Dear Professor Morin,

We thank you for the additional comments on our manuscript. Here, in response to the comments of the Reviewers and your additional feedback we elaborate further regarding the reliability of our regression model, most especially given its suitably to the arid and dynamic conditions of our study system. The response presented here should be considered in its entirety as the "final response to the Editor" in conjunction with the submission of the revised manuscript. For clarity, we also address additional comments from Reviewer #2 made indirectly via the Editor.

Reviewer 2
Comment:
My main concern remains with the model, and I don't think this has been addressed. They say the model is robust because of the adjusted r2 value, which has nothing to do with prediction, or indeed with the robustness of regression parameters, only with the ability of the multiple linear regression to capture the spread of data.

Response:
We agree with the reviewer that the information we provide concern the reliability of our reconstruction rather than its robustness. We have thus provided further details in the manuscript that support the reliability of our model to reconstruct past surface water change on the Fortescue Marsh, which we detail further in the responses below.

p. 11922, l. 15
Replaced "robust" by "reliable"

Comment:
As a first step, it would be good to know what happens to the regression if you leave each of the predictor variables out sequentially and determine which one is providing the most response. Conceptually, adding both rain days and monthly rainfall in the same regression model doesn't seem to me to be very meaningful, and may just be a way to increase the r2 without any actual additional mechanistic information being included (and therefore lowering any predictive confidence). Because the r2 says nothing about the regression parameters, I don't accept that they are robust over such a large period of time with such large variability in the predictor variables as stated by the authors in their response.

Response:
These standard regression exploratory methods described by the Reviewer have been conducted, as reported in the methods section of our original manuscript (section 3.1), although we did not include explicit details in our original manuscript. We now provide further details on these analyses, including also the fit to the independent data, prediction error and significance level; some but not all of this information was included in the original manuscript (section 3.1).

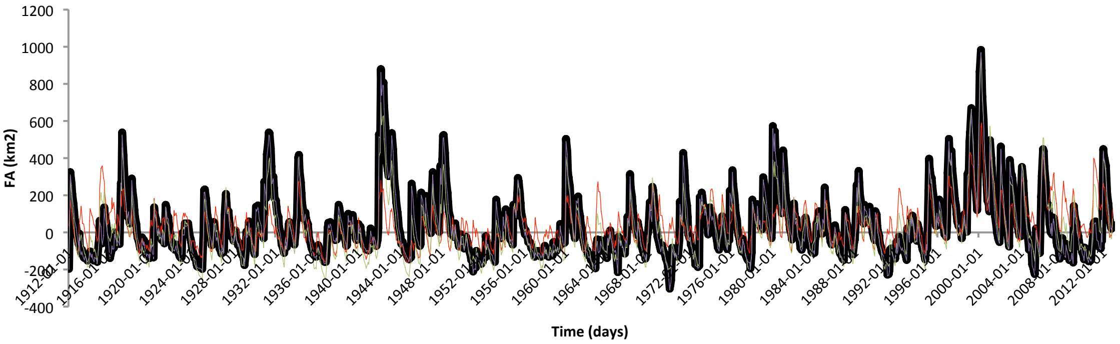
Table 1, below, summarises the outcomes of the sensitivity analysis, and Fig. 1 displays the reconstructions based on the different models tested. Table 1 allows comparison of the independent contributions of the collinear variables R (total mm/month) and R_d (number of days on which it rained/month) to the model, as well as the performance of the model without any one of the four variables used in the final model. As explained in our manuscript, the sensitivity analysis demonstrates that R and R_d (and $F_{At\text{-}1}$) both significantly improved the fit (R^2_adj) and the prediction accuracy of the model measured as the root mean squared error between predicted and observed values (E_{RMS}), whether included independently or together. We considered it important to include both hydroclimatic variables (R and R_d) from a mechanistic point of view, precisely because of the highly variable nature of our system. For example, take a month that has 200 mm of rain. In our study system, while it is common that 200 mm may fall over just two days, at other times 200 mm may fall over 28 days (www.bom.com.au). These very contrasting monthly distributions of rainfall demonstrate vastly different intensities and in turn generate quite different run-off; the dynamics of rainfall in such a highly heterogeneous climate are thus best captured by inclusion of both variables independently, and this is supported by a significant improvement of the model's performance.

It is also possible to visualise in Fig. 1b that variable F_{At-1}, on top of significantly contributing to changes in ΔF_A also acts as an autoregressive variable in the model. The variable "Interval" (*Int*) was the only variable included in the final model that did not highly significantly improve the total percentage of variance explained) (Table 1). However, from a mechanistic point of view, Interval was included to account for ΔF_A values being calculated over slightly different time intervals in the calibration period (i.e., 30±7 d) and in the reconstruction period, where months of the year varied between 28 to 31 days. This variable was not collinear with any other.

Table 1: Sensitivity analysis

Final	Model												
	R^2_{adj}	0.79											
	p	<0.001											
	E_{RMS}	52											
	Driver	Coefficient	Std Error	p									
	R	2.9	0.2	<0.001									
	R_d	-18.8	2.4	<0.001									
	F_{At-1}	-0.13	0.02	<0.001									
	Int	-0.99	0.54	0.070									
	Intercept	4.3	18.3	0.816									
1-variable	Model												
	R^2_{adj}	0.64			0.28								
	p	<0.001			<0.001								
	E_{RMS}	68			96								
	Driver	Coefficient	Std Error	p	Coefficient	Std Error	p						
	R	1.86	0.11	<0.001	-	-	-						
	R_d	-	-	-	18.29	2.29	<0.001						
	F_{At-1}	-	-	-	-	-	-						
	Int	-	-	-	-	-	-						
	Intercept	-67.158	6.42	<0.001	-58.351	9.898	<0.001						
4-variable	Model												
	R^2_{adj}	0.35			0.71			0.72			0.79		
	p	<0.001			<0.001			<0.001			<0.001		
	E_{RMS}	91			61			59			52		
	Driver	Coefficient	Std Error	p	Coefficient	Std Error	p	Coefficient	Std Error	p	Coefficient	Std Error	p
	R	-	-	-	1.8	0.1	<0.001	3.0	0.2	<0.001	2.9	0.2	<0.001
	R_d	18.0	2.2	<0.001	-	-	-	-18.8	2.7	<0.001	-18.4	2.4	<0.001
	F_{At-1}	-0.14	0.03	<0.001	-0.13	0.02	<0.001	-	-	-	-0.13	0.02	<0.001
	Int	0.18	0.94	0.847	-0.57	0.63	0.370	-0.93	0.62	0.133	-	-	-
	Intercept	-39.6	31.9	0.216	-26.0	21.1	0.220	-20.8	20.5	0.311	-27.1	6.4	<0.001

Note: R = total rainfall·month^{-1} on the upper Fortescue (mm); R_d = number of days with > 0 mm of rain·month^{-1} (days); F_{At-1} = flood area of the previous month (km^2); *Int* = the time interval between observations (days); Std Error = Standard error; p = significance level a)



b)

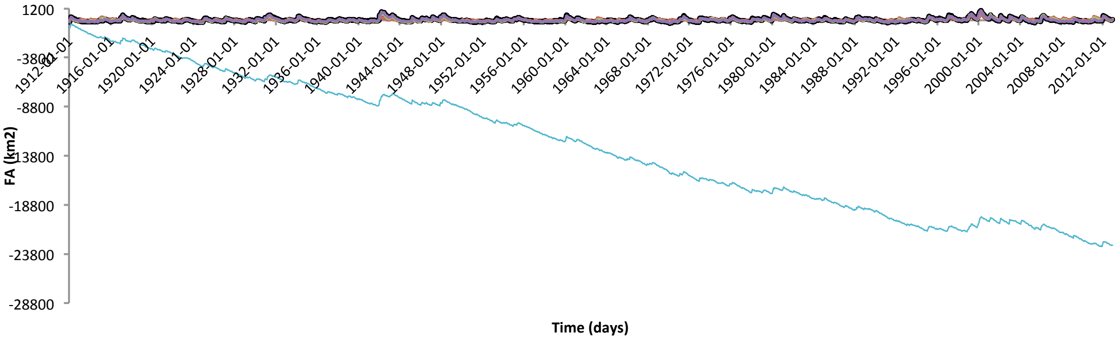


Fig 1. Surface water extent at the Fortescue Marsh reconstructed using the final model based on the full 1988-2012 calibration period (black line), and models tested for parameter sensitivity, i.e., sequentially removing one of each of the variables included in the final model, i.e., **a)** R (red line), and R_d (green line), and *Int* (purple line) and **b)** F_{At-1} (blue line)

p. 11914, l.18

Replaced: "Variables that were significant in explaining the variation in F_A, provided the best fit as per the adjusted coefficient of variation (R^2_{adj}) for the number of variables and the smallest root mean square error E_{RMS} were used in the final model."

by: "Initially, the sensitivity of each predictor was tested and only the hydroclimatic variables that were significant in explaining the variation in F_A were used in the model. The model that provided the best fit between the predicted and observed values in the calibration set as per the coefficient of variation (R^2_{adj}) adjusted for the number of variables and the smallest root mean square error E_{RMS} was selected."

p. 11915, l. 20

Replaced: "the most important contributors to ΔF_A variation."

by: "the most important contributors to ΔF_A variation. R alone tested independently of the other variable explained 64% of the variance ($p < 0.001$), and including R_d, improved variance explained by only 8% ($p < 0.001$). Although there is some collinearity between R and R_d (Table A4), we considered it important to include both hydroclimatic variables (R and R_d) from a mechanistic point of view, precisely because of the highly variable nature of our system. For example, in our study system, while it is common that 200 mm may fall over just two days, at other times 200 mm may fall over 28 days (www.bom.com.au). These very contrasting monthly distributions of rainfall demonstrate vastly different intensities and in turn generate quite different run-off; the dynamics of rainfall in such a highly heterogeneous climate are thus best captured by inclusion of both variables, where more R_d modulates negatively the impact of R. In addition, the inclusion of *R and* R_d may account to some extent for the recorded changing rainfall intensity over the century (Shi et al., 2008; Taschetto and England, 2009; Gallant and Karoly, 2010; Fierro and Leslie, 2013)."

p. 11916, l. 17
Removed: "In particular, the inclusion of R_d in addition to R makes the model and reconstruction robust against the recorded changing rainfall intensity over the century (Shi et al., 2008; Taschetto and England, 2009; Gallant and Karoly, 2010; Fierro and Leslie, 2013)."

p. 11918, l. 7
Replaced: "Intervals (Int) between observations (number of days over which the change was observed) did not significantly improve the fit of the model ($\mathrm{Int}_\beta = -8$ km^2; p value= 0.07). This variable (Int) thus rather acted as a constant that contributed to the decrease of surface water every month".

by: "Intervals (Int) between observations (number of days over which the change was observed) did not significantly improve the fit of the model ($\mathrm{Int}_\beta = -8$ km^2; p value= 0.07). This variable (Int) was nevertheless included in the model to account for ΔF_A values being calculated over slightly different time intervals (i.e., 30±7 d) in the calibration period and because months of the year include 28 to 31 days. This, Int acted as a constant that contributed to explaining the decrease of surface water every month".

Comment:
The extrapolation of the time series is massive, with absolutely no attempt at realistic error bounds given. At the very least, I would think they need to try a series of cross validations of the model on the data. By that I mean use half the data (half model, half predict), then leave one out, etc (these are standard regression exploratory methods), to build different models, and see how the extrapolations compare. If they converge within a similar range then we can start to have slightly more confidence, otherwise we know multiple linear regression isn't a great tool for capturing highly non-linear feedbacks.

Response:
While we certainly agree with the Reviewer re the limitations of using a multiple linear regression approach to many systems, our model parameters (significant and high variance explained and low error of predictions) show that this multiple linear regression model is reliably capturing the hydrological variability at the Marsh. We did run a series validation tests (including a series of cross validations), which we explain further below.

In our manuscript, we described how we tested the predictive accuracy of this model based. We used ten random independent subsets (i.e., "ten-fold") of 16 observations (E_RMSCV) and further analysed three independent block subsets of the calibration period (E_RMSP). The summary results of the model performance assessment were provided in the original manuscript in section 3.1. as follows: "The model's predictive accuracy was similar for both tests performed, i.e., the E_RMSCV and the best $E_\mathrm{RMSP} = 56$ km^2. However, the subset model used to calculate E_RMSP, which excluded the particularly wet and variable 1998–2004 period from the calibration period, performed the worst at reconstructing ΔF_A for the 1998–2004 verification period ($R^2_\mathrm{adj} = 0.64$; $E_\mathrm{RMSP} = 86$ km^2), indicating this period constituted an important range for calibration of the model. Both other calibration models (excluding the 1988–1997 or the 2005–2012 periods) were more accurate ($E_\mathrm{RMSP} = 58$ and

56 km^2, respectively), and the overall variance explained improved to 81 and 82% when either of these dry, less variable periods was removed from the model.”

Here, to further clarify our validation tests, we have included the details of these tests also here in Table 2, Table 3, Fig. 2 and Fig 3. The Cross-Validation Error (E_{RMSCV}) was calculated by averaging the root-mean square error obtained for all ten independent test sets (Table 2; Fig. 2).

Table 2: E_{RMSCV} from random ten-fold cross-validation (CV), i.e. 16 independent observations for every fold, computed using the CVlm function of the DAAG R package v. 1.16 (Maindonald and Braun, 2013)

	E_{RMS} (km^2)
Fold 1	60
Fold 2	74
Fold 3	46
Fold 4	57
Fold 5	26
Fold 6	39
Fold 7	40
Fold 8	41
Fold 9	57
Fold 10	28
Average E_{RMSCV}	56

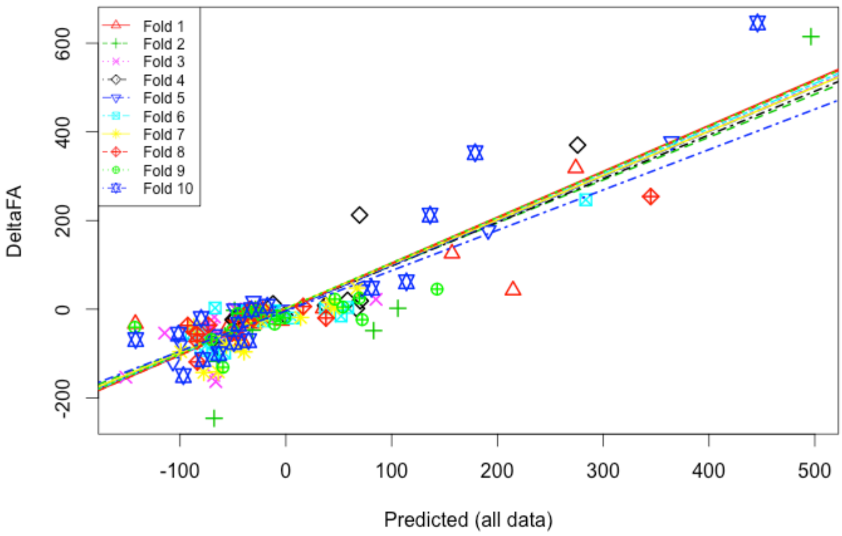


Fig. 2: Spread of the observations from the random ten-fold cross-validation (CV) computed using the CVlm function of the DAAG R package v. 1.16 (Maindonald and Braun, 2013)

As stated in the manuscript (section 3.1), the largest of the errors we calculated was the E_{RMSP} of 86 km^2 for periods that would have much larger inundation events than that of the full calibration period, but this error was even relatively small comparing with the amplitude of inundated area changes (Fig. 3 green line). E_{RMSP} was even smaller (56 km^2) for periods similar or of lesser intensity of inundations as the calibration period (Fig. 3 in the original manuscript).

