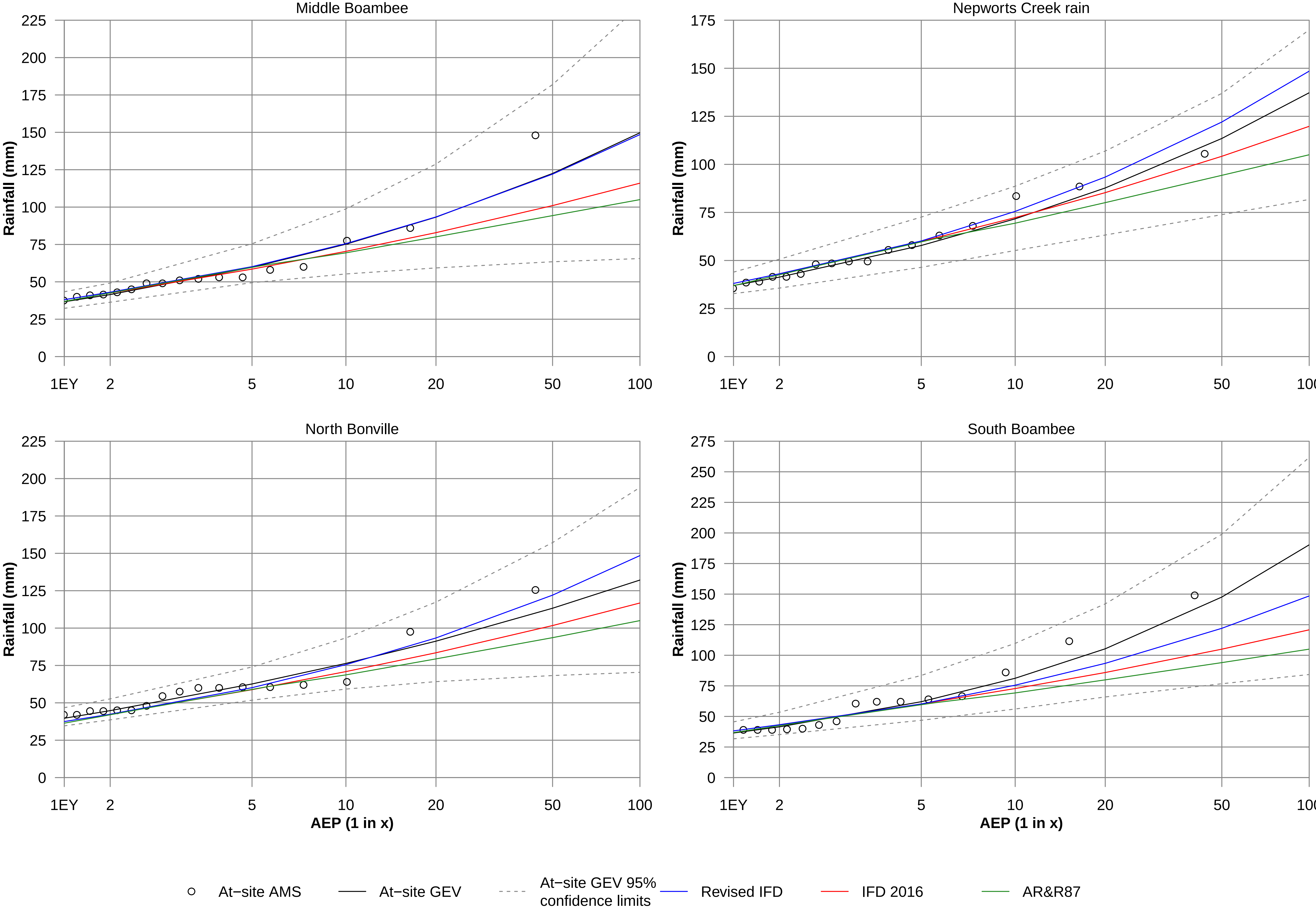


FIGURE C1
COFFS HARBOUR REGION SUBDAILY GAUGE LOCATIONS

J:\Jobs\116105\arcgis\report_mxd\FigureC1_CoffsHarbour_SubdailyGauge_Locations_Updated.mxd


059040 − Coffs Harbour Airport
Perry Drive
Red Hill
Shepards Lane
Rainfall (mm)
AEP (1 in x)
1EY
2
5
10
20
50
100
At−site AMS
At−site GEV
At−site GEV 95% confidence limits
Revised IFD
IFD 2016
AR&R87

COFFS HARBOUR AREA STATIONS
1 HOUR IFD COMPARISON



COFFS HARBOUR AREA STATIONS
2 HOUR IFD COMPARISON

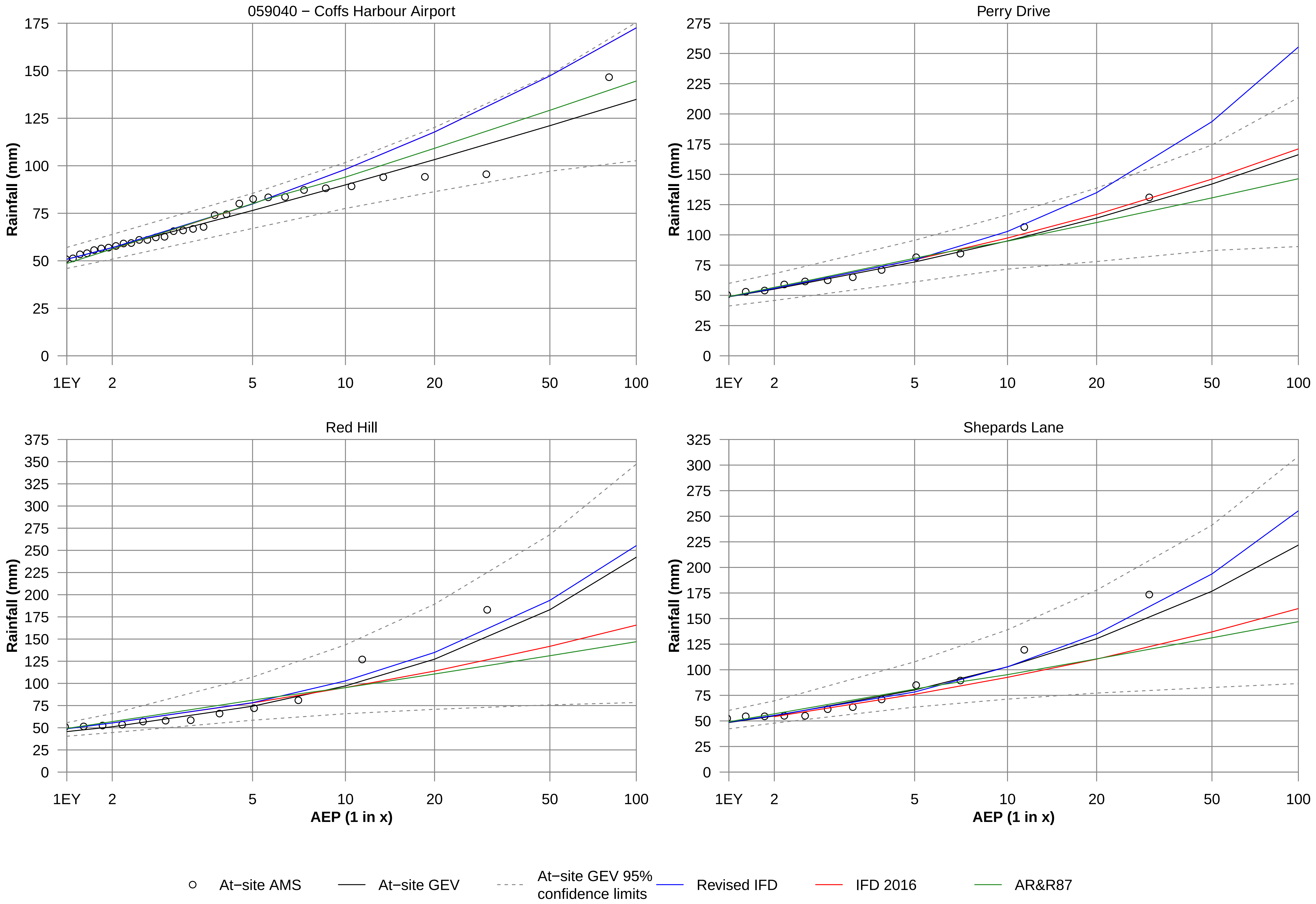
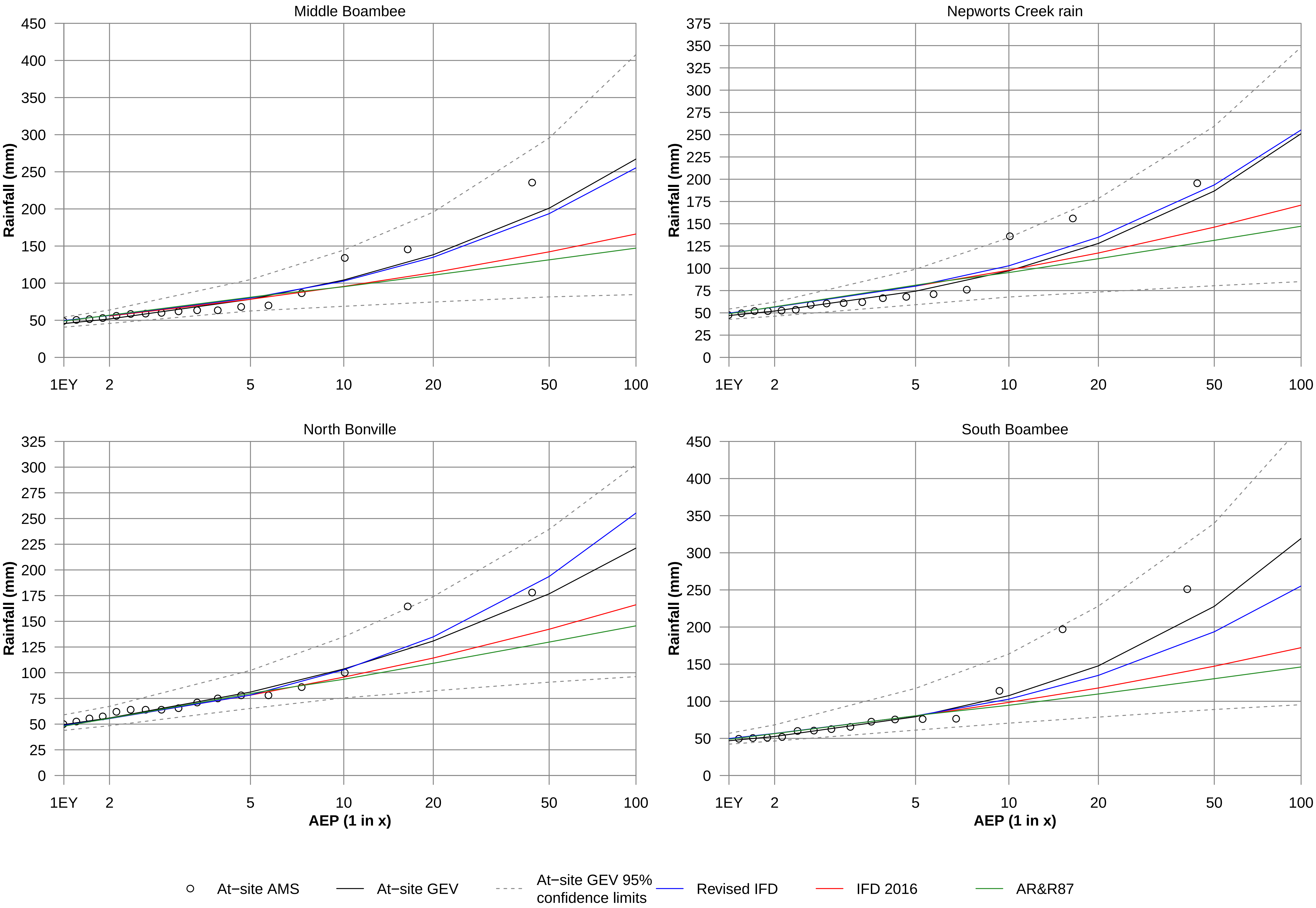