Table 3: Analysis of predictive accuracy (E_{RMSP}) of the final model based on the full 1988-2012 calibration period and the subsets for the 1998-2012, 1988-1997; 2005-2012, 1988-2004 periods.

Period	1988-2012			1998-2012			1988-1997; 2005-2012			1988-2004		
R^2_{adj}	0.79			0.82			0.64			0.81		
p	<0.001			<0.001			<0.001			<0.001		
E_{RMS}	52			51			46			56		
E_{RMSP}	-			58			86			56		
Driver	Coefficient	Std Error	p	Coefficient	Std Error	p	Coefficient	Std Error	p	Coefficient	Std Error	p
R	2.9	0.2	<0.001	2.9	0.2	<0.001	2.1	0.2	<0.001	3.3	0.2	<0.001
R_d	-18.8	2.4	<0.001	-17.7	2.6	<0.001	-10.7	3.0	<0.001	-24.0	3.4	<0.001
F_{At-1}	-0.13	0.02	<0.001	-0.13	0.02	<0.001	-0.17	0.03	<0.001	-0.12	0.02	<0.001
Int	-0.99	0.54	0.070	-0.73	0.71	0,874	-1.24	0.61	0,044	-1.02	0.67	0.134
Intercept	4.3	18.3	0.816	-3.7	23.4	0.305	15.3	20.9	0,467	4.3	23.0	0.853

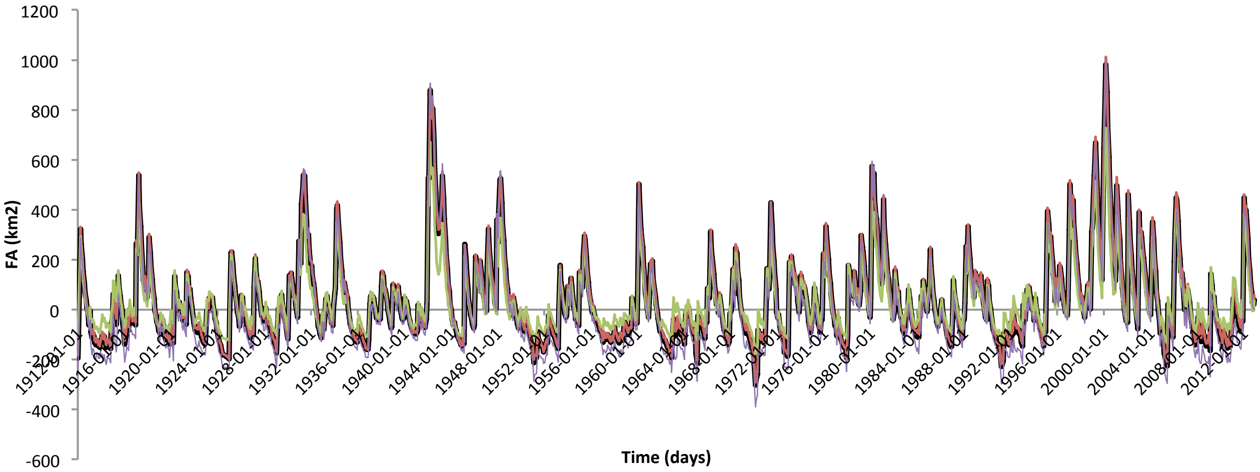


Fig 3: Surface water extent at the Fortescue Marsh reconstructed using the final model based on the full 1988-2012 calibration period (black line) and the subsets for the 1998-2012 (red line) 1988-1997; 2005-2012 (green line), 1988-2004 (purple line) periods.

As previously explained, only R and R_d exhibit collinearity (Table A3 in the original manuscript). While this may be an issue in many instances, this does not invalidate including both variables in the model when the main objective is that of prediction within the range of the calibration variables (Dormann et al., 2013). Here, our main purpose for building this model was to extend the hydrological record for the Fortescue Marsh over the last 100 years. As we explain in our manuscript and in earlier responses, we sought to establish a baseline that likely cannot be reconstructed using a catchment water balance model. This is because the entire 500,000 km^2 Pilbara region is data poor and alternative approaches are required: instrumental data are too sparse/inconsistent in the early 1900's (and remains so for much of the region to the current day) for this remote part of Australia. Consequently, for this purpose, we aimed to develop a simple continuous model that would explain the most variance in ΔF_A (change in inundation area) on a monthly basis. Hence, including both R and R_d explains the most variance in ΔF_A (significantly improves variance by 8% and reduces the E_{RMS} over the model without R_d).

We acknowledge that the strong collinearity between R and R_d does affect to some extent our assessment of the relative importance of R and R_d. However, our interpretation of parameter estimates is quite conservative, and generally limited to suggesting that R_d significantly modulates total rainfall, which is in not surprising in our study system. We provide beta coefficients (Table A3, original MS) as an indication of the scale to which the variables might weight in our system over 25 years for the purposes of this reconstruction and our interpretations of the final model are at this scale. We thus believe that the model is as reliable as possible. In the manuscript we have also sought to validate our reconstruction against other historical records and have summarised the limitations of this model, which is of course a simplification of complex catchment hydrological processes. For example, it is clear from our model fit ($R^2_{adj} = 0.79$) that there remains (at least) 21% of the variance that is not accounted for by the variables that have been included. We agree that non-linear processes such as evaporation, infiltration and plant water use all likely contribute to this unaccounted for variance. However, these processes remain poorly quantified empirically for the region and are also strongly determined by rainfall in hot arid regions (e.g. inclusion of PET did not improve the model).

To further support the reliability of the reconstruction, we include below a figure demonstrating that the relationship between R and R_d remains strongly linear with only minor changes in the R^2_{adj} (0.66 to 0.71), slope and intercept between equivalent time periods in the past (Figure 4, below). Figure 2 also clearly shows that the ranges of variation for R and R_d over the calibration period are also very similar (or beyond) those of the other three periods, selected to encompass similar durations. In the absence of substantial changes in the way these two predictors correlate over time, there should only be a small effect on the accuracy of predictions (Doorman et al., 2013). Mechanistically, we f do not expect the influence of rain days and rainfall totals on surface flow to have changed drastically in the semi-arid region over the last 100 years where for the same volume of rain, more water flushes through the river network if it occurs over fewer rain days.

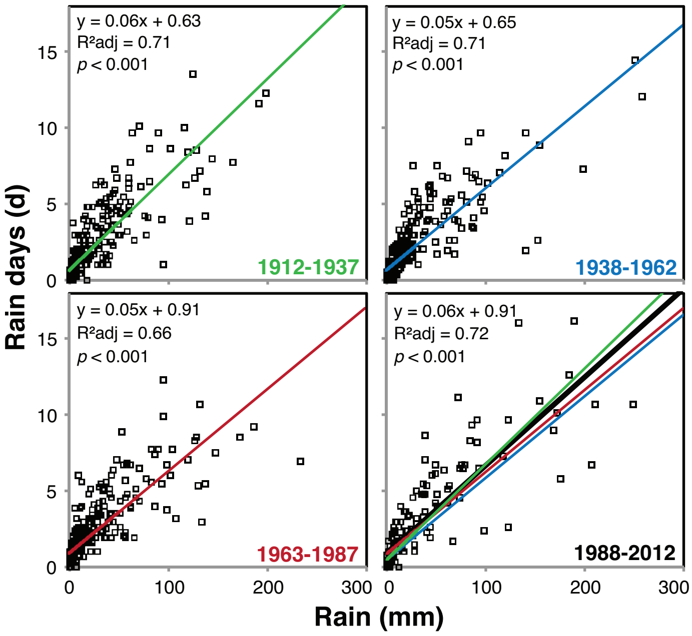


Fig. 4: Collinearity between R and R_d over the last century (1912-1937; 1938-1962; 1963-1987) compared to the calibration months (1988-2012).

Overall, we thus we believe our more parsimonious approach has indeed resulted in a reliable model with a reasonably small error for the purpose of reconstructing past changes in surface water change on the Marsh based on the best data available.

p. 11916, l. 17

Included now in our manuscript: "While our calibration period captures an exceptional range of intraseasonal and interannual variability in this extreme system, changes in the collinearity structure between highly collinear variables may occur over time and thus affect the relative contribution of the predictors and the reliability of the reconstructed estimates (Dormann et al., 2013). However, the relationship between R and R_d variables appears to have remained strongly linear between equivalent time periods over the reconstructed period, with only minor changes in the fit, slope and intercept. Nevertheless, the coefficients of these variables should not be used outside the scope of this study. Mechanistically, we do not expect the mutual influence of R and R_d on surface flow to have changed drastically in the semi-arid region over the last 100 years, where for the same volume of rain more water flushes through the river network if it occurs over fewer rain days, or at least not beyond the reported error of the model. Hence, this reconstruction should be used to examine long-term patterns of change in hydrological status and meteorological determinants as opposed to fine-grained catchment processes of recharge provided by higher spatio-temporally resolved hydrological models."

p. 11927, l.7
Included:
Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., García Marquéz, J.R., Gruber, B., Lafourcade, B., Leitão, P.J., Münkemüller, T., McClean, C., Osborne, P.E., Reineking, B., Schröder, B., K. Skidmore, A., Zurell, D., and Lautenbach, S.: Collinearity: a review of methods to deal with it and a simulation study evaluating their performance, Ecography, 36, 27-46, 2013.

p. 11937, Fig. 3 caption
Replaced: "(solid black line with dots for each observation)"

by: "(solid black line with dots for each observation; monthly E_{RMSP} of ΔF_A = 56 km^2) "

This is important because all the large events they talk about are mostly 'extrapolations', not actual measured points, so it would be prudent science to examine as rigorously as possible their realism before using them as a basis for interpreting 'extremes' vs 'averages'.

Response
We believe the Reviewer is not correct in the assertion that "all the large events they talk about are mostly 'extrapolations', not actual measured points". One of our main findings actually shows that many of the largest events have occurred over the last 25 years (esp. 1999-2006), i.e., the calibration period fully covered by satellite records, and that the range of variation of the calibration period fully encompasses the gradient of variability of the previous 75 years. We further provide historical validation supporting this reconstruction and the timing of large events in the early 1900's (e.g., Section 3.3). Hence, these are not extrapolations but reconstructions that are supported by complementary data i.e., analagous to a "multi-proxy" approach.

Finally, we acknowledge that no one model is perfect, especially when seeking to reconstruct past events in complex systems, and especially challenging around questions relating to hydroclimate. With this in mind, in our manuscript we also provide further confirmation of the largest events (e.g. long droughts, large floods) of our reconstruction (and therefore increased confidence in the reconstruction) by referring to historical records and other documentary evidence (see Section 3.3, for example).

The last point I think needs addressing is only a small one, but for some reason it really disagrees with me. The negative dFA values are still used to say the groundwater resources are being depleted, though I note they have heavily modified the previous text. I can't see how numbers less than zero can be conceptually reflective of any other hydrological processes other

than there is no surface water in the marsh, and although it is reasonable to assume the groundwater is level lower than the surface, there is no way to know if they are being depleted or remaining at some stable value below the surface, so I recommend this is just deleted.

Response
We appreciate the Reviewer's issues around this point. However, the modifications we made to the text only conceptually reflect further hydrological drying of the system under meteorologically dry conditions and we believe should be included in this paper. Groundwater level at the Fortescue Marsh (unpublished) has been very recently measured in bores and show continued drying of the water during periods without rain (e.g., max amplitude observed between July 2013 and November 2014 was around 1.5 m), which is in agreement with this statement. We think the negative dFA values are very useful in this instance as the study site is a wetland.

On this basis, I think if the authors can provide a large test of their model from multiple angles, then the revisions could be considered for publication, but without it I think the interpretations lack the technical merit to be considered for publication.

Response
We thank the Reviewer for the points raised and have revised the text accordingly to incorporate much of the above Discussion. We have conducted the testing of the model suggested by the reviewer and report the results of these tests in our manuscript and provided further details on these different tests in the responses. However, as the reviewers' highlights, sensitivity and accuracy tests for predictions are standard procedures for linear regression models and as such consider inclusion of additional tables and figures to the already rather extensive manuscript as unnecessary when described in the text. However, these can be included as Supplementary information if required.

We thank the Editor and the Reviewers once again for their valuable comments and a very fruitful discussion.

(Original) Responses to Referee #1 and list of changes in the manuscript

Overall this paper is good, interesting and suitable for HESS. However, you nearly lost me in the abstract and the first paragraph (see details below). There are a few other questions and comments I have which if satisfactorily addressed would make this paper acceptable for publication. Hence my decision "accept subject to major revisions".....the revisions listed are mostly minor but there is a lot and i would like to re-review hence the choice of "major revisions".

My comments, questions and suggested additions/revisions are listed below:

1. The first paragraph I think should be deleted. It isn't needed (better to start with line 19 "Quantifying the "hydroclimatic expression" of regional events remains challenging. . ...") and what is written has several problems:

Response
This suggestion from the reviewer has helped to better focus the paper. As suggested, we have shortened and edited the initial opening paragraph. We also agree that the concept of trends in such highly variable context may be misleading (this is a very good point to make), especially when relatively small temporal windows are provided. We have thus also included numerous edits throughout to the manuscript to better acknowledge the importance of variability and potential 'cyclicity' in this system, as opposed to 'trends'. We think that our reconstruction now highlights the more 'periodic' hydrological expression of rainfall variability (rather than 'average conditions') and reveals the importance of the 'extreme' features of this regime, such as protracted drought, severe inundations or prolonged wet periods.

p. 11906
Replaced: "Globally, there has been much recent effort to improve understanding of climate change-related shifts in rainfall patterns, variability and extremes. Comparatively little work has focused on how such shifts might be altering hydrological regimes within arid regional basins, where impacts are expected to be most significant."

by: "Long-term hydrological records provide crucial reference baselines of natural variability that can be used to evaluate potential changes in hydrological regimes and their impacts. However, there is a dearth of studies of the hydrological regimes for tropical drylands where intraseasonal and interannual variability in magnitude and frequency of precipitation are extreme."

p. 11907
Removed: lines 2-18; 19 until "Quantifying hydroclimatic…"

l. 19
Replaced: "Quantifying the "hydroclimatic expression" of regional events remains challenging for not only the Australian northwest but for arid environments more generally; these regions…"

by: "Quantifying the hydrological responses to changes in the rainfall patterns remains challenging in arid environments, especially for remote tropical and minimally gauged drylands such as the Pilbara region of northwest Australia. Tropical drylands …"

l.24
Replaced: "…the Pilbara region of northwest Australia can reach…" by "…the Pilbara can reach…"

l. 28
Replaced: "…challenges for prediction of consequences of changes in intensity and frequency of extremes."
by: "…challenges for prediction of resultant impacts of hydroclimate change on catchment hydrology. Several lines of evidence suggest the Pilbara has been particularly wet during the late 20th century (e.g., Cullen and Grierson, 2007; Shi et al., 2008; Taschetto and England, 2009; Fierro and Leslie, 2013) and that the frequency of extreme precipitation events may be increasing (e.g., Gallant and Karoly, 2010). However, there is no consensus on whether the observed higher summer rainfall can be attributed to an overall 'wettening trend' or whether the recent 'wet' period may be a feature within the range of natural 'extreme' variability characteristic of this region."

a. My understanding is TCs are weather events not climate

<u>Response</u>
Please refer to above response to comment #1. The reviewer is correct and we have revised our wording accordingly.

b. TC, rain and drought "are projected to become more intense and less frequent". According to IPCC (and hundreds of other references I could cite) my understanding was: (i) the jury is still out on whether TCs/typhoons/hurricanes would become more/less frequent or intense; (ii) same with whether or not extreme rain will become more frequent or intense (see IPCC special report on extremes where they classify this as something with "high uncertainty"); and (iii) for Australia, IPCC, CSIRO, BoM and many other studies suggest drought will become more frequent but again there is high uncertainty. If you want to make such a statement then I think you need a lot more evidence and references to existing literature to support it (while also fairly representing the published literature that says the opposite). Bottom line is there is a high degree of uncertainty about what will happen to intensity and frequency (and duration for droughts) of extremes in the future. This is a complex issue and doesn't need to be covered in this paper. My suggestion is delete first para.