FIGURE C5
COFFS HARBOUR AREA STATIONS
2 HOUR IFD COMPARISON



COFFS HARBOUR AREA STATIONS
3 HOUR IFD COMPARISON

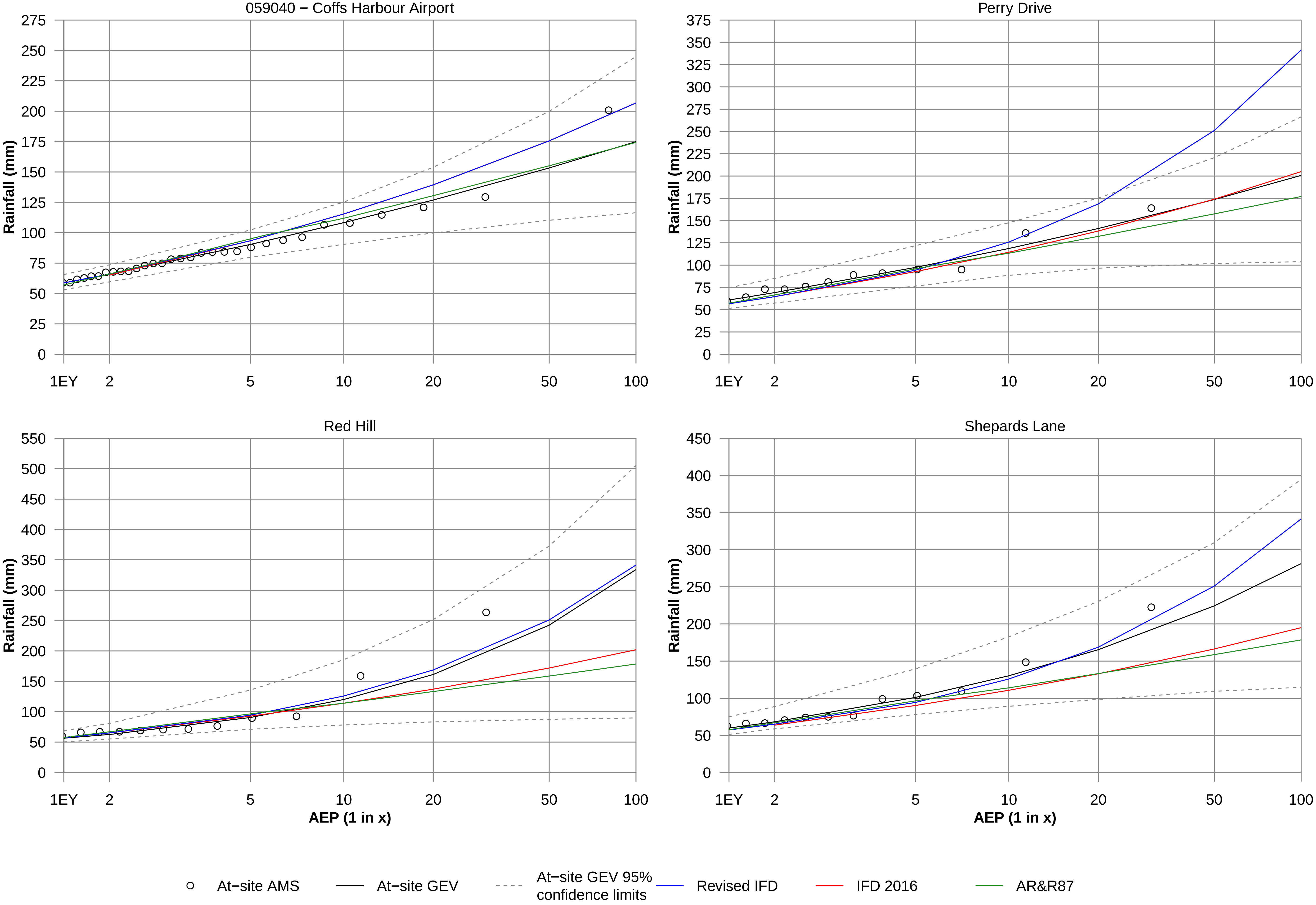


FIGURE C7
COFFS HARBOUR AREA STATIONS
3 HOUR IFD COMPARISON

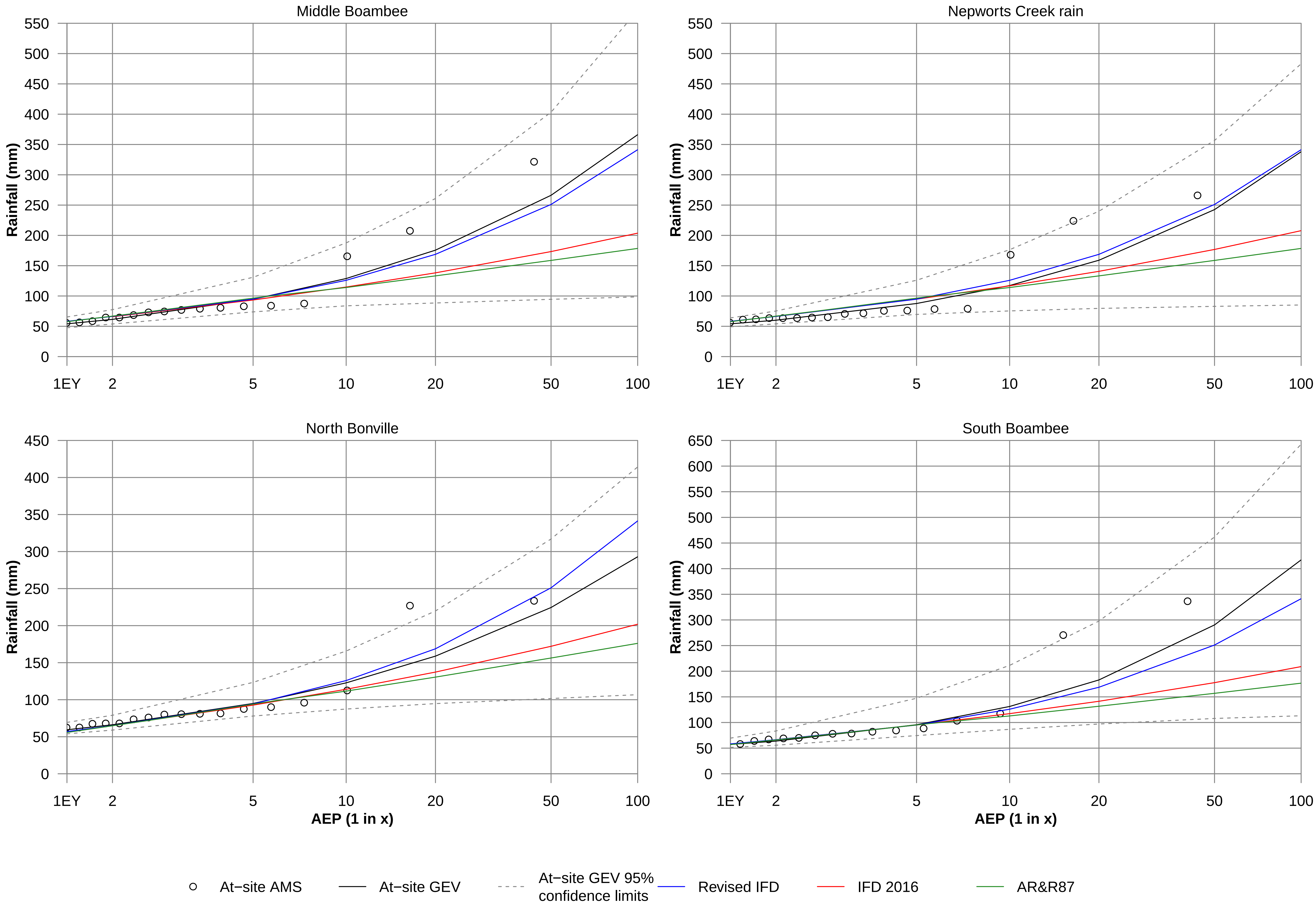
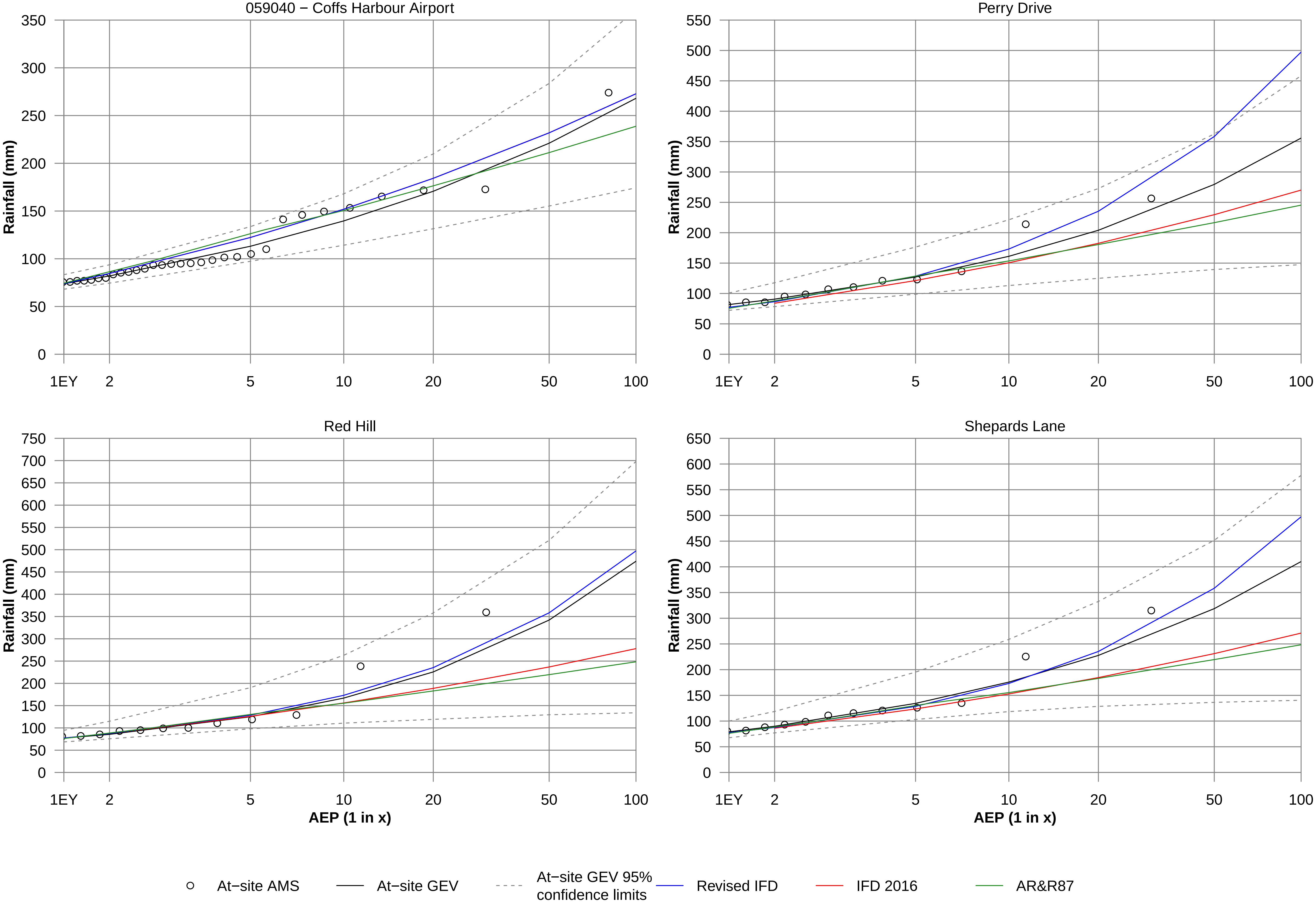


FIGURE C8
COFFS HARBOUR AREA STATIONS
6 HOUR IFD COMPARISON



COFFS HARBOUR AREA STATIONS
6 HOUR IFD COMPARISON

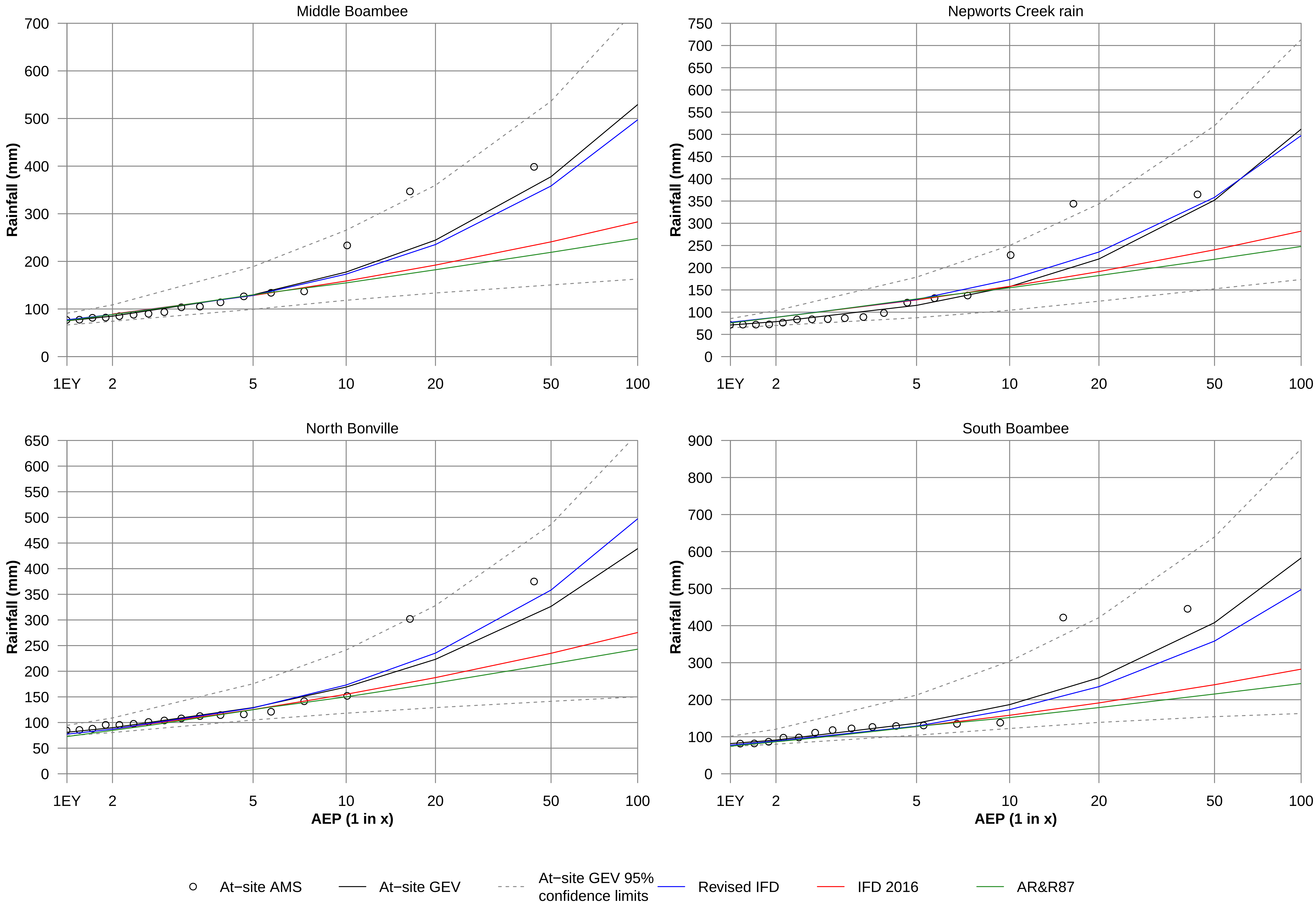


FIGURE C10
COFFS HARBOUR AREA STATIONS
12 HOUR IFD COMPARISON

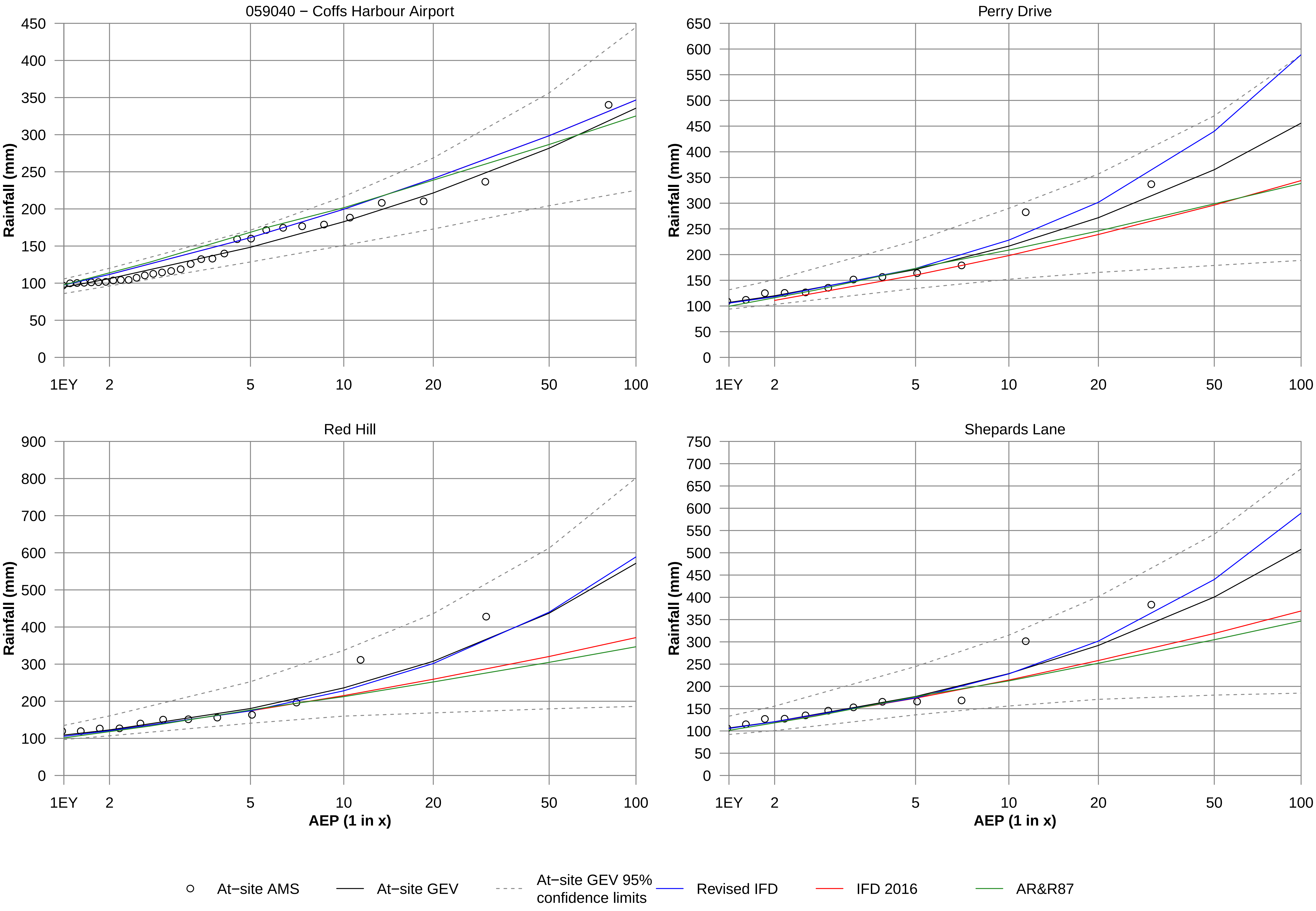