<u>Response</u>
Please see the above response to comment #1. We have revised as the reviewer suggests.

c. Post-1955 wettenning in north-west Australia (line 12) is also misleading. . .. . ..both in terms of what the literature says and what your own data and model says (e.g. fig 3a and fig 3c). Yes there was a wet period from ~mid-1950s to mid-2000s and yes 1999- 2006 appeared to be particularly wet. . .. . but since about 2006 things have not been so wet (maybe with exception

of 2012). . ..with 2006-2012 mostly back to average (maybe even drier than average).......either way it is misleading to lump 2006-2012 in with 1955-2012 and say "post-1955 wettenning" as the so called trend appears to be more of a cycle (See next point). . .. . ..again better to avoid the semantics and controversy and just leave this paragraph out (but you will need to fix the abstract)

Response
Please see the above response to comment #1. Revisions made as suggested.

d. Talking about "trends" in this paragraph is misleading. . ...looking at the data (e.g. figure 3 and other observations from the area) what I see is dry (~1988-1996), wet (1999- 2006) then dry again post-1997. . .. . .I don't see a trend in either fig 3a or 3c. . .. .i see cycles or variability or interannual to multidecadal wet/dry phases. I am aware the papers cited (and others) say otherwise but I disagree and the very recent literature is beginning to recognise this. You also recognise this on page 11920 (lines 23-27) when you mention the importance of exploring "cyclicity". I would avoid mentioning trends. . ...and in the case of para 1 just delete it and start at line 19.

Response
Please see the above response to comment #1. This is an important point and we agree that there has been a shift in thinking moving from generalising to trends to trying to understand cyclicity across different time frames. We are in fact attempting such an approach by combining the presented results with tree ring and other records in the near future.

2. Abstract. . ...2nd sentence. . ..you mention inundations of 1000km2 and 300km2 but reader cannot put this into context without knowing the total possible area. . ...this is covered on page 11910 line 15 but the total area ~1300km2 also needs to be in the abstract

Response
Unfortunately, to date there has been no published high-resolution delineation of the total possible floodplain area for the Fortescue Marsh, either from inundation extents or from high-resolution vegetation survey. The outline currently provided in official map layers from Geoscience Australia or at the Department of Water is coarsely resolved, roughly corresponding to the 410 m elevation contour; we have used this estimate to constrain our analysis (i.e. ~1300 km^2) and included the information in the Abstract.

p. 11906, l. 16
Replaced "The most severe inundation (~ 1000 km^2) over the last century was recorded in 2000." by:
"The most severe reconstructed inundation over the last century was in March 2000 (1000 km^2), which is slightly less than the 1300 km^2 area required to overflow to the adjacent catchment."

3. Abstract. . ..line 22„„1999-2006 were "above average". . ...average calculated on what period? 1988-2012 or 1912-2012 or both or something else??

Response
We suggest the following replacement to clarify the message here:

p. 11906, l. 21
Replaced: “Duration, severity and frequency of inundations between 1999 and 2006 were above average and unprecedented when compared to the last century.”
by: “The prolonged, severe and consecutive yearly inundations between 1999 and 2006 were unprecedented compared to the last century.”

4. Abstract. . .final sentence. . ..in line with comment 1c and 1d. . ...yes if wet epochs like 1999-2006 continue then wetland will become more persistent. . .. . ..but where is the evidence that frequency or intensity of rain/TCs etc will increase or be same as 1999- 2006?? I don’t see it in this paper (in fact Fig 3a and fig3c suggests opposite) and I don’t see it in other literature. . .. .therefore need to tone this done a bit. . .. . .something like “While there is high inter-annual variability in the system, it is clear that that the wetland will become more persistent if the frequency and intensity of extreme rainfall events for the region were to increase (or be similar to 1999-2006), which in turn will likely impact on the structure and functioning of this highly specialized ecosystem.”

<u>*Response*</u>
Edited as suggested by the reviewer:

p. 11906, l. 21
Replaced “While there is high inter-annual variability in the system, changes to the flooding regime over the last 20 years suggest that the wetland will become more persistent in response to increased frequency and intensity of extreme rainfall events for the region, which in turn will likely impact on the structure and functioning of this highly specialized ecosystem.”

by: “While there is high inter-annual variability in the system, if the frequency and intensity of extreme rainfall events for the region were to increase (or be similar to 1999-2006), surface water on the Marsh will become more persistent, in turn impacting its structure and functioning as a wetland.”

5. Page 11908, line 4....suggest the following Australian specific references should also be included here. . .. . ..you should also include this when talking about ENSO/IOD cycles on page 11920:
a. Flood
i. Kiem, A.S., Franks, S.W. and Kuczera, G. (2003): Multi-decadal variability of flood risk. Geophysical Research Letters, 30(2), 1035, doi:10.1029/2002GL015992.
ii. Ishak, E.H., Rahman, A., Westra, S., Sharma, A. & Kuczera, G., 2013, Evaluating the non-stationarity of Australian annual maximum floods, Journal of Hydrology, 494, 134-145, DOI: 10.1016/j.jhydrol.2013.04.012.
iii. Kiem, A.S. and Verdon-Kidd, D.C. (2013): The importance of understanding drivers of hydroclimatic variability for robust flood risk planning in the coastal zone. Australian Journal of Water Resources, 17(2), 126-134.
iv. Pui, A., A. Lal, and A. Sharma (2011), How does the Interdecadal Pacific Oscillation affect design floods in Australia?, Water Resour. Res., 47, W05554, doi:10.1029/2010WR009420.
b. Drought
i. Kiem, A.S. and Franks, S.W. (2004): Multi-decadal variability of drought risk – Eastern Australia. Hydrological Processes, 18(11), 2039-2050.
ii. Verdon-Kidd, D.C. and Kiem, A.S. (2010): Quantifying drought risk in a non-stationary climate. Journal of Hydrometeorology, 11(4), 1019-1031.

<u>*Response*</u>

We thank the reviewer for providing these very supporting references that substantiate our study rationale and findings on the long-term variability of floods and droughts. These references have been cited in the text as follows.

p. 11908, l. 14

Replaced: “In the case of the Pilbara, TCs and other low-pressure systems forming off the west Australian coast in the tropical Indian Ocean often result in extreme flooding events (WA Department of Water, 2014).”

by: “In the Pilbara, tropical cyclones and other low-pressure systems forming off the west Australian coast in the tropical Indian Ocean often result in severe flooding events (WA Department of Water, 2014).”

p. 11908, l. 10

Added “(e.g., Kiem et al., 2003; Kiem et al. 2004; Verdon-Kidd and Kiem, 2010; Ishak et al. 2013).” after “…and temporal scales.”

p. 11920, l. 23

Replaced: “The appraisal of multi-decadal trends in the hydrological regime could be improved by exploring the impact of cyclicity of known larger scale climatic drivers of (summer) rainfall in the northwest of Australia such as the El Niño –Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the Madden–Julian oscillation (MJO) – phasing of these different modes (Risbey et al., 2009).”

by “However, rigorous analysis of periodicities would be required for the appraisal of multi-decadal trends in the hydrological regime against such a high background of variability (e.g., Kiem et al., 2003; Kiem et al. 2004; Verdon-Kidd and Kiem, 2010; Ishak et al. 2013). In fact, future investigations and risk analyses in the region should strive to assess the potential influence of known larger scale climatic drivers and their interaction of intraseasonal and interannual hydroclimate variability in the northwest of Australia (e.g., Kiem and Frank, 2004; Pui et al., 2011; Kiem and Verdon-Kidd, 2013), such as El Niño-Southern Oscillation, the Indian Ocean dipole, the Madden Julian oscillation and the southern annular mode (Risbey et al., 2009; Fierro and Leslie, 2013).”

6. Page 11912. . ...line 25. . ..are the units correct?? I think what you are saying is 22 mm of rain per rain day??.....but what does 22 mm of monthly rain per rain day mean?? Please check and clarify.

<u>*Response*</u>

Thank you to the reviewer for picking up this mistake: we meant "22 mm of rain per rain day" and clarified this in the text.

p. 11912, l. 25

Replaced “…22 mm monthly rain rain d-1)” by “…22 mm of rain per rain day)”
Replaced “…10 mm monthly rain rain d-1)” by “…10 mm of rain per rain day)”

7. Page 11913. . ...30 out of 60 mths when extremes happened were associated with one or more cyclones. . ..so 50%.....what were the other 50% of extremes associated with or caused by?? Need a comment on this. What else causes rainfall extremes in this region?

Response
Tropical cyclones and other closed lows were found to account for most of the extreme rainfall events in the northwest of Australia by Lavender and Abbs (2013); these authors did not distinguish between weather systems. We are not aware of any other study that has directly identified other specific drivers of rainfall extremes in the region but they are likely to include troughs, monsoonal depressions, and onshore circulations. The relative contribution of each of these potential sources of rain has not, to our knowledge, been investigated even though, as the Reviewer points out, they can account for ~ 50% of extreme rainfall events. We have thus been more careful with our wording and included the following modifications to the text to clarify that heavy rainfall events are not only associated with tropical cyclones:

p. 11912, l. 6
Included: “Rainfall in the Pilbara comes from troughs, monsoonal depressions, and onshore circulations (Leroy and Wheeler 2008; Risbey et al. 2009)”.

p. 11912, l. 19
Added after: “…2014).”:
“Tropical cyclones and other closed lows accounted for most of the extreme rainfall events in the northwest of Australia over the 1989–2009 period (Lavender and Abbs, 2013).”

8. Page 11913. . ...line 10-26„„, all these other sources of verification sounded interesting to me (especially the field and helicopter groundtruthing). . . . . .I might have missed it but I couldn’t find where the results of this are reported or discussed. I think you need a section that covers:
a. how your reconstruction compares with Landsat (Appendix A, sect A2 describes this but you need images/plots to verify and demonstrate your model/reconstruction is realistic)
b. how your reconstruction compares with the 40 cm and 5 m ortho images. . ... again, plots, figures etc would be good
c. demonstrate how your reconstruction compares with the groundtruthed info (helicopter and field expedition)

Response
We have now included an additional supplementary figure (Fig. A1 in the resubmitted version) that allows visual comparison of the water delineation with the ortho-photos and the groundtruthing, which we undertook by helicopter in 2012 after Cyclone Heidi and on foot during the 2012 dry season. However, while the model reconstruction itself can be compared with Fig. A1 (p. 11943) for validation ($R^2_{adj} = 0.79$; p value < 0.001, $E_{RMSP} = 56$ km^2), it is not sufficiently spatially explicit to compared with the images directly. Of course, similar extents of water resulted in similar spatial patterns of inundations, but they also varied depending on whether several consecutive months had inundations, the maximum FA for the year, and other factors. Fig. 6 illustrates the range of observed extents from the calibration dataset for visual comparison with reconstruction values, which we hope at least partly addresses the suggestions of the Reviewer. We have also modified the text.

Replaced: "To provide further confidence in our dataset within the estimated errors we used two 40 cm digital ortho-images produced from aerial photographs taken in July 2010, April 2012 (Fortescue Metals Group Limited, Perth, Australia) and one 5 m resolution image taken in August 2004 (Landgate, Government of Western Australia), to confirm that our flood areas mapped from Landsat images taken on similar dates (i.e., within one week of the ortho-image dates) were within 1 pixel (30m) of the flood area visible in the ortho-images. A groundtruthing expedition from the dry season (November 2012) and a helicopter delineation of the inundation plume in the wet season (February 2012) were also conducted."

by: "To provide further confidence in our dataset within the estimated errors we used two 40 cm resolution digital ortho-images produced from aerial photographs taken in July 2010, April 2012 (Fortescue Metals Group Limited, Perth, Australia) and one 5 m resolution image taken in August 2004 (Landgate, Government of Western Australia), to confirm that our flood areas mapped from Landsat images taken on similar dates (i.e., within one week of the ortho-image dates) were within 1 pixel (30m) of the flood area visible in the ortho-images (Fig. A1a). A groundtruthing expedition in the dry season (November 2012; Fig. A1 b, c) that noted boundaries by GPS route tracking while walking along the water edge (~1-2 m distance from standing water) of the Moorimoordinia Native Well and a delineation of the inundation plume in the wet season (February 2012; Fig. A1 d) by GPS route tracking during low altitude helicopter survey along the water plume were also conducted and confirm that our thresholding method captured standing water on the Marsh (Appendix A2)."

p. 11943
Included:
"**Figure A1:** Validation and groundtruthing of standing water on the Fortescue Marsh, including: **a)** standing water on the 14 Mile Pool extracted from Level 1T Landsat image (Jul 2010; solid white line = threshold pixel value ≤ 40; LT5; USGS) and close up against a 40-cm resolution ortho-photo (Jul 2010); delineation by GPS route tracking while walking along the water edge (1-2 m distance from standing water; solid white line) and close up against **b)** a Level 1T Landsat image of Moorimoordinia Native Well (Nov 2012; blue fill = threshold pixel value ≤ 40; LE7-SLC-off, USGS) and **c)** a RGB image showing the extent of the dry channel bed (Dec 2006; SPOT-5); **d)** delineation of standing water by GPS route tracking during a low altitude helicopter survey along the water plume of the Fortescue Marsh (2012 Feb 12; solid red line) and close up against standing water extracted from Level 1T Landsat image (2012 Feb 14; blue fill = threshold pixel value ≤ 40; corrected LE7-SLC-off; USGS), overlain on a 2.5 m resolution RGB image taken during dry season (Dec 2006; SPOT-5)."