FIGURE C11

COFFS HARBOUR AREA STATIONS

12 HOUR IFD COMPARISON

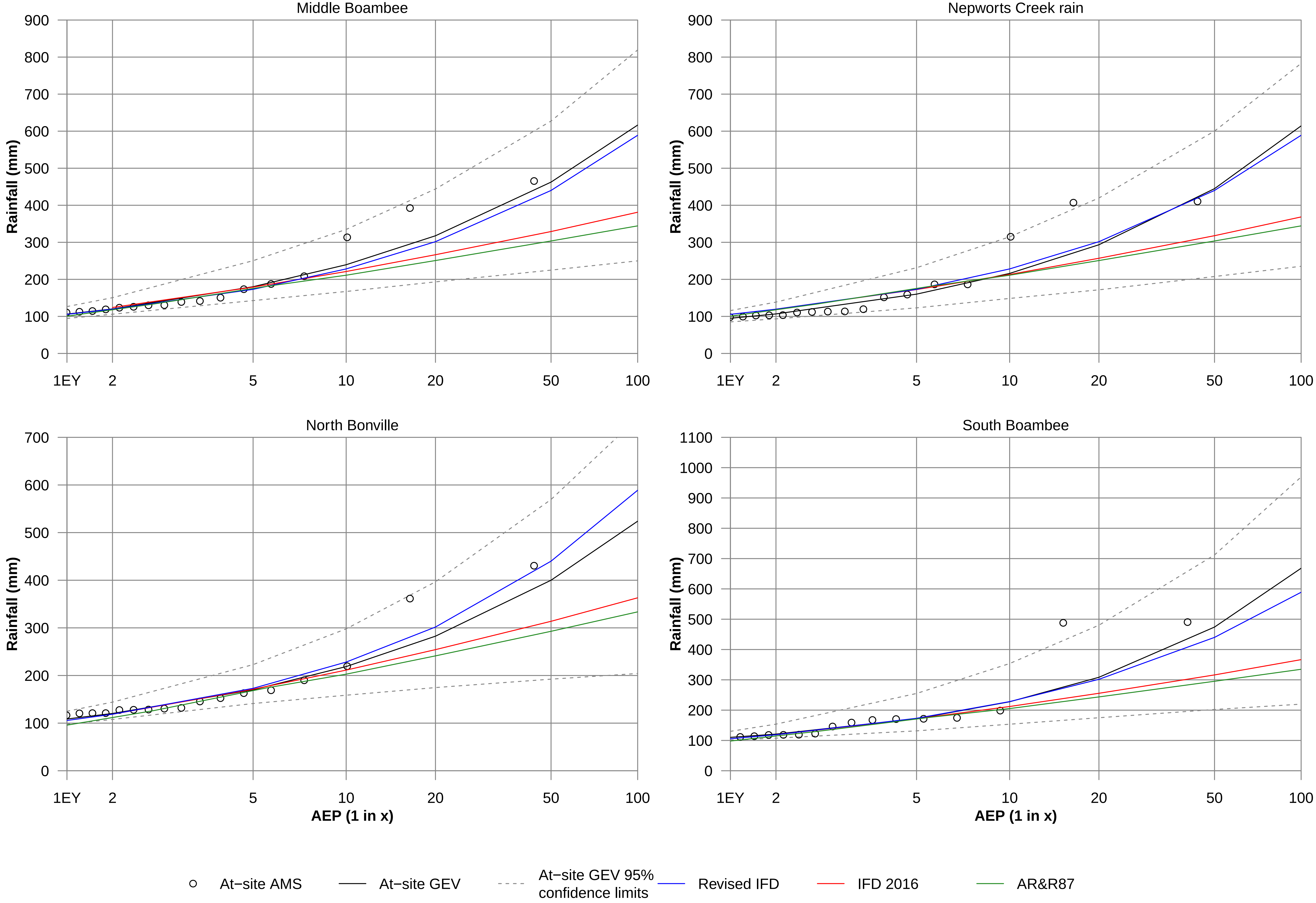


FIGURE C12

COFFS HARBOUR AREA STATIONS
24 HOUR IFD COMPARISON

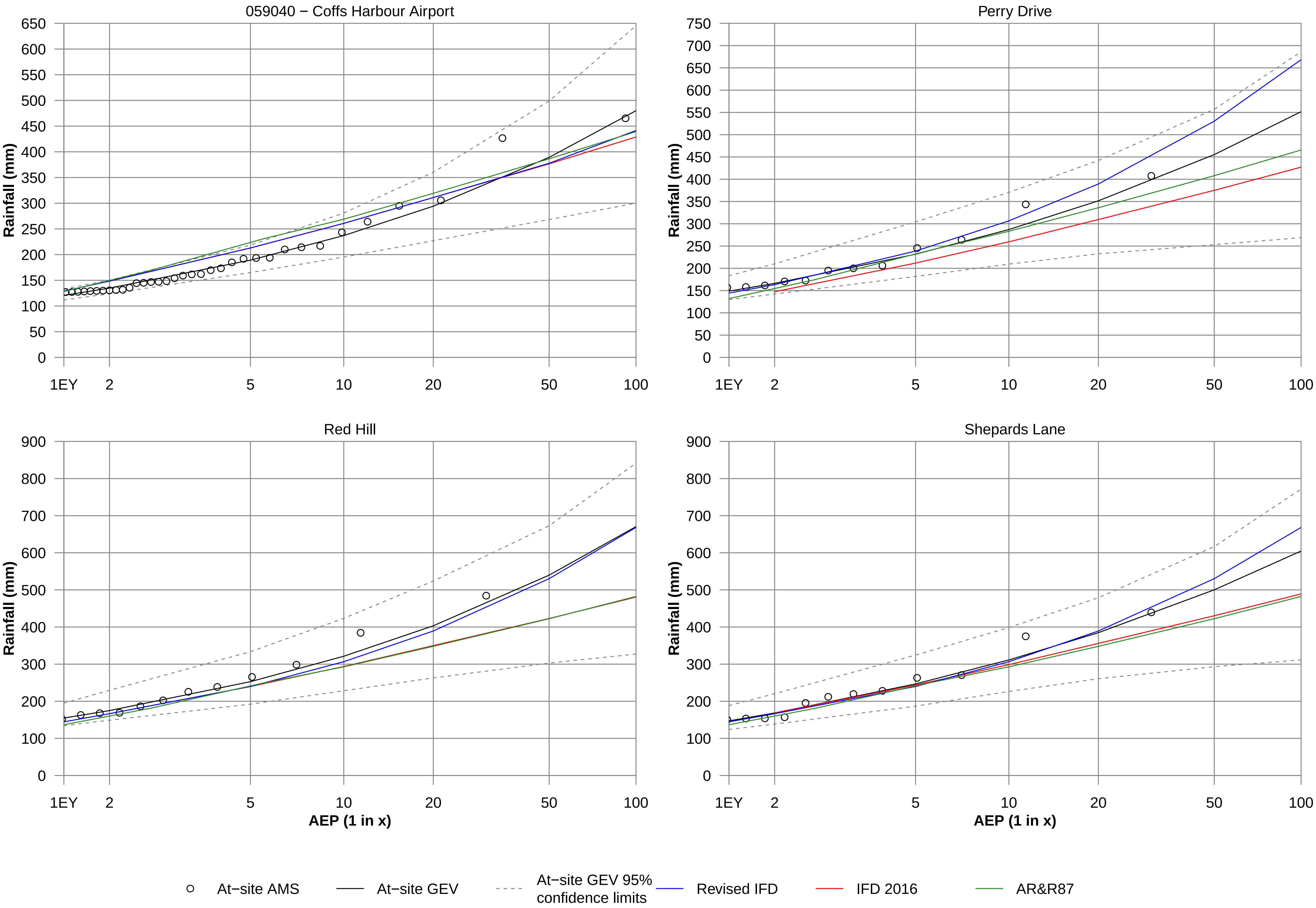
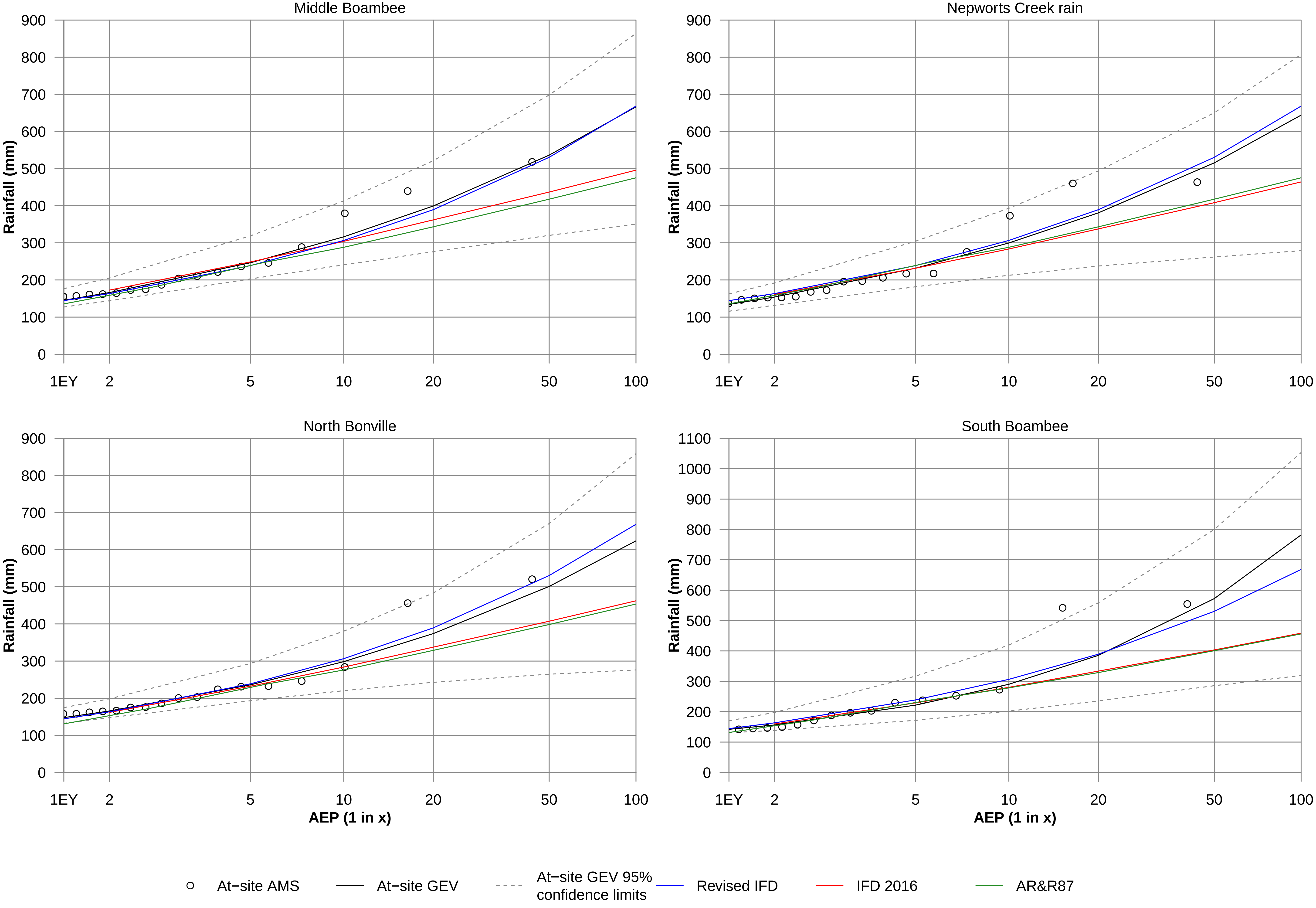