9. page 11918, first para. . ..this is confusing and I think needs to be reworded. . ...rather than speaking about years you need to talk about months since F(A) and change in F(A) are monthly terms. . ...are you saying that all preceding months in 1941 were drier than 1999??? i think what you are saying is that if the Marsh is inundated in mth x to say 80% then the decrease from that month of inundation to the next is larger than if month x was inundated to say 50%??? Is that right?? If so that would make sense as more water to lose to evaporation etc. . .. .or are you saying something else??? Either way this para is confusing and needs clarification.

<u>Response</u>
The reviewer interpreted our meaning correctly and we apologise for the confusion around terms: we have made the following changes to the text:

p. 11918, l. 2
Replaced: “When still inundated from the previous month (F_{At-1}> 0 km2), decrease of the total area flooded was significantly larger (F_{At-1} = 29 km2; p value < 0.001). For example, although the largest inundated area was recorded in 2000, the 1942 net ΔF_A was larger but resulted in slightly less inundated area at the Marsh owing to the drier conditions than in 1999 in the previous month.”

by: “Water loss (-ΔF_A) on the Marsh from one month to the next was larger over a months after higher inundation extent (F_{At-1} > 0 km^2). For example, after large 560 km^2 inundation in August 1942, the water extent decreased by 100 km^2 over the first month. In contrast, an extent of 200 km^2 in May 1912 decreased by 50 km^2 over the first month, despite a lack of rain in both cases.”

l. 10
Included before “Unsurprisingly…”: “Loss of surface water on the Marsh through evaporation and transpiration was reconstructed to be up to 150 km^2 (i.e., lowest ΔF_A). The most severe water losses occurred during especially dry April, May and June (i.e. <3.5 mm rainfall; Fig. 4) following very wet summers.”

10. Page 11920. . ..line 14-20. . ..you said it. . ..”significance of this finding should be treated with some caution”.......yet abstract and intro does not show the caution you recommend......see previous comments on apparent trends and their spurious significance. . ..suggest remove or reword so it is toned down and caveats above are included........there are also issues with using linear regression tests for processes that are inherently non-linear and non-stationary....see refs listed above for further details on this

<u>Response</u>
We agree with the reviewer that this section should be altered to better reflect the limitations in our findings, as per our earlier comment and suggestions for the abstract. We have modified the Abstract and Introduction accordingly (see also our earlier comments).

p. 11920, l.14
Replaced: "The increased flood severity and duration over recent decades relative to the previous 80 or so years observed in our flooding record is consistent with the increasing trend in heavier summer rainfall events recorded in the region for the same period (Shi et al., 2008; Taschetto and England, 2009; Gallant and Karoly, 2010; Fierro and Leslie, 2013). A simple linear regression between time and yearly duration of floods (FA > 0 km2) further demonstrates slightly increased inundation length since the beginning of the century (p value = 0.046). However, the significance of this finding should be treated with some caution given the non-independence of the FAmax (especially be- tween two consecutive years) and the limited number of observations included (n = 25 flooding events)."

by: "The near yearly recurrence of severe and prolonged inundations over the 1999-2006 period in our record is unprecedented relative to the previous 80 or so years and consistent with the heavier summer rainfall events observed in the region over the recent decades (e.g. Shi et al., 2008; Taschetto and England, 2009; Gallant and Karoly, 2010; Fierro and Leslie, 2013)."

11. Page 11920. . ..line 17. . .Fierro and Leslie 2013 ref not in ref list....check all cites and references as there may be others missing also.

Response
p. 11927, l. 11
Included: Fierro, A.O., and Leslie, L.M.: Links between Central West Western Australian Rainfall Variability and Large-Scale Climate Drivers, J. Clim., 26, 2222-2245, 2013.

12. Page 11920.....line 25-28.....this is good.....and I think this point should be included in the abstract. . .. .also suggest including Interdecadal Pacific Oscillation (IPO) and cites to refs listed in comment #5 which discuss its role in driving multidecadal variability of flood and drought risk in Aust. . . ...most of this work has focused on eastern Aust but it is still relevant and needs to be investigated for WA.

Response
We have included theses references earlier and very much agree with the reviewer that such work, on both floods and drought risk, is necessary for WA and believe our dataset may be useful for such future investigations, especially when coupled with other proxies (see below).

For the interest of the reviewers, we report our preliminary analyses of periodicity and regime shifts, below (Figs. S1 & S2). We have begun more in-depth analyses of these components of long-term variability by integrating our "inundation" dataset with newly developed, regional tree-ring based records that encompass longer time-spans (> 200 years), which would better likely help identify decadal and multi-decadal cyclicity and large-scale drivers of hydroclimate change. However, we feel that this analysis is beyond the scope of the current study and we would rather not include these additional figures in the manuscript.

Wavelet analysis of periodicities:

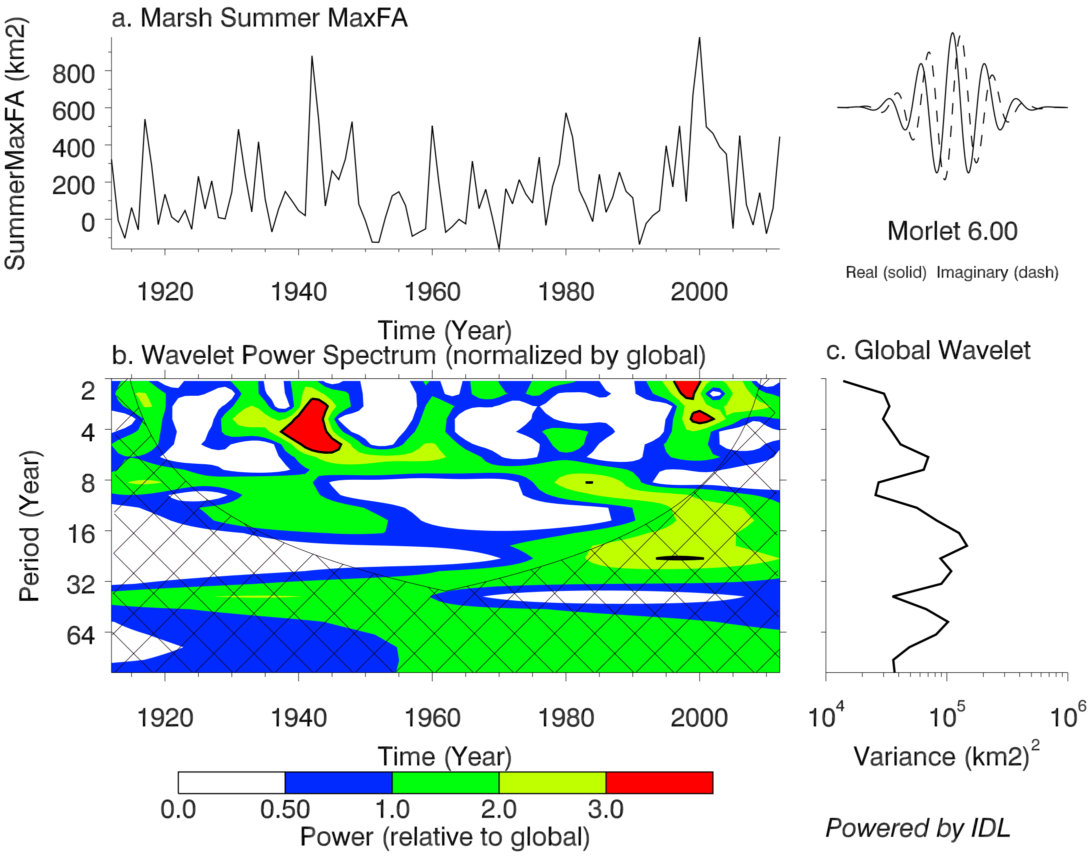
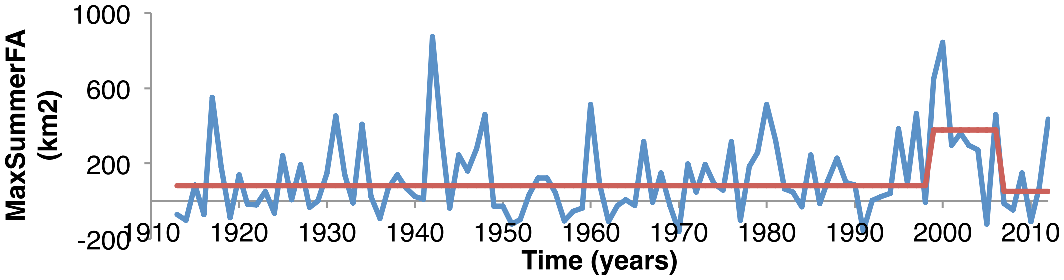


Fig. S1: **a)** Fortescue Marsh maximum inundated area in summer (Nov-Apr); **b)** The wavelet power spectrum. The power has been scaled by the global wavelet spectrum (at right). The cross-hatched region is the cone of influence, where zero padding has reduced the variance. Black contour is the 5% significance level, using the global wavelet as the background spectrum; **c)** The global wavelet power spectrum. (source: paos.colorado.edu/research/wavelets/)

Reference:

Torrence, C., and Compo, G.P.: A practical guide to wavelet analysis, Bulletin of the American Meteorological society, 79, 61-78, 1998.

Regime shift analysis:



a.

b.

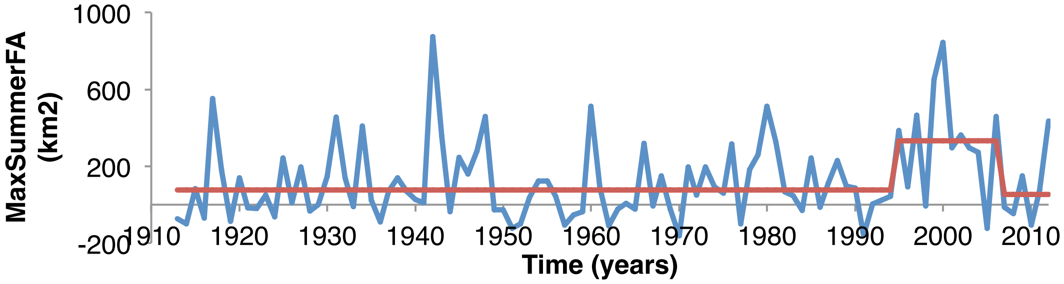


Fig. S2: Regime shifts (i.e., point changes in the -weighted mean- red line for **a)** $p<0.05$ and **b)** <0.1) were detected based on the mean level of fluctuations shifts using a sequential t-test method that can signal a possibility of a regime shift in real time (Rodionov, 2004; source: www.beringclimate.noaa.gov/regimes/). To account for the presence of serial correlation in our time series, the time series was filtered prior to testing with a first order autoregressive model to estimate red noise using the IP4 (Inverse Proportionality with 4 corrections), which is based on the assumption that the bias is approximately inversely proportional to the size of the sample, as described in Rodionov (2006).

References:

Rodionov, S.N.: A sequential algorithm for testing climate regime shifts, Geophysical Research Letters, 31, L09204 1-4, 2004.

Rodionov, S.N.: Use of prewhitening in climate regime shift detection, Geophysical Research Letters, 33, L12707 1-4, 2006.

13. Page 11908. . .line 7. . ...severity, intensity, duration. . ..what is difference between severity and intensity? Do you mean frequency, intensity and duration?

Response

We agree with the reviewer that intensity may be used to infer severity in some contexts even though they are quite different attributes of a disturbance e.g. in forest fires where hot fires (more intense) can result in greater consumption of biomass/fuels and thus more tree deaths (more severe effects). Disturbance size and severity are also distinct properties, even though they are often related. Magnitude is often used synonymously in the literature, but severity does NOT equal intensity, even though for physical processes one may be used to infer the other. In lotic systems, for example, intensity may be an appropriate surrogate for severity if measuring severity is too hard but they remain different aspects of a disturbance regime. However, that is not our intention here. For example, a disturbance can be large and severe, or small and severe. Intensity might be measured (if systems were gauged) by flow velocity and bed movement in the surrounding streams. However, additional factors influence severity of the disturbance: aerial extent (whole Marsh, only parts of the Marsh, etc) and timing of the event (relative to prior events). We thus believe that the term severity is correctly applied here.

14. Fig 1. . ...in legend PLACES NAME should be PLACE NAME. . .. . ..also places indicated in Fig 1c (e.g. Roy Hill, Warrie Outcamp) should also be included on Fig 1b so easier to get bearings etc

Response

Suggestions have been included in Fig. 1.

Responses to reviews from Referee #2 and suggested manuscript corrections

The authors should be commended on developing a record of lake / marsh extent using remote sensing data, especially from an arid region (very underrepresented in the literature) and increasingly under climate and human pressures. This kind of data is therefore extremely valuable for science and management.

We thank the reviewer for this observation.

Unfortunately, I do not support a large part of the analyses and some of the interpretations. There is also a poor (and inconsistent) use of terminology throughout the paper. For example, flood regime is in the title and within the paper, yet no clear analysis of catchment flooding is provided (e.g. magnitude and frequency structure), probably since the data is not available. This is not simply semantic, we have to reserve 'extremes' for when we have some understanding of the distribution of catchment hydrological events.

Response
The reviewer is correct in pointing out the need for careful definition in our analysis and for suggesting a refinement in our terminology for greater consistency. These comments are consistent with Reviewer #1, and we refer to our earlier responses. We have made some additional further changes summarised below to improve clarity and consistency. In particular, the paper title has been made. However, we believe that the use of 'extreme' hydrology in the title accurately reflects the highly contrasting hydrological features (characterised by very high magnitude) that we reconstruct over the last century at the Fortescue Marsh, as opposed to 'average conditions' (low magnitude).

p. 11905
Title
Replaced: "Impacts of a changing climate on a century of extreme flood regime of northwest Australia"
"Impacts of high interannual variability of rainfall on a century of extreme hydrological regime of northwest Australia"

p. 11908, l. 8
Replace "(floods and droughts)" by "(floods, inundations and droughts)"

Moreover, no catchment hydrology information is provided (or available?), only the lake / marsh extent, which is obviously related to, but definitely not the same thing as catchment flooding.

Response
We agree with the reviewer that we have not described catchment hydrology; there are simply insufficient data for this remote area for a full hydrological description sufficient to develop an accurate catchment water balance model. We have thus summarised the catchment hydrological data (or lack thereof) to better explain that the building of a sensible water balance modelling approach for this catchment is not possible because of the lack of gauging data and only fragmented meteorological information.

As noted by the reviewer, we acknowledged in the Introduction that such approaches have been used elsewhere but in generally smaller and well-gauged catchments (e.g. Karim et al. 2012; Trigg et al., 2013). We provide an overview of recent literature in the introduction (p. 11909, l. 14-20; e.g., Bates, 2012; Neal et al., 2012; Wen et al., 2013). In addition, official daily pluviographs (www.bom.gov.au) are sparse in the catchment and not temporally consistent over the last 100 years (described in Appendix B and Table A1, p. 11932), or even for the period covered by satellite imagery (Fig. 1; Table A1). Official sub-daily pluviographs are also mainly available for the northwest coastal area (www.bom.gov.au). In the large (31,000 km^2) Upper Fortescue River catchment, however, data is not sufficiently well resolved in time nor space to calculate inflow, retention times, evaporation etc., from the different sub-catchments and their relationship to rainfall, which is also highly heterogeneous.

We did not intend to reconstruct catchment flooding because of the above (as it requires temporal data at a much higher resolution than our monthly images dataset), but rather point out that the inundation extent observed at the Fortescue Marsh as an indicator that flooding occurred on the catchment and general moisture availability (p. 11918, l. 14; Haas et al., 2011). We concur with the reviewer's comment that the hydrological regime we describe is that of the Fortescue Marsh wetland, i.e. inundation magnitude, duration, return interval, interannual variability. We have thus suggest modified the text to clarify our interpretations (e.g., intense rainfall resulted in fast and severe inundations at the Marsh, potentially due to one or more large catchment runoff events).

To summarise, the use of a direct water mass balance model based on (limited) gauging data from the catchment is not possible without very high uncertainty. The use of linear modelling linking rainfall with the area of Marsh inundation is a simplified way of comparing to a full water mass balance model but it is not an oversimplification. As the performance of the linear model calibration shows ($R^2_{adj} = 0.79$; p value < 0.001, $E_{RMSP} = 56$ km^2) it is reliable for reconstructions in statistical sense. The uncertainty in the model fit provided results from non-linear components of the hydrological regime mentioned by reviewer #2 that cannot be fully integrated in such model. Please also refer to our further comments in our response provided to the editor.

p. 11911, l. 10
Replaced: "The Marsh acts as an internally draining basin for the 31 000 km2 upper Fortescue River catchment (21–23˚ S; 119–121˚ E; Fig. 1). The flood level required for the Marsh to overflow to the Lower Fortescue catchment is not formerly established but digital elevation models (Geosciences Australia, 2011) suggest water could flow if inundations reached > 410 m a.s.l. The upper Fortescue River is the main drainage of the catchment, flowing north to northwest into the wetland system. Flow in the Fortescue River is characterized as "variable, summer-dominated and extremely intermittent" (Kennard et al., 2010), where very large volumes of runoff are generated following heavy rainfall, which is in contrast with the empty beds of the dry season (WA Department of Water, 2014)."

by: "The Marsh acts as an internally draining basin for the 31 000 km^2 Upper Fortescue River catchment (21–23°S; 119–121°E; Fig. 1), which is physiographically separated from the Lower Fortescue River catchment (www.water.wa.gov.au). The upper Fortescue River is the main drainage of the catchment, flowing north to northwest into the wetland system. However, numerous ephemeral creeks on the southern and northern flanks of the Fortescue Valley (Fig. 1) discharge to the marsh directly (www.water.wa.gov.au; Table A1). Flow in the Fortescue River is characterised as "variable, summer-dominated and extremely intermittent" (Kennard et al., 2010), and only very large rainfall events generate continuous flow, which contrasts with the normally dry stream beds of the dry season (WA Department of Water, 2014). Only one official daily stream gauging station is currently operational on the river (>100 km upstream of the Marsh). The other stations were only installed along the main creeks in two of the 13 sub-catchments of the Upper Fortescue River catchment (Fig. 1), and records did not overlap consistently in time (Table A1). Recently, sub-daily gauging stations were installed along Coondiner Creek and sections of Weeli Wolli Creek with pluviographs and used to implement stable isotope water balance models for these sub-catchments over relatively short (i.e., < 6 years) time periods (Dogramaci et al., 2015)."

p.11935
Modified Figure 1 to include sub-catchments (provided in separate file).

Replaced: "Geoscience Australia, 2011), and meteorological stations (green circles, see full list in Appendix A, Table A1"

by: "Geoscience Australia, 2011), stream gauging stations (blue circles, see full list in Appendix A, Table A1; WIN, 2014) and meteorological stations (green circles, see full list in Appendix A, Table A2"

p. 11932
Added table in Appendix:

Table A1: Temporal coverage of all official stream gauging stations in the Upper Fortescue River catchment and maximum recorded daily discharge

Site number	Stream Name	Name	Operational date	Last measurement	Max discharge (m^3/sec)	Total discharge (GL)
708001	Marillana Ck	Flat Rocks	15/08/1967	23/02/1983	1327	72
708006	Fortescue River	Goodiadarrie Crossing	01/12/1972	01/10/1986	*	*
708008	Fortescue River	Roy Hill	01/09/1973	29/09/1986	*	*
708011	Fortescue River	Newman	09/01/1980	Present	1730	78
708013	Weeli Wolli Ck	Waterloo Bore	30/11/1984	Present	4137	142
708014	Weeli Wolli Ck	Tarina	10/05/1985	Present	2100	62
708016	Weeli Wolli Ck	Weeli Wolli Springs	08/10/1997	14/07/2008	423	10

Note: * Only daily stage height available; location of stations marked on Fig. 1

Table A1 shows all available gauging data for the Upper Fortescue River catchment. The temporal coverage of the different gauging stations is poor (only three of the sub-catchments), inconsistent with one another and the satellite imagery cover. Consequently, these data are insufficient for the building of a sensible water balance model for this catchment.

p. 11930, l. 24
Include: "Water INformation (WIN) database - discrete sample data. [21 May 2014]. Department of Water, Water Information section, Perth Western Australia."

Of course it is reasonable to suppose that a quick rise in lake extent must be due to a large catchment runoff event, but this response is likely to be highly non-linear (especially concerning the role of antecedent conditions) therefore it is not possible to link lake extent alone to a formal analysis of flooding without more information.

Response

The relationship between change in surface water extent (ΔF_A) and the four instrumental parameters incorporated in our model is perhaps simplified compared to a regular whole catchment hydrological model, however, the discussed response is linear and statistically sound, as can be assessed by the performance of the multiple linear regression model ($R^2_{adj} = 0.79$; p value < 0.001, $E_{RMSP} = 56\ km^2$; p. 11943, Fig. A1; p. 11931, Table. 1). The proposed method, despite simplification, still provides very valuable information about the extent of FM inundations and this is the best what can be done in such remote but important from mining perspective catchment.

A smaller point relates to the attribution of a changing climate on the hydrology, the variability is so large I'm not sure it would be possible to extract a statistically meaningful trend from this data, and nor have the authors attempted it, so it is unclear why the authors do not instead try to assess the role of extreme climate variability rather than climate change.

Response

We acknowledge the Reviewer about this point and have modified our discussion to focus on climate variability rather than trends (see also our responses to Reviewer #1) (p. 11920, l.18). Nevertheless, in the analysis of surface water on the Marsh, a significant trend (p value = 0.046) was obtained using "a simple linear regression between time and yearly duration of floods (FA > 0 km2)", which showed a slight increased length of inundations since the beginning of the century. However, as bot Reviewer 1 and 2 have pointed out, we think this approach does not take into account the influence of periodicities and other drivers of interannual variability in the system and thus decided to replace it with the more useful characterisation of 'wet' of 'dry' periods. We have revised the wording referring to cyclicity and trends throughout (please also refer to changes suggested in response to referee #1, comment #5). The large variability, particularly in precipitation, actually makes the model more robust. Crucially, analysing data with less variability would make interpreting the relative changes in the flooded area more difficult when taking into account the uncertainty in the data and model.

My main concern is with the data analysis and the lack of a water balance to at least provide some realism for the extrapolated time series.

Response

Please refer to response in previous comment. A water balance model is simply not appropriate or possible in this system, which is why we have used an alternative approach.

The construction of the linear regression model is unclear, but it seems the final model has four variables, all of which would seem to be highly correlated with each other (monthly rainfall and number of rainfall days for example), but most importantly given the extreme variability, I have no doubt that the correlation structure between all these variable should shift over time. Given this noise, the parameters derived would have very little robustness, and thus any extrapolation (over 4 times the observation length in this case!) would have substantial errors (though the authors have made no attempt to quantify this), and I suspect therefore little value for prediction. This is of course one reason why multiple linear regression models are rarely used in trying to conceptualise highly non-linear catchment hydrological processes.
That being said, lake extent could be tackled using a simple water balance approach very effectively, and one that is much more robust to the variable hydrology, and the authors clearly have much of the requisite data to achieve this.

Response

Standard statistical information for this model and the details of the different parameters are also provided in Table 1 and in Appendix (Table A3; Fig. A1). The validation steps of the model's predictive abilities are described in section "2.4.2 Validation of model and 1912–2012 reconstruction", and error was assessed by RMSE, RMSECV and RMSEP. As suggested by the reviewer, the error we provide (e.g., RMSEP = 56 km^2) is likely the results of the non-linear processes such as the influence of evaporation, transpiration and infiltration. These nonlinear components of hydrological cycles adds uncertainty to other ways linear relationship, as statistically confirmed in this study ($R^2_{adj} = 0.79$; p value < 0.001, $E_{RMSP} = 56$ km^2), between precipitation and extend of inundation of the Fortescue Marsh. In addition, we also accounted for the error associated to the image resolution and estimates in calibrating the model (Section **2.3 Mapping flood history based on the Landsat archive (1988–2012)**; Section **A2 Flood area delineation and error**), and point out that both spatial and temporal distribution of rainfall has an influence on accuracy of estimates (p. 11914, l. 9; p. 11924, l. 5). We also acknowledge that our model likely provides underestimations of the maximum area flooded at the time of large rainfall events (happen earlier in month) due to the limited number of high quality sat images (2-weekly snapshot and cloud cover during these events.) We acknowledge that the correlation structure between variables may change with time, however the Pearson correlation matrix (Appendix Table A3) shows only two of the variables, R (total rainfall) and R_d (number of rain days), are in fact correlated with one another. Typically in a regression model, R and R_d may have been included as one variable, but here were included separately as to account for their potential changing effect in time. In addition, our 25 year-calibration period includes a very high degree of interannual variability that provides more confidence in the model testing. Overall, we do not think changes in these variables would seriously affect the model's predictions ability beyond the uncertainty provided and taking into account the monthly scale of observations and reconstructions.

Despite our model uncertainty and considering that a catchment water balance approach, even if possible, would also result in relatively high uncertainties due to the lack of historical data (see above), we believe our reconstruction provides a useful background of monthly hydrological change (supported by historical evidence) and tool for management. It is certainly the first attempt to do so for the entire northwest of Australia and provides the first extended baseline of natural variability in hydrology for the region.

A more minor concern relates to the vague catchment description, the authors mention there is an upper and lower catchment (with the Marsh in the upper part), and that the Marsh may overflow, but then end it there! Surely the dynamics of the overflow are fundamental to the marsh hydrology, so why isn't this analysed in further detail or taken into account in any of the further analyses? How can we have confidence in the large time series extrapolation if we don't know anything about how the outflow dynamics of the system operate? This would not be particularly onerous to achieve, but its omission detracts from confidence in the results and interpretation.

Response

We agree with the reviewer that our hydrological description of the catchment was insufficient and have elaborated on our earlier description, including reference to our previous studies (e.g. p. 11911, l. 10; see previous response).

For these reasons I do not recommend the manuscript be published in its current form, and given the scale of the required changes, a new paper would basically need to be written.

Response
As we understand form Reviewer 2's comments, the main issue identified by the reviewer for endorsing the publication of this paper is that we have not used or validated against a catchment water-balancing modelling approach. However, our approach was used precisely because the catchment that we have worked on, while encapsulating a large and significant proportion of the northwest of Australia, is remote, sparsely populated and with poor records, let alone systematic gauging of the many ephemeral and intermittent streams that feed the Fortescue marsh. We have thus tried to explain this aspect of the study better in our revisions. We have highlighted in our responses several problems specific to our area of study that precluded the use of a water balance approach. We also consider the alternative used to be valid and well-corroborated and that our interpretations are in line with our study objectives.

Some more specific comments are provided below:

Introduction
“Changes in hydroclimatic patterns and extremes that might alter the natural distur- bance regime...” what would be a ‘natural disturbance regime’ in one of the most variable climates on earth, and how would we know if it is altered?

Response
The reviewer is correct that defining "normal" or average is challenging in a system that is known to be highly variable. More information is available in this seminal reference (and >3500 citing articles) and in the more recent review by Mori et al. (2011). We have moderated our introduction accordingly, consistent also with the input of Reviewer #1.

As to how would we know if the regime were to become altered, the reviewer highlights a very important point, where the interpretation relies completely on the temporal window available for comparison and the understanding of the underlying mechanisms. Further, it relates to the setting of targets that may for example be entirely human-defined depending on conservation goals. In the most recent Environmental Protection Authority strategy plan for the Fortescue Marsh Management Area, several of the management objectives aim to “Maintain the natural flow regime of the Marsh”, “Protect [aquatic invertebrate, waterbird and halophytic vegetation] species and their habitat” (EPA, 2013). Taking a definite stance on how to make these important decisions is beyond the scope of this paper, however we hope that our reconstruction may inform decision-makers of the range of hydrological variability (natural variation in the extend of the Fortescue Marsh inundation in the scale of last 100 years) that have been for the last century and some of the hydroclimatic determinants that may most influence functioning of the Marsh to assess the risk and potential impacts of changing hydrological regimes.

Reference:
Environmental Protection Authority: Environmental and water assessments relating to mining and mining-related activities in the Fortescue Marsh management area. Report and Recommendations of the Environmental Protection Authority No 1484., Perth, The Government of Western Australia, 51 pp., 2013.

“the interannual variability of rainfall is high” is used repetitively in the introduction, once is enough.

Response

We agree with the reviewer and suggest the following changes (in addition to those included in earlier responses):

p.11909
l. 6
Removed: "As interannual variability of rainfall is high in arid regions, long temporal series are essential to capture the background variability of systems at appropriate temporal scales (Mori, 2011).

Study site

"as the largest freshwater feature" how fresh is this if it is dominated by 'salt tolerant species'? Perhaps there is a short lived pulse of freshwater during initial inundation, but how quickly does this deteriorate?

Response

We collected water from the Fortescue Marsh over the course of three years (2010-2012). The flood-related freshwater become increasingly more brackish with time, and the rate at which this happens depends on the initial volume of freshwater discharged originally. A fine crust of salt is left on the surface over a relatively very limited area as the water evaporates completely; if the vegetation withstood the inundation and soil waterlogging (which recent research has shown *Tecticornia* spp dominant on the Marsh can do for some time through physiological adaptations), it then has to grow in relatively salty soils, hence their salt-tolerance. In general, the surface water on the marsh is fresh to brackish and groundwater is highly saline. The prevailing dry condition of the marsh results in a lack of salt accumulation on the surface. The subsequent inundation events dissolve the limited amount of salt from the surface and wash it down to the groundwater aquifer during the initial pulse of water. We refer to Skrzypek et al. (2013) for more information on the hydrochemical dynamics of the Marsh, which have been previously described. Therefore, the conditions on the marsh are generally fresh to brackish and salt deposition is very limited, but only allow for salt tolerant plants to grow. We have added further details to the manuscript to better characterise the marsh.

"The marsh acts and an internally draining basin" but just below you say it can overflow into the lower Fortescue catchment, so how is it an internal basin? The authors say the lake can overflow at 410 m asl, but we have no way to compare this to the data in the rest of the paper since no depth scale is ever used, so the corresponding marsh extent would be very useful. This feeds into the larger issue regarding the overflow dynamics mentioned above in the general comments.