FIGURE C13
COFFS HARBOUR AREA STATIONS
24 HOUR IFD COMPARISON



Appendix D

Gauge ID	Gauge Name	Start year	End year	Number of year of AMS	Number of year missing data
061003	Avoca Beach	1934	1970	37	0
061012	Cooranbong (Avondale)	1903	2011	81	28
061023	Gosford (Gertrude Place)	1877	1993	107	10
061074	The Entrance (Eloora Street)	1943	2012	52	18
061082	Wyee (Wyee Farms Rd)	1899	2012	113	1
061083	Wyong (Wyong Golf Club)	1885	2010	117	9
061087	Gosford (Narara Research Station) Aws	1916	2012	79	18
061093	Ourimbah (Dog Trap Road)	1953	2012	58	2
061108	Gosford State Nursery	1901	1946	40	6
061117	Wamberal Post Office	1896	1942	37	10
061220	Yarramalong (Lewensbrook)	1966	2012	38	9
061294	Avoca Beach Bowling Club	1970	2012	41	2
061318	Woy Woy (Everglades Country Club)	1964	2010	45	2
061319	Gosford North (Glennie St)	1971	2012	32	10
061351	Peats Ridge (Waratah Road)	1981	2012	30	2
066002	Balgowlah (Ethel Street)	1940	1989	49	1
066035	Manly Town Hall	1914	1963	49	1
066044	Cromer Golf Club	1898	2011	67	47
066045	Newport Bowling Club	1931	2010	47	33
066079	Avalon Beach (Avalon (Palmgrove Rd))	1958	2012	32	23
066128	Palm Beach (Sunrise Road)	1965	2012	37	11
066141	Mona Vale Golf Club	1969	2012	40	4
066153	Manly Vale (Manly Dam)	1906	2006	33	68
066182	Frenchs Forest (Frenchs Forest Rd)	1957	2012	55	1
566051	Warriewood Stp (Composite)	1981	2010	26	4
566068	Dee Why Bowling Club	1990	2010	20	1
BATEAUBAY	Macquarie-Tuggerah Lakes At Bateau Bay	1987	2008	20	2
BERKELEYVAL	Macquarie-Tuggerah Lakes At Berkeley Vale	1988	2009	20	2
KINCUMBER	Kincumber	1987	2017	30	1
MANDALONG	Macquarie-Tuggerah Lakes At Mandalong	1988	2009	20	2
MARDIDAM	Macquarie-Tuggerah Lakes At Mardi Dam	1988	2009	20	2
MOUNTELLIOT	Hawkesbury River At Mount Elliot	1987	2009	21	2
STRICKLAND	Strickland	1987	2017	30	1
WYOMING	Hawkesbury River At Wyoming	1988	2009	20	2
059040	Coffs Harbour Mo	1943	2012	55	15
059026	Upper Orara (Aurania)	1899	2011	100	13

Gauge ID	Gauge Name	Start year	End year	Number of year of AMS	Number of year missing data
COFFSPERRYD	Bellinger River At Coffs Perry Drive	1999	2009	10	1
COFFSREDHIL	Bellinger River At Coffs Red Hill	1999	2009	11	0
COFFSSHEPAR	Bellinger River At Coffs Shepards La.	1999	2009	11	0
MIDDLEBOAMB	Bellinger River At Middle Boambee	1990	2009	19	1
NEWPORTSCRE	Bellinger River At Newports Creek	1990	2009	18	2
NORTHBONVIL	Bellinger River At North Bonville	1990	2009	18	2
SOUTHBOAMBE	Bellinger River At South Boambee	1991	2009	18	1
STUARTSISLANDDS	Stuarts Island Downstream	1998	2017	18	2
068117	Robertson (St.Anthonys)	1962	2005	42	2
068131	Port Kembla (Bsl Central Lab)	1963	2012	40	10
212053	Stonequarry Creek At Picton	1990	2008	12	7
568004	Cordeaux Air Strip	1983	2008	20	6
568047	Nepean Dam	1981	2008	26	2
568048	Cataract Dam	1981	2008	24	4
568049	Cordeaux Quarters	1981	2008	22	6
568053	Picton Stp	1998	2010	8	5
568058	Hambridge	1981	2008	23	5
568060	Ironbark	1983	2008	19	7
568061	Browns Road	1983	2008	22	4
568065	Letterbox Tower	1981	2008	25	3
568068	Upper Cordeaux (No.2 Dam)	1981	2008	23	5
568069	Reverces	1983	2008	21	5
568071	Upper Avon	1981	2008	21	7
568072	Cobbong	1983	2008	23	3
568076	Brogers No.2	1981	2008	23	5
568078	Budderoo	1981	2008	21	7
568097	Mount Keira(Kentish No.2)	1981	2008	20	8
568102	Mount Murray	1981	1996	11	5
568119	Shellharbour Stp (Composite)	1990	2010	19	2
568136	Wollongong Stp	1998	2010	11	2
568153	Bellambi Bowling Club (Formerly Corrimal)	1987	2010	21	3
568159	Kanahooka Sps1113 Formerly Kanahooka Sps308	1989	2010	19	3
568162	Balgownie Reservoir	1990	2010	20	1
568169	Port Kembla (Sps176)	1990	2010	19	2
568171	Albion Park Bowling Club	1990	2010	17	4
568172	Bulli Bowling Club (Formerly Thirroul Bc)	1990	2010	19	2
568173	Berkeley (Berkeley Sports And Social Club)	1990	2010	19	2