Response

We agree with the reviewer that this section is unclear. The official boundary for the Upper Fortescue River catchment suggests that the 'Upper' and 'Lower' Fortescue catchments are physiographically separate systems, isolated by a low range of hills (www.water.wa.gov.au). They might have been hydrologically connected in the geological past, however there is no overflow at present or in the recent past. The two sub-catchments are thus considered hydrologically disconnected unless exceptionally high inundation would occur. The overflow is possible from a geomorphological point of view, i.e., if water reached 410 m a.s.l. However, this water level would require a surface area of 1300 km2 (and a volume of >3000 GL; Fig. 8), which was not observed in the last century. We have clarified this text (see responses to reviewer #1).

“the residence time of water in the upper sections of the catchment is short” how do you know, and what do you mean by short? Do you have age data, or tracer studies to determine the transit time distribution? If so then it would seem very important to include.

Response
We have recently published a paper encapsulating some of these data and now refer to Dogramaci et al. (2015) for further information.

p. 11911, l. 25
Replaced: "The residence time of water in the upper sections of the catchment is short: surface runoff is high via the steep gradients of creeks and gorges."

by: "Surface runoff is high via the steep gradients of creeks and gorges; recent tracer studies from the Weeli Wolli Creek and Coondiner Creek (Fig. 1) showed that residence time of water in the upper sections of the catchment was short (days to weeks) (Dogramaci et al. 2015)".

“does not retain water significantly diluted nor flushed by groundwater” if the groundwater is salty then I guess the pool is not really diluted by this inflow

Response
We agree with the reviewer that it is not; however, the shallow aquifer groundwaters in this systems are fresh on alluvial fans and marginal areas of the Fortescue Marsh (see our results published in Skrzypek et al., 2013).

Mapping flood history
“a groundtruthing expedition . . .” and did it match the remote sensing?

Response
See added Figure A1 and please refer to suggestions to Referee #1, comment #8. We agree that we did not explain what groundtruthing was undertaken and have now explained this more fully.

Model development and selection
The use of the dFa metric means a water balance would not at all be difficult, see general comments

Response
There are no gauging stations for all of the Upper Fortescue River sub-catchments (added Table A1) nor has meteorological data been consistently recorded (Table A2) over the 1988-2012 calibration period. Please see the more detailed responses above.

Results
“Because it was not possible to calculate dFa. . .” why not, shouldn’t it just be 0?
Lines 8-15: this is completely beyond the explanatory capacity of the ‘model’ and is crazy that the authors try to explain their model extrapolation in this way, please delete. There is no data or water balance to verify any of this

Response

We agree with the reviewer that negative surface area values are not commonly used in mass balance approaches/hydrology. Here, we attempt to conceptually explain the meaning of these data based on our understanding of the Marsh's hydrogeology.

p. 11916, l. 4
Replaced: “The enhanced performance of the subset models built without as many “dry” periods highlights an important limitation of the observation dataset. Because it was not possible to calculate deltaFA from the calibration set when the surface water at the Marsh was dry, water loss, i.e., soil water storage depletion, was therefore underestimated during these periods. Concurrently, however, the reconstruction of monthly FA values below 0 km2 reflects the ability of our model to provide quantitative information on soil water storage, or the unsaturated zone of the Marsh where rapid infiltration of rainwater was observed following heavy rainfall at the Marsh (Skrzypek et al., 2013). This zone between water table and ground surface likely acts as a buffer to net surface water gain or loss.”

by “A lack of surface water is returned by the model as areas ≤ 0 km^2. The negative values (≤ 0 km^2) for ‘area’ can conceptually be explained as the depletion of the groundwater resources and lowering of the water table below ground level.”

Spatial and temporal patterns of inundations
To me this is the most interesting part of the paper (and could be done with the re- mote sensing data alone), however the timing, duration, and magnitude dynamics of the marsh extent change are barely touched on (mostly aggregated statistics of the dataset). Teasing out the dynamics of these changes with different event magnitudes and possible thresholds would be a very interesting addition to this work.

Response
We thank the reviewer for this observation and agree with this comment. We have thus better summarised the key aspects of the inundation dynamics. We have also undertaken a wavelet analysis exploring some of the cyclicity in the data (see responses to reviewer 1). However, while we agree that a more comprehensive analysis of the dynamics and particularly the identification of thresholds is very interesting, this would be better undertaken using a multi-proxy approach (see earlier comments to Reviewer 1).

Line 23: this makes me ask about any possible impacts of mining (given there is so much in the area) on the marsh hydrology. Has there been persistent mine dewatering, and if so, has some found it’s way into the system which, even in a small way, might be a causal factor here?

Response
This is an interesting question and certainly underpins much of the motivation for better understanding the hydrogeology and functioning of the Pilbara region. Dogramaci et al. (2015) recently demonstrated that no direct impact to the volume of surface water discharged to the Marsh could be found from the continuous release of water along the Weeli Wolli Creek line (Fig. 1), where one of the largest iron ore mine operates and which has been discharging dewatering water to the creek for > 6 years, corresponding to the period a major mining expansion in the vicinity of the Fortescue Marsh. Overall, the volumes generated by large rainfall events have been driving inundations at the Marsh and the magnitude of volume delivered during a single event (e.g. Cyclone Heidi in 2012) is similar to the total discharge from mining sites upstream in the catchment over the last 8 years or so. However, this does not mean that the cumulative impacts of

mining expansion and dewatering in the region may not ultimately influence the system, particularly at smaller and more localised scales and especially during relatively dry years. For example, mining discharge can increase groundwater levels, particularly in alluvial fans, reducing the saturation zone and therefore the buffering capacity of this zone during future flooding.

Reference:
Environmental Protection Authority: Environmental and water assessments relating to mining and mining-related activities in the Fortescue Marsh management area. Report and Recommendations of the Environmental Protection Authority No 1484., Perth, The Government of Western Australia, 51 pp., 2013.

Lines 26-28, shouldn't the marsh overflow also be critical to consider here?

Response
Overflow to the Lower Fortescue River is limited by a physiographic barrier (Goodiadarrie Hills) and is unlikely to have occurred in the last 100 years at least. Please see earlier response.

3.3 significance of predictability and persistence of drought
Lines 4-5: this is an arid climate, how would you expect a different result?

Response
We agree we the reviewer that this sounds rather obvious, nevertheless we believe this result was important to highlight, especially because the most recent period (>1999) has been particularly wet (a relative measure in an arid environment) when compared to the longer-term record. Hence, using only the most recent years as 'background', which is often the case in the area because water resources have been monitored only during those year, may be particularly misleading in assessing impacts of change to the regime.

The use of drought in this section is also problematic, since it seems the authors simply mean low marsh water extent.

Response
There is no doubt that the term 'drought' may be defined as e.g., meteorological (i.e. lack of rain), hydrological or from a 'moisture availability' perspective in the agricultural context, and may be defined as 'below average'. Here, as the reviewer has pointed out, we use 'drought' in a hydrological context as being an absence of surface water. We have made the following changes to the text to clarify our use of drought.

p. 11921, l. 5
Replaced: "Our reconstruction shows that the Fortescue Marsh floodplains have more often been dry than wet over the last century (Fig. 3c). Droughts of at least one year were frequent (21 %) between 1912–2012 (Figs. 3c d, and 7)."

by: "Our reconstruction shows that the Fortescue Marsh floodplains have more often been dry (i.e., where no surface water is evident on the Marsh, or $F_A \leq 0$ km^2) than wet over the last century (Fig. 3c). Hydrological droughts (i.e., series of consecutive months where $F_A \leq 0$ km^2) of at least one year were frequent (21 %) between 1912–2012 (Figs. 3c d, and 7)."

l. 8

Removed: “(where no surface water is evident on the Marsh)”

l. 17

Replaced: “this documented drought corresponded to largely dry conditions ($F_{\mathrm{Amax}} < 150$ km^2)”

by: “this documented drought corresponded to minimal surface water ($F_{\mathrm{Amax}} < 150$ km^2)”

Moreover, I’m not sure how conceptually useful it is to describe arid areas as being in drought or not, since they fundamentally lack surface water for most of the time, otherwise they would not be arid.

Response

We agree that drought is a relative term. According to the PDSI, for example, the Pilbara has been "in drought" for all but two brief periods over the last two hundred years (O'Donnell et al., unpublished data based on tree ring reconstructions). However, both the presence and lack of surface water, particularly in a drought-ridden landscape, are important components of the hydrological regime that contribute to the ecological functioning in different ways and thus we consider it important to characterise both.

If this is the norm, then a more useful exercise is to analyse the frequency and dynamics of wet punctuations in an otherwise dry (or drought ridden) landscape.

The reviewer makes a very good point and this observation is consistent also with Reviewer #1. We completely agree that with the reviewer and have thought long and hard about ways to characterise systems were the dynamics and their natural variations may also occur as very long (multi-decadal) cycles. As described in our earlier responses, we will attempt to do this in a coming analysis by extending the time period and using a multi-proxy approach. We thus consider this analysis might be better suited in a different article (e.g., Kiem et al., 2003; Kiem et al. 2004; Verdon-Kidd and Kiem, 2010; Ishak et al. 2013).

Additional changes to the discussion manuscript by the authors

p. 11908, l.13
Replaced: “by the most variable”
by: “by some of the most variable”

l.20
Replaced: “…population dynamics…”
by: “…population dynamics across the region…”

l.22
Replaced: “…regime play…”
by: “…regime in turn play…”

l.26
Removed: “However, while the ecological response to extreme flood or drought has been documented for several arid and semi-arid river basins, characterization of the disturbance regime has focussed primarily on the rivers only, and generally been qualitative and coarsely resolved both temporally and spatially (Kennard et al., 2010; Mori, 2011; Stendera et al., 2012).”

p. 11909, l. 3
Replaced: "variability of arid zone remote wetlands (e.g., McCarthy et al., 2003; Bai et al., 2011; Thomas et al., 2011), as well as understanding ecohydrological processes"

by: "variability of arid zone remote wetlands in the arid zone (e.g., McCarthy et al., 2003; Bai et al., 2011; Thomas et al., 2011), as well as and improved understanding of ecohydrological processes at the regional scale particularly"

l.25
Replaced: "(Roshier et al., 2001; Viles and Goudie, 2003)"
(Roshier et al., 2001; Mori, 2011; Ishak et al. 2013; Kiem and Verdon-Kidd 2013)

p. 11910, l. 23
Replaced: “the Marsh…” by: “the Marsh (*Martuyitha*)…”

p. 11925, l. 12
Added prior to “This research…”: “We thank the two anonymous referees and the Editors for their helpful comments, which have helped focus and improve the quality of the manuscript.”

p. 11926, l. 15
Removed: “Berry, G., Reeder, M. J., and Jakob, C.: Physical mechanisms regulating summertime rainfall over northwestern Australia, J. Climate, 24, 3705–3717, 2011”.

l. 28
Removed: “Coumou, D. and Rahmstorf, S.: A decade of weather extremes, Nat. Clim. Change, 2, 491–496, 2012.”

p. 11927, l. 4

Included: “Dogramaci, S., Firmani, G., Hedley, P., Skrzypek, G., and Grierson, P.F.: Evaluating recharge to an ephemeral dryland stream using a hydraulic model and water, chloride and isotope mass balance, J. Hydrol., 521, 520-532, 2015”.

l. 7
Removed: “Emanuel, K. A.: Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century, P. Natl. Acad. Sci. USA, 110, 12219–12224, 2013.

l. 24
Removed: “Goebbert, K. H. and Leslie, L. M.: Interannual variability of Northwest Australian tropical cyclones, J. Climate, 23, 4538–4555, 2010”.

l. 31
Removed: “Hassim, M. E. E. and Walsh, K. J. E.: Tropical cyclone trends in the Australian region, Geochem. Geophy. Geosy., 9, 1–17, 2008”.

p. 11928, l. 1
Included: “Ishak, E.H., Rahman, A., Westra, S., Sharma, A., and Kuczera, G.: Evaluating the non-stationarity of Australian annual maximum flood, J. Hydrol., 494, 134-145, 2013”.

l. 7
Included: “Kiem, A.S., Franks, S.W., and Kuczera, G.: Multi-decadal variability of flood risk, Geophys. Res. Lett., 30, 1-4, 2003

Kiem, A.S., and Verdon-Kidd, D.C.: The importance of understanding drivers of hydroclimatic variability for robust flood risk planning in the coastal zone, Aust. J. Wat. Res., 17, 126, 2013.”.

p. 11930, l. 9
Included: “Verdon-Kidd, D.C., and Kiem, A.S.: Nature and causes of protracted droughts in southeast Australia: Comparison between the Federation, WWII, and Big Dry droughts, Geophys. Res. Lett., 36, 1-6, 2009”.

l. 11
Removed: “Wang, L., Huang, R., and Wu, R.: Interdecadal variability in tropical cyclone frequency over the South China Sea and its association with the Indian Ocean sea surface temperature, Geophys. Res. Lett., 40, 768–771, 2013”.

Journal: *Hydrology and Earth System Sciences*

Manuscript type: Research Article

~~Impacts of a changing climate on a century of extreme flood regime of northwest Australia~~ Impacts of high interannual variability of rainfall on a century of extreme hydrological regime of northwest Australia

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Abstract

~~Globally, there has been much recent effort to improve understanding of climate change-related shifts in rainfall patterns, variability and extremes. Comparatively little work have focused on how such shifts might be altering hydrological regimes within arid regional basins, where impacts are expected to be most significant.~~ Long-term hydrological records provide crucial reference baselines of natural variability that can be used to evaluate potential changes in hydrological regimes and their impacts. However, there is a dearth of studies of the hydrological regimes for tropical drylands where intraseasonal and interannual variability in magnitude and frequency of precipitation are extreme. Here, we sought to identify the main hydroclimatic determinants of the strongly episodic flood regime of a large catchment in the semi-arid, subtropical northwest of Australia and to establish the background of hydrologic variability for the region over the last century. We used a monthly sequence of satellite images to quantify surface water expression on the Fortescue Marsh, the largest water feature of inland northwest Australia, from 1988 to 2012. We used this sequence together with instrumental rainfall data to build a multiple linear model and reconstruct monthly history of floods and droughts since 1912. We found that severe and intense regional rainfall events, as well as the sequence of recharge events both within and between years, determine surface water expression on the floodplain (i.e., total rainfall, number of rain days and carried-over inundated area; $R^2_{adj} = 0.79$; p value < 0.001, $E_{RMSP} = 56$ km^2). ~~The most severe inundation (~1000 km^2) over the last century was recorded in 2000~~ The most severe reconstructed inundation over the last century was in March 2000 (1000 km^2), which is less than the 1300 km^2 area required to overflow to the adjacent catchment. The Fortescue Marsh was completely dry for 32% of all years, for periods of up to four consecutive years. Extremely wet years (seven of the 100 years) caused the Marsh to remain inundated for up to 12 months; only 25% of years (9% of all months) had floods of greater than 300 km^2. ~~Duration, severity and frequency of inundations between 1999 and 2006 were above average and unprecedented when compared to the last century~~ The prolonged, severe and consecutive yearly inundations between 1999 and 2006 were unprecedented compared to the last century. ~~While there is high inter-annual variability in the system, changes to the flooding regime over the last 20 years suggest that the wetland will become more persistent in response to increased frequency and intensity of extreme rainfall events for the region~~ While there is high inter-annual variability in the system, if the frequency and intensity of extreme rainfall events for

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the region were to increase (or be similar to 1999-2006), surface water on the Marsh will become more persistent, in turn impacting its structure and functioning as a wetland.

1 Introduction

~~Extreme climatic events such as tropical cyclones, heavy rainfall and severe drought are projected to become more intense and less frequent globally over the next hundred years in response to anthropogenic-driven climate change (Coumou and Rahmstorf, 2012). Tropical cyclones (TC) have been increasing in intensity in the semi-arid northwest of Australia since the 1970's, although trends in both their occurrence and the distribution of associated rainfall remain unclear (Hassim and Walsh, 2008; Goebbert and Leslie, 2010; Emanuel, 2013; Wang et al., 2013). Instrumental data and modeling suggest that the subtropical region has also experienced an increase in summertime rainfall since 1950 and overall wettening (Shi et al., 2008; Taschetto and England, 2009; Fierro and Leslie, 2013). Rainfall anomalies over the 1919–1999 period retrieved from tree ring records provide further evidence of a post-1955 wettening trend in northwest Australia (Cullen and Grierson, 2007). This wettening, since at least the 1980's, has been attributed to increased occurrence of monsoonal lows and TCs (Berry et al., 2011; Lavender and Abbs, 2013) and is also consistent with increases in extreme wet and hot conditions during the summer monsoon period in the Australian tropics over recent decades (Gallant and Karoly, 2010).~~

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~~However, resultant impacts of shifts in hydroclimate on catchment hydrology are still poorly understood. Quantifying the "hydroclimatic expression" of regional events remains challenging for not only the Australian northwest but for arid environments more generally;~~ Quantifying the hydrological response to changes in the rainfall patterns remains challenging in arid environments, especially for remote tropical and minimally gauged drylands such as the Pilbara region of northwest Australia. Tropical drylands are often characterised by extreme hydroclimatic conditions, where rainfall is highly heterogeneous in its distribution and the majority of streams and rivers are ephemeral but highly responsive to intense rainfall events. For example, peak surface flow rates generated from ephemeral rivers and creeks in the Pilbara ~~region of northwest Australia~~ can reach thousands of cubic metres per second after such events (WA Department of Water, 2014). These factors contribute to high spatial and temporal heterogeneity of recharge-discharge mechanisms across any one catchment, which in turn presents considerable challenges for prediction of ~~consequences of changes in intensity and frequency of extremes~~ resultant impacts of hydroclimate change on catchment hydrology. Several lines of evidence suggest the Pilbara has been particularly wet during the late 20th century (e.g., Cullen and

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Grierson, 2007; Shi et al., 2008; Taschetto and England, 2009; Fierro and Leslie, 2013) and that the frequency of extreme precipitation events may be increasing (e.g., Gallant and Karoly, 2010). However, there is no consensus on whether the observed higher summer rainfall can be attributed to an overall 'wettening trend' or whether the recent 'wet' period may be a feature within the range of natural 'extreme' variability characteristic of this region. The consequences of intensification and shifts in frequency of the hydrological cycle as well as greater variability of precipitation patterns have already been documented in other parts of the world, including alterations in the seasonality and extent of floods or drought (Harms et al., 2010; Feng et al., 2013).

Ecological disturbances such as flood and drought cycles are usually described by their extent, spatial distribution, frequency (or return interval), predictability and magnitude (i.e., severity, intensity and duration) (White and Pickett, 1985). Determining how altered hydrologic regimes (floods and droughts) may in turn impact vulnerable ecosystems, including wetlands, requires detailed understanding of the links between the distribution of precipitation and flows across multiple spatial and temporal scales (e.g., Kiem et al., 2003; Kiem et al. 2004; Verdon-Kidd and Kiem, 2010; Ishak et al. 2013). The Pilbara region of northwest Australia, in common with other hot arid regions of the world including the Indian Thar, Namib-Kalahari and Somali deserts, is characterised by some of the most variable annual and inter-annual rainfall patterns on the planet (van Etten, 2009). ~~In the case of the Pilbara, TCs~~ In the Pilbara, tropical cyclones and other low-pressure systems forming off the west Australian coast in the tropical Indian Ocean often result in ~~extreme~~ severe flooding events (WA Department of Water, 2014). These events punctuate years of prolonged drought, which together define the "boom-bust" nature of productivity in highly variable desert ecosystems (McGrath et al., 2012). Surface water availability or persistence of water features, physical disturbances and hydrological connectivity resulting from this highly dynamic regime in turn play a central role in shaping aquatic and terrestrial ecosystem processes, species life history strategies and interactions and population dynamics (Box et al., 2008; Leigh et al., 2010; Pinder et al., 2010; Sponseller et al., 2013). Changes in hydroclimatic patterns and extremes that might alter the natural disturbance regime would thus have profound consequences for the structure and functioning of often highly specialised and adapted arid ecosystems (Newman, 2006; Leigh et al., 2010). ~~However, while the ecological response to extreme flood or drought has been documented~~

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~~for several arid and semi-arid river basins, characterization of the disturbance regime has focussed primarily on the rivers only, and generally been qualitative and coarsely resolved both temporally and spatially (Kennard et al., 2010; Mori, 2011; Stendera et al., 2012).~~

Remote sensing has proven to be the most suitable and often only tool for investigating spatial and temporal variability of ~~arid zone remote~~ wetlands in the arid zone (e.g., McCarthy et al., 2003; Bai et al., 2011; Thomas et al., 2011), ~~as well as~~ and improved understanding of ecohydrological processes at the regional scale particularly (Gardelle et al., 2010; Haas et al., 2011; McGrath et al., 2012). ~~As interannual variability of rainfall is high in arid regions, long temporal series are essential to capture the background variability of systems at appropriate temporal scales (Mori, 2011).~~ High temporal resolution is also needed to accurately characterise the seasonal cycles and mechanisms generating the complex spatial and temporal patterning of floods at basin and regional scale and to effectively address the consequences of changes in disturbance regimes for different ecosystems. For example, satellite imagery has recently been successfully combined with hydrological modelling to extend wetland flood regime records from tropical Australia (e.g., Karim et al., 2012) and to investigate mechanisms such as connectivity among floodplains (e.g., Trigg et al., 2013). Similar approaches have also been used to understand the evolution of daily flood and dynamics of floodplain vegetation on the east coast of Australia (Powell et al., 2008). Remote sensing techniques have also been utilised to calibrate hydraulic models of dynamic flow processes during floods, albeit over relatively short time periods (e.g., Bates, 2012; Neal et al., 2012; Wen et al., 2013). However, flood regime analyses based solely on remotely-sensed data do not adequately capture the lengthy temporal scales of flood and drought cycles in many arid and semi-arid regions, which require calibration periods that encompass variability at interannual, decadal and multidecadal scales, especially to elucidate relationships with climatic drivers and geomorphological processes (Roshier et al., 2001; Mori, 2011; Ishak et al. 2013; Kiem and Verdon-Kidd 2013).

Here, we sought to identify the main hydroclimatic determinants of flooding regimes at the catchment scale and to establish the background of variability of surface water expression over the last century in the semi-arid northwest of Australia. First, we identified the main rainfall variables influencing surface water expression on the Fortescue Marsh, the largest

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internally draining wetland in the Pilbara region (Fig. 1), by combining monthly remote sensing imagery from the Landsat archive to instrumental data from 1988–2012 via multivariate linear modelling. Second, we used the model to extend the flooding regime record of the Marsh to the 1912–2012 period based on instrumental records of rainfall. The development of this high-resolution temporal series allowed us to explore and better understand the factors governing surface water expression in a semi-arid landscape at multiple temporal scales, and particularly the significance of extreme events. These larger temporal windows are needed to better understand long-term functioning of arid zone wetlands such as the Marsh but more broadly to establish improved context for more informed water management strategies in these sensitive regions.

2 Methods

2.1 Study site – the Fortescue Marsh

The Fortescue Marsh (hereon referred to as the Marsh; Fig. 1) is an ephemeral wetland of some 1300 km^2, which is comprised of a complex network of riverine floodplains and freshwater and floodplain lakes. The Marsh is the largest wetland of inland northwest Australia and formally recognised as nationally significant for its ecological and hydrologic values (Environment Australia, 2001; McKenzie et al., 2009; Pinder et al., 2010). Vegetation across the Marsh is dominated by salt-tolerant chenopod (*Tecticornia*) shrublands, with eucalypt and Acacia woodlands growing adjacent to the most permanent water features (Beard, 1975). As the largest freshwater feature for hundreds of kilometres, the Marsh (*Martuyitha*) is also of considerable heritage significance including as a key focus for aboriginal communities for more than 40 000 years and since the late 1800’s for early European pastoralists (Slack et al., 2009; Law et al., 2010; Barber and Jackson, 2011).

The Marsh acts as an internally draining basin for the 31 000 km^2 upper Fortescue River catchment (21–23˚S; 119–121˚E; Fig. 1), which is physiographically separated from the Lower Fortescue River catchment by the Goodiadarrie Hills (> 410 m a.s.l.; www.water.wa.gov.au). ~~The flood level required for the Marsh to overflow to the Lower~~

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~~Fortescue catchment is not formerly established but digital elevation models (Geosciences Australia, 2011) suggest water could flow if inundations reached > 410 m a.s.l.~~ The upper Fortescue River is the main drainage of the catchment, flowing north to northwest into the wetland system. However, numerous ephemeral creeks on the southern and northern flanks of the Fortescue Valley (Fig. 1) discharge to the marsh directly (www.water.wa.gov.au; Table A1). Flow in the Fortescue River is characterised as “variable, summer-dominated and extremely intermittent” (Kennard et al., 2010), ~~where very large volumes of runoff are generated following heavy rainfall, which is in contrast~~ and only very large rainfall events generate continuous flow, which contrasts with the normally dry stream ~~empty~~ beds of the dry season (WA Department of Water, 2014). Only one official daily stream gauging station is currently operational on the river (>100 km upstream of the Marsh). The other stations were only installed along the main creeks in two of the 13 sub-catchments of the Upper Fortescue River catchment (Fig. 1), and records did not overlap consistently in time (Table A1). Recently, sub-daily gauging stations were installed along Coondiner Creek and sections of Weeli Wolli Creek with pluviographs and used to implement stable isotope water balance models for these sub-catchments over relatively short (i.e., < 6 years) time periods (Dogramaci et al., 2015). The Ophthalmia Dam, constructed on the Fortescue River at Newman in 1981 to provide the town with drinking water, has a 32 GL capacity and receives from a relatively small and low lying fraction of the catchment (14.5%) with minimal observed impact on the riverine ecosystem at the mouth of the Marsh (Fig. 1; Payne and Mitchell, 1999).

The Fortescue River Valley paleodrainage, eroded from the Hamersley Basin sedimentary rocks, lies between the Hamersley Range in the south and the Chichester Range in the north, constituting the main topographical features of the Eastern Pilbara (Dogramaci et al., 2012). The Fortescue Marsh consists of colluvial and alluvial sedimentary deposits up to ~50m developed on the top of the Oakover Formation, a sequence of younger Tertiary lacustrine carbonate, silcrete and mudstone rocks deposited in the Fortescue River Valley (Clout, 2011). The Oakover Formation is underlain by fractured dolomite and shale of the Wittenoom Formation (Clout, 2011). The recent sediments consist mainly of detrital clays, iron oxides and gypsum. The alluvial and colluvial aquifers of the Fortescue Marsh are frequently confined by impermeable consolidated massive clays and calcrete and silcrete layers. ~~The residence time of water in the upper sections of the catchment is short: surface~~

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~~runoff is high via the steep gradients of creeks and gorges.~~ Surface runoff is high via the steep gradients of creeks and gorges; recent tracer studies from the Weeli Wolli Creek and Coondiner Creek (Fig. 1) showed that residence time of water in the upper sections of the catchment was short (days to weeks) (Dogramaci et al., 2015). The groundwater under the Marsh is highly saline and likely developed by evaporation of floodwater and consequent recharge to underlying aquifers (Skrzypek et al., 2013). The most reported permanent water feature on the Marsh is 14 Mile Pool, located at the mouth of the upper Fortescue River; this pool does not retain water significantly diluted nor flushed by groundwater, which contrasts to other small through-flow pools in upper parts of the secondary tributaries of the catchment (Fellman et al., 2011; Skrzypek et al., 2013).

2.2 Climate and rainfall patterns

Rainfall in the Pilbara comes from troughs, monsoonal depressions, and onshore circulations (Leroy and Wheeler 2008; Risbey et al 2009). Over the 1912–2012 historical period, the upper Fortescue River catchment received on average 290 mm yr^{-1}, of which 75% fell during the monsoonal summer (November–April) (Fig. 2a; Australian Bureau of Meteorology, www.bom.gov.au/cgi-bin/silo/cli_var/area_timeseries.pl). "Meteorologically dry" years received less than 200 mm rainfall, while "wet" years received over 300mm (Fig. 2a), as defined by the left-skewed mode of the yearly rainfall frequency distribution (35% of all years). Scattered, small-scale storms cause daily rainfall to be highly variable among the 17 weather stations (Fig. 1a, Appendix A, Table 1) of the upper Fortescue River catchment (www.bom.gov.au/climate/data/). Evaporation is highest during the summer and generally exceeds rainfall (Skrzypek et al., 2013); average temperatures in summer range between 30–40 °C, and in winter months between 24–35 ˚C (www.bom.gov.au/climate/data/).

Heavy summer storms and tropical cyclones often generate large floods in the major river systems of the Pilbara, particularly on the coast, while winter rainfall is typically not sufficient to generate surface flows (Fig. 2; WA Department of Water, 2014). Tropical cyclones and other closed lows accounted for most of the extreme rainfall events in the northwest of Australia over the 1989–2009 period (Lavender and Abbs, 2013). Numerous historical tracks of cyclones have been recorded in the upper Fortescue River catchment during the last century (www.bom.gov.au/cyclone/history/). When TC tracks were recorded within a 500 km radius of the Marsh, total monthly rainfall in the catchment was significantly greater (p value< 0.01) than the 1912–2012 monthly averages for no-TC months (Fig. 2b). Rain intensity during TC months was also higher (17–22 mm ~~monthly rain rain d^{-1}~~ 22 mm of rain per rain day) than in no-TC months (8–~~10 mm monthly rain rain d^{-1})~~ 10 mm of rain per rain day). Not surprisingly, extremes in the rainfall record (defined here as exceeding the 95th and 99th percentile of all monthly total rainfall occurrences, or Ex_{95} and Ex_{99}, respectively) are linked to the occurrence of tropical cyclones. In fact, half of the months falling in the Ex95 (i.e., >104 mm rainfall/month) recorded at least one TC (30 out of 60 months). Further, at least one TC occurrence was recorded for nine out of 12 months falling in the Ex_{99}, i.e., months recording 190–258 mm of rainfall.