Gauge ID	Gauge Name	Start year	End year	Number of year of AMS	Number of year missing data
568180	Dapto Citizens Bowling Club	1991	2010	18	2
568185	Wongawilli (Bhp Dust Monitoring Site)	1992	2010	16	3
568186	Tongarra [Glenhaven]	1992	2010	17	2
568187	Jamberoo (Woodstock)	1992	2010	18	1
568188	Kiama [Water Tank]	1992	2010	17	2
568190	Mount Murray No.2	1996	2008	10	3
568296	Thurns Road Tbrg	1991	2008	16	2
CLEVELANDRO	Wollongong Coastal At Cleveland Road	1985	2009	23	2
CLOVERHILL	Wollongong Coastal At Clover Hill	1985	2009	23	2
DARKESROAD	Wollongong Coastal At Darkes Road	1994	2009	14	2
DOMBARTON	Dombarton Loop	1985	2016	32	0
HUNTLEYCO	Huntley Colliery	1983	2016	34	0
LITTLELAKE	Wollongong Coastal At Little Lake	1991	2009	17	2
MOUNTKEMBLA	Wollongong Coastal At Mount Kembla	1985	2009	23	2
MTPLEASANT	Mt Pleasant	1997	2016	20	0
NORTHMACQUA	Wollongong Coastal At North Macquarie	1985	2009	23	2
NURREWIN	Nurrewin	2005	2016	11	1
PORTKEMBLA	Wollongong Coastal At Port Kembla	1983	2009	26	1
RIXONSPASS	Wollongong Coastal At Rixons Pass	1985	2009	23	2
RUSSELVALE	Russell Vale	1985	2016	32	0
UPPERCALDER	Wollongong Coastal At Upper Calderwood	1985	2009	23	2
WONGAWILLI	Wollongong Coastal At Wongawilli	1983	2009	26	1
YELLOWROCKR	Wollongong Coastal At Yellow Rock Road	1983	2009	24	3

Appendix E

Independent Review of WMAWater Report 116015 ‘Revised 2016 Design Rainfalls’

Client: WMAWater

Report No: UA183004-RP-01

Date of Issue: 1 June 2018

Report Title:

Independent Review of WMAWater Report 116015 'Revised 2016 Design Rainfalls'

Report No: UA183004-RP-01

Date of Issue: 1 June 2018

Report Prepared for:

WMAWater

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v1.1	Preliminary Draft Report	16/5/18	M. Leonard
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1 Summary of Comments

Published in 2016, the Bureau of Meteorology (BoM) undertook a significant revision of IFDs for Australia with larger datasets and improved methodology over the 1987 IFDs. It is well understood in the hydrological community that a lot of time and effort was spent on the 2016 IFD through a very considered and deliberate approach by the BoM.

In 2017, a report '*Revised 2016 design rainfalls investigations into the need for and derivation of local techniques*' (Draft Interim Report, 116105), was prepared for the NSW Office of Environment and Heritage by Mr Mark Babister and Mr Scott Podger. The WMAWater report has questioned the efficacy of the 2016 IFDs for specific locations on the NSW coastline where there are steep rainfall gradients (Wollongong, Gosford, Coffs Harbor).[1] The report details reasons for contesting the 2016 IFDs in these regions and proposes the adoption of localised IFDs. I note that the authors have a strong familiarity with the methods used in the 2016 IFD Revision: Mr Babister served as Chair of the Technical Committee for ARR Revision Projects and Mr Podger contributed to the revision project while employed at the BoM.

Based on my review of the report and inspection of the data used for analysis, I am supportive of the revised IFDs developed by WMAWater. I appeal to the matching of at-site data as a higher priority than maintenance of any particular methodology, and that the arguments for locally developed IFDs in Wollongong, Coffs Harbor and Gosford are rooted in quantitative assessment. The arguments in support of a departure from the 2016 BoM methodology for the regions identified especially focus on (i) the availability of additional data, (ii) that there are strong rainfall gradients, (iii) that a newly identified covariate can better explain regional variability and (iv) that there can be trade-offs in the method of regionalisation when pooling station years at a subdaily scale. These arguments arise as a confluence of specific factors and do not challenge the broad applicability of the 2016 IFDs for the vast majority of the Australian continent, nor the tremendous amount of work undertaken by BoM in establishing them.

I have made a number of detailed comments in the body of this document, but have also summarised a number of actions for improving the WMAWater report:

- The authors should review the representation of the 2016 IFD rainfalls accounting for all relevant references.
- Section 3 should provide a fairer summary of BoM 2016 IFD and avoid using differences between 1987 and 2016 as a proxy for possible issues with the 2016 IFDs. The only reasonable inference from the differences in Section 3 is that higher differences are impactful to an end-user and may therefore be of interest to investigate. This interest might explain some of the motivation, but does not necessarily establish any 'issues' with 2016 IFDs since discrepancy could be attributed to 1987 values. A similar observation is made about physical reasoning. Such reasoning can be supportive (i.e. orography is a plausible explanatory mechanism), but where possible, the weight

[1] *"The 2016 IFDs are based on a much larger dataset and more up to date techniques than the 1987 IFDs, and will in general yield better estimates for most of NSW. However, it was recognised that for some areas on the coastal strip, such as near Wollongong, Gosford and Coffs Harbour the rapid variation in the terrain can result in unique local rainfall driving mechanisms"*

of any argument should be carried quantitatively rather than by assumed explanatory power of a conceptual mechanism.

- The quality of additional non-BoM sites should be further verified and if discrepancies arise, their material impact on results should be explained. The verification should include basic statistics of the sites and how they were handled/filtered for selection, spot-checking of key influential data points and any additional comments, observations or knowledge of the underlying data or events. Such a quality analysis cannot be on the same scale as that performed by BoM, but should be enough to further establish the defensibility of the approach. The appeal to at-site data is strongly supported by the provision of at-site plots in the Appendices, but more could be done to establish the reliability of the data given that at-site fits are pivotal to acceptance of the revised IFDs.
- Improve reporting of to the smoothing procedure.

2 Differences between 1987 and 2016 IFDs

Section 3.1 could be clearer at points. The first paragraph under Table 3 is confusing.[2] Is the word 'higher' intended to mean (i) 'more pronounced' or (ii) to imply a quantitative bias towards higher values? I assume the former is intended, but the reader could be easily confused that an interpretation was being offered that the 2016 IFDs have a trend to generally higher values. The explanation for more pronounced differences at rarer AEPs and shorter durations could be reworded to emphasize (a) variability of quantile estimators with AEP is a fundamental statistical attribute, (b) shorter durations of rainfall are in themselves more variable and skewed and (c) bigger differences occur where there has been a bigger increase in data (i.e. subdaily data).

Two paragraphs on page 6 are used to explain BoM method for deriving 2016 IFDs. These seem to be intentionally brief but are in themselves fair. More details could be offered to demonstrate that BoM has provided consideration on observed differences between 1987 and 2016.

In my opinion, the issue of trends in differences is a complicated point and not the most constructive argument to make, whether for or against the method used to derive 2016 IFD estimates. Firstly, assertions over the source of 'trends' in differences (or absences thereof) are highly dependent on the specified scale of interest and establishing the priority of certain scales can be challenging. Secondly, and more importantly, differences do not provide indication that there are issues with the 2016 method. As already noted in the introduction,[3] the 2016 estimates are generally expected to be more accurate than 1987 estimates. Two things have changed since 1987, the data and the method, and it is not straightforward to delineate how each will have contributed to a difference. In the absence of further reasoning, a default or naïve interpretation would be that a difference is suggestive of limitations with 1987 IFDs rather than 2016 IFDs. Separate reasoning would be required to establish a deficiency of 2016 IFDs.

[2] *"In general, the differences are higher for the rarer AEPs and shorter durations."*
[3] *"In general, the additional data and new methods create significantly better estimates than the previous instalment"*

The most relevant comment to make where large differences are observed is that it may warrant further scrutiny, not because something is necessarily wrong, but since larger differences will have more significant implications for end-users. A comment along these lines is made in Section 3.2.[4] It would then require additional supporting evidence to substantiate that there is a discrepancy between the 2016 estimate and some 'truer' estimate of IFDs. For this reason, I would suggest that Section 3 just sticks to commentary that some differences are noted and that this lends some motivation for further scrutiny. For example, a phrase appears in Section 3.1 suggesting issues with the 2016 method, but this is out-of-place.[5] The function of that paragraph is to simply state that key durations have been identified at each location for illustrative purposes according to some basic rationale, which can be established without commentary about 'issues'.

Sections 3.2, 3.3 and 3.4 go on to make comments about 2016-1987 differences for the regions of Wollongong, Coffs Harbor and Gosford respectively. A difficulty with these sections is that they juxtapose the idea of differences in revisions with physical reasoning of each region. The reasoning is plausible, but it is better to separate out the two ideas. I would suggest a subsection focused on the observation of differences between 1987 and 2016 from Figure 1 stating where they are high or low. The summary of this section is that the differences warrant further scrutiny because they are potentially impactful and there is interest in understanding in more detail what is happening. I would suggest a separate subsection on physiographic understanding of the regions. This reasoning is essentially additional expert knowledge which is a possible reason for bias in 2016 estimates. Again, this is not evidence of issues or sufficient explanation for differences in Figure 1, only motivation for further study. The strength of the proposed argument should be established quantitatively (as pursued in subsequent sections) rather than by the plausibility of the mechanism. Separating and rewording these subsections will help avoid any impression of 'issues' with 2016 IFD estimates on the basis of the difference or physiographic observations in themselves.

3 Spatial interpolation of IFDs

WMAWater commented that the 2016 IFD design rainfalls were derived as a 'broad-scale national approach', representing a significant improvement in the vast majority of cases. I agree with this comment, including the implied sentiment of possible discrepancies in some cases. If bias is to be detected, then it is most likely to be of consequence in regions with very strong gradients, which is only a small number of regions.

Notwithstanding the large amount of work done by BoM, the challenge with spatial estimates is that there is a degree of smoothing and this is most likely to be more pronounced in regions with known gradients. The BoM has undertaken many activities to test their approach, but the WMAWater report has some compelling arguments (i) an additional covariate (Standard Deviation of Elevation - SDE), (ii) challenges with regionalisation in steep gradients (6-site pooling vs 500 year pooling that includes daily regressed values) and (iii) additional subdaily data.

[4] *"These differences persist throughout most durations over this area, and will significantly impact design flood estimates."*

[5] *"…to simplify the issues and to better highlight aspects of the method that may be adversely affecting the results…"*

The method of splines used for spatial interpolation is by construction globally unbiased, but this depends on the domain and does not preclude conditional (local) biases. On this basis, BoM undertook further investigations at the request of the ARR technical committee and did not determine evidence for significant bias. While BoM was diligent in this regard, it does not of itself preclude the possibility of local bias if new evidence is raised. The WMAWater report emphasizes the change in terrain as a significant influence relating to orographic enhancement. To my recollection, while covariates such as aspect and slope were considered by BoM as part of testing and review, SDE was not raised and therefore not considered.

The question of smoothing is of critical importance and appears in more than just the step of spatial interpolation, but also in the construction of the region-of-influence for estimating moments and in the polynomial smoothing of estimates across durations. The WMAWater report also questions the method of pooling for the region of influence. These issues taken together represent a significant departure from 2016 IFD estimates.

The main support in favour of the WMAWater method rests with the quality of at-site fits provided (continued in following Section).

4 At-site fitting of extremal distributions

The role of at-site estimates lies at the heart of the matter. To what extent should information from at-site estimates be trusted versus a given method which synthesizes the at-site data to produce regionally consistent estimates?

Design rainfalls are necessarily derived, but that in itself does not diminish the credibility of at-site estimates. It would be useful to have more details of quality checking of the additional 79 additional gauges from Manly Hydraulics Laboratory to establish the reliability of the series used. Unless the data are indeed of poor quality or overly short, the assessment of at-site fits against the data is a stringent and useful test. There are understandably differences from at-site estimates when constructing regional estimates for design purposes (e.g. a site may have low information content relative to representative neighbouring sites), but where there are systematic differences across a region, the observance of a specified design method is not a strong defence.

The WMAWater report establishes that there are significant regions of interest (Wollongong, Coffs Harbour, Gosford), and that there are systematic patterns in the discrepancies of 2016 IFD estimates against the at-site estimates for these regions. Regional consistency of a model is a very demanding requirement to meet, as it supposes the ability of a model to represent all relevant sources of variability in a region (not just those in available data). Methodology can be opaque because it involves a great many steps. Where a model overturns, outweighs or down-weights information in observations (as in a regional estimate of IFDs that yield significant at-site discrepancies) it is incumbent on the modeller to establish the justified basis within the model for this occurrence. While there are many such possibilities, it is much less demanding to establish that additional data at multiple sites are representative for the purpose of validation. Observed data are immediate and providing they are representative, it is difficult to dispute what has been observed.

Based on the at-site fits for the sites obtained from Manly Hydraulics Laboratory (shown in Appendix A and C), I consider it tough to argue that the 2016 IFD methodology is more regionally consistent than the WMAWater revised IFDs.

5 Treatment of observation data

The provision of at-site plots within Appendices A and C goes a long way to indicating the consistency of the data, but additional details would be helpful to establish the reliability of the sites and of the quality assurance procedure. In addition to reporting basic indicators of the gauge data (e.g. record length, percentage missing) it would be useful to have some of the large influential values spot-checked (e.g. Coffs Harbor Airport 2hr, HuntleyCo 12 hr; site 568162 all durations).

6 General method

The following comments relate to Table 4:

- **Extract AMS** – the methods used are comparable and reasonable, providing additional reporting on gauge quality.
- **Fit L-moments** – the two methods are comparable
- **Subdaily derivation** – the lack of BGLSR is not ideal as there could be additional daily-derived data to support or reject conclusions. However, this is countered for with the provision of numerous additional sub-daily gauges. I also note that the method of deriving subdaily estimates from daily estimates assumes greater importance for regions having less subdaily gauges. I consider the justification on p.15 to this effect reasonable.[6]
- **Regionalisation** – this is a significant difference between the two methods. I find the arguments in p.18 persuasive.[7] The region of influence is an important source of smoothing in the overall construction of IFD estimates and should be in sharper focus for regions with steep gradients.
- **Gridding** – the method of kriging in commensurate with 'thin plate smoothing analysis of scattered point data'. I assume the smoothing parameter was selected by minimising the general cross validation estimate. It would be beneficial to report some of the validation statistics from the kriging along with the package used and parameters. More importantly, the main feature of the spatial interpolation is the use of SDE as a covariate which had not been identified in prior studies. The region size over which the SDE is calculated should be reported. There is some difference in the method for interpolating index rainfall and moments vs interpolating parameters, but I do not expect these to be substantial reasons for discrepancies.
- **Post-processing**. This is not a critical element of the procedure and exists to tidy up inconsistent artefacts between durations. If this issue were observed in the revised IFD estimates it should be considered, but would be unlikely to materially change the reasoning for revising the IFD estimates.

I consider the arguments for the use of a 6-station pooling for regional estimates and the use of SDE to both be compelling. The support for these arguments suggests a strong understanding of the regional topographies. The validity of the revised IFDs is strongly informed by the comparison to at-site frequency analyses.

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[6] *"In areas such as Wollongong however, there is a high density of continuous rainfall gauges with relatively significant periods of record"*

[7] *"Using the requirement of 500 years for AMS would include a very large number of sites in regions when there are no regressed daily sites with large AMS pools. To limit the pooling of sites whose characteristics are too dissimilar, much smaller regions were chosen that always have 6 sites."*