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2.3 Mapping flood history based on the Landsat archive (1988–2012)

We mapped the flood history (i.e., surface water expression) of the Marsh floodplain area (~1300 km^2; Fig. 1) between 1988 and 2012 from high-resolution (i.e., ca. two-week intervals) Landsat images that captured patterns of surface water expression (see Appendix A, Sect. A2 for details). The Marsh floodplain area is defined here as elevations below 410ma.s.l. and within the upper Fortescue River catchment (Fig. 1). Surface water features were extracted from Landsat images using an automated thresholding method in *ArcGIS* v. 9.2 and flood areas (*F*A) were calculated using *Fragstats* v. 4.1 (see Appendix A, Sect. A2 for details). We calculated potential errors associated with using the pixel resolution (30 m) of Landsat images and the thresholding approach to classify surface water features (see Appendix A, Sect. A2 for details). Based on these potential errors, estimated monthly change in flood area (ΔF_A) of less than 6 km^2 should be considered with caution. However, given the scale of variation in F_A on the Marsh (ca. 0–1000 km^2, Fig. 3) this error is relatively small.

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To provide further confidence in our dataset within the estimated errors we used two 40 cm resolution digital ortho-images produced from aerial photographs taken in July 2010, April 2012 (Fortescue Metals Group Limited, Perth, Australia) and one 5 m resolution image taken in August 2004 (Landgate, Government of Western Australia), to confirm that our flood areas mapped from Landsat images taken on similar dates (i.e., within one week of the ortho-image dates) were within 1 pixel (30m) of the flood area visible in the ortho-images (Fig. A1a). A groundtruthing expedition in the dry season (November 2012; Fig. A1 b, c) that noted boundaries by GPS route tracking while walking along the water edge (~1-2 m distance from standing water) of the Moorimoordinia Native Well and a delineation of the inundation plume in the wet season (February 2012; Fig. A1 d) by GPS route tracking during low altitude helicopter survey along the water plume were also conducted and confirm that our thresholding method captured standing water on the Marsh (Appendix A2).

2.4 Modelling floodplain wetting and drying events

2.4.1 Model development and selection

Of the 493 Landsat images processed, only 208 images (TM & ETM) were used to build a calibration dataset for hydrological modelling between the 1988–2012 period (Fig. 3). Following selection of the latest observation for each month (or of the first observation of the next month if within the first week; $n = 265$), only ΔF_A between two consecutive months ($n = 232$) that were above the estimated errors were included. As a result, 160 ΔF_A values were used in the final calibration dataset. Most (70 %) ΔF_A values were calculated over a ca. month-long interval (i.e., 30±7 d), but this interval ranged from 16 to 48 days for the full calibration dataset.

We used a multiple linear regression (in *R* v. 2.11.1) to identify the main climatic drivers of ΔF_A on the Marsh and generate a predictive model to reconstruct monthly F_A for the last century (1912–2012). Climatic variables tested as predictors in the model included: monthly total rainfall, number of rain days, mean temperature and potential evapo-transpiration calculated from weather station records and monthly gridded datasets (see Appendix B, Table A3 for details). To account for the potential effect of system memory, we included *F*A in the previous 1 to 12 months as predictors in the model. ~~Variables that were significant in explaining the variation in F_A, provided the best fit as per the adjusted coefficient of variation (R^2_adj) for the number of variables and the smallest root mean square error E_RMS were used in the final model.~~ Initially, the sensitivity of each predictor

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was tested and only the hydroclimatic variables that were significant in explaining the variation in F_A were used in the model. The model that provided the best fit between the predicted and observed values in the calibration set as per the coefficient of variation (R^2_{adj}) adjusted for the number of variables and the smallest root mean square error E_{RMS} was selected.

2.4.2 Validation of model and 1912–2012 reconstruction

The model's predictive accuracy was tested by both cross-validation and calculation of the E_{RMS} of prediction (E_{RMSP}). A random ten-fold cross-validation (CV) was computed using the CVlm function of the DAAG R package v. 1.16 (Maindonald and Braun, 2013). The E_{RMSP}, which indicates how well the model fits an independent subset of the data, was obtained by removing block subsets representing a third of the calibration occurrences (i.e., 1988–1997; 1998–2004; 2005–2012).

We used the modelled ΔF_A to reconstruct the total area flooded (FA) from the earliest available instrumental data in the region, i.e., from March 1910 to December 2012. However, the value of F_A in March 1910 being unknown, the observed F_A minimum, average and maximum of the calibration period (1988–2012) were used as starting points and long-term statistics for the hydrological regime were calculated from the meeting point of the three time series, i.e., January 1912. Yearly statistics were calculated for the rain year, i.e., November–October. We used comparisons with an aerial photographic survey from 1957 (Edward de Courcy Clarke Earth Science Museum, UWA), early MSS Landsat imagery (1972–1988) and droughts/flood events reported by early surveyors and pastoralists to local newspapers (www.trove.nla.gov.au) to provide historical anchors to our 1912–2012 time series (see references in-text).

3 Results and discussion

3.1 Hydroclimatic determinants of floods and droughts

Total rainfall in the upper Fortescue River catchment (R), number of rain days (R_d) and carried-over inundated area ($F_{\mathrm{A}t-1}$) were the strongest hydroclimatic determinants of the monthly flooding and drying (ΔF_A) regime at the Fortescue Marsh (p value < 0.001; Table 1). The high R^2_{adj} (0.79, p value < 0.001) indicates that the final model included the most important contributors to ΔF_A variation. R alone tested independently of the other variable explained 64% of the variance ($p < 0.001$), and including R_d, improved variance explained by only 8% ($p < 0.001$). Although there is some collinearity between R and R_d (Table A4), we considered it important to include both hydroclimatic variables (R and R_d) from a mechanistic point of view, precisely because of the highly variable nature of our system. For example, in our study system, while it is common that 200 mm may fall over just two days, at other times 200 mm may fall over 28 days (www.bom.com.au). These very contrasting monthly distributions of rainfall demonstrate vastly different intensities and in turn generate quite different run-off; the dynamics of rainfall in such a highly heterogeneous climate are thus best captured by inclusion of both variables, where more R_d modulates negatively the impact of R. In addition, the inclusion of R and R_d may account to some extent for the recorded changing rainfall intensity over the century (Shi et al., 2008; Taschetto and England, 2009; Gallant and Karoly, 2010; Fierro and Leslie, 2013). The model's predictive accuracy was similar for both tests performed, i.e., the E_{RMSCV} and the best $E_{\mathrm{RMSP}} = 56$ km^2. However, the subset model used to calculate E_{RMSP}, which excluded the particularly wet and variable 1998–2004 period from the calibration period, performed the worst at reconstructing ΔF_A for the 1998–2004 verification period ($R^2_{\mathrm{adj}} = 0.64$; $E_{\mathrm{RMSP}} = 86$ km^2), indicating this period constituted an important range for the calibration of the model. Both other calibration models (excluding the 1988–1997 or the 2005–2012 periods) were more accurate ($E_{\mathrm{RMSP}} = 58$ and 56 km^2, respectively), and the overall variance explained improved to 81 and 82% when either of these dry, less variable periods was removed from the model.

~~The enhanced performance of the subset models built without as many "dry" periods highlights an important limitation of the observation dataset. Because it was not possible to calculate ΔF_A from the calibration set when the surface water at the Marsh was dry, water loss, i.e., soil water storage depletion, was therefore underestimated during these periods. Concurrently, however, the reconstruction of monthly FA values below 0 km^2 reflects the ability of our model to provide quantitative information on soil water storage, or the unsaturated zone of the Marsh where rapid infiltration of rainwater was observed following~~

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~~heavy rainfall at the Marsh (Skrzypek et al., 2013). This zone between water table and ground surface likely acts as a buffer to net surface water gain or loss.~~ A lack of surface water is returned by the model as areas ≤ 0 km^2. The negative values (≤ 0 km^2) for 'area' can conceptually be explained as the depletion of the groundwater resources and lowering of the water table below the ground level. While our calibration period captures an exceptional range of intraseasonal and interannual variability in this extreme system, changes in the collinearity structure between highly collinear variables may occur over time and thus affect the relative contribution of the predictors and the reliability of the reconstructed estimates (Dormann et al., 2013). However, the relationship between R and R_d variables appears to have remained strongly linear between equivalent time periods over the reconstructed period, with only minor changes in the fit, slope and intercept. Nevertheless, the coefficients of these variables should not be used outside the scope of this study. Mechanistically, we do not expect the mutual influence of R and R_d on surface flow, where for the same volume of rain more water flushes through the river network if it occurs over fewer rain days, to have changed drastically in the semi-arid region over the last 100 years, or at least not beyond the reported error of the model. Hence, this reconstruction should be used to examine long-term patterns of change in hydrological status and meteorological determinants as opposed to fine-grained catchment processes of recharge provided by higher spatio-temporally resolved hydrological models. For further details on the modelling statistics, refer to the Pearson correlation matrix for the modelled variables (Appendix A, Table A4) and the distribution of observed against reconstructed ΔF_A values (Appendix A, Fig. A2).

The goodness-of-fit and relatively small errors of the model provide confidence in the reconstruction starting in the early 1900's. While our calibration period captures an exceptional range of intraseasonal and interannual variability in this extreme system, changes in the collinearity structure between highly collinear variables may occur over time and thus affect the relative contribution of the predictors and the reliability of the reconstructed estimates (Dormann et al., 2013). However, the relationship between R and R_d variables appears to have remained strongly linear between equivalent time periods over the reconstructed period, with only minor changes in the fit, slope and intercept. Nevertheless, the coefficients of these variables should not be used outside the scope of this study. Mechanistically, we do not expect the mutual influence of R and R_d on surface

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flow to have changed drastically in the semi-arid region over the last 100 years, where for the same volume of rain more water flushes through the river network if it occurs over fewer rain days, or at least not beyond the reported error of the model. Hence, this reconstruction should be used to examine long-term patterns of change in hydrological status and meteorological determinants as opposed to fine-grained catchment processes of recharge provided by higher spatio-temporally resolved hydrological models. ~~In particular, the inclusion of R_d in addition to R makes the model and reconstruction robust against the recorded changing rainfall intensity over the century (Shi et al., 2008; Taschetto and England, 2009; Gallant and Karoly, 2010; Fierro and Leslie, 2013).~~ However, the model tended to underestimate ΔF_A following very intense rainfall events (large rainfall over 1–3 days), which might be partly attributed to the monthly resolution (Appendix A, Fig. A2). Reconstructed values of ΔF_A for any given month are calculated for the last day of the month and as such do not account for the timing of intense events during that month. A large rainfall event occurring early in the month would thus result in smaller ΔF_A. The underestimation of ΔF_A values during intense events might also be due to the high spatial heterogeneity of rainfall in the catchment, which was readily apparent when events were much larger closer to the Marsh (e.g., Marillana Station, Fig. 1b; www.bom.gov.au/climate/data/). Consequently, our time series mostly reflects regional-scale events rather than more localised events. The use of weighted contributions of the different meteorological stations or sub-catchments within the upper Fortescue River catchment might improve the downscaling of this model. However, the instrumental records in this region are both temporally and spatially patchy, and using higher resolution gridded data would not necessarily truly improve the resolution of the data evenly for the last century (Fig. 1; www.bom.gov.au/climate/data/).

Severe and intense rainfall events (i.e., high R and low R_d) clearly drive the hydrologic regime of this system over the last century. Total rainfall contributed most ($R_\beta = 145$ km^2; p value < 0.001) to monthly flooding of the Marsh (…*F*A). More than 75mm rain/month in the catchment systematically caused a net wettening (increase in *F*A) of the Marsh’s floodplains while <30 mm rain month^{-1} was generally insufficient to impact on *F*A (Fig. 4). However, more intense rainfall events resulted in much larger flooding episodes. Conversely, for the same total rainfall, more rain days in the month strongly dampened the extent of floods ($R_{d\beta} = -63$ km^2; p value < 0.001). These “flash floods” drive the current

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hydrological regime of the Marsh but are also consistent with the hydrochemical evolution and modern recharge of shallow groundwater under the Marsh (Skrzypek et al., 2013). By washing down of surface salts deposited on the Marsh during previous evaporation episodes, large floods not only recharge the system, but also deliver freshwater that becomes available at surface for extended periods of time. This heavy rainfall (as opposed to groundwater) driven system is rather unusual in the arid zone, where many wetlands are groundwater-dominated, playa-like ecosystems (Bourne and Twidale, 2010; Tweed et al., 2011). In arid zone playas, the hypersaline groundwaters from the deep aquifer are connected to surface processes and result in saline waters being exposed (Bourne and Twidale, 2010; Cendon et al., 2010). In contrast, our results support that the Fortescue Marsh is rather a paleosaline lake where vegetation can grow and surface water is largely fresh, but then eventually becomes brackish due to the concentration of solutes with time owing to evaporative losses.

The sequence of events, or the "system memory", was also an important determinant of surface water availability on the Marsh. ~~When still inundated from the previous month ($F_{At-1} > 0$ km^2), decrease of the total area flooded was significantly larger ($F_{At-1\beta} = 29$ km^2; p value< 0.001). For example, although the largest inundated area was recorded in 2000, the 1942 net ΔF_A was larger but resulted in slightly less inundated area at the Marsh owing to the drier conditions than in 1999 in the previous month~~ Water loss ($-\Delta F_A$) on the Marsh from one month to the next was larger over a months after higher inundation extent ($F_{At-1} > 0$ km^2). For example, after large 560 km^2 inundation in August 1942, the water extent decreased by 100 km^2 over the first month. In contrast, an extent of 200 km^2 in May 1912 decreased by 50 km^2 over the first month, despite a lack of rain in both cases. ~~Intervals (Int) between observations (number of days over which the change was observed) did not significantly improve the fit of the model ($Int_\beta = -8$ km^2; p value$= 0.07$). This variable (Int) thus rather acted as a constant that contributed to the decrease of surface water every month.~~ Intervals (Int) between observations (number of days over which the change was observed) did not significantly improve the fit of the model ($Int_\beta = -8$ km^2; p value$= 0.07$). This variable (Int) was nevertheless included in the model to account for ΔF_A values being calculated over slightly different time intervals (i.e., 30±7 d) in the calibration period and because months of the year include 28 to 31 days. This, Int acted as a constant that contributed to explaining the decrease of surface water every month.

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Monthly loss of surface water on the Marsh through evaporation and transpiration was reconstructed to be up to 150 km^2 (i.e., lowest ΔF_A). The most severe water losses occurred during especially dry April, May and June (i.e. <3.5 mm rainfall; Fig. 4) following very wet summers. Unsurprisingly, cumulative severe floods resulted in the longest inundation periods recorded on the Marsh, and often contributed to the following year's hydrological status. Over the 1912–2012, 32% of years had up to 400 km^2 (40% fullness) surface water expression carried over to the next year (i.e., winter to summer). In contrast, 68% of years ended with no surface water and depleted aquifers in October (Fig. 5b).

Our findings indicate that the reconstructed total area flooded at the Marsh represents an integrated ecohydrological catchment response to rainfall, which is expected from such terminal basins (Haas et al., 2011). We observed that the impact of rainfall on inundations and droughts is at least in part modulated by the high local evaporation rate (five to ten-fold greater than rainfall), which acts as a constant drying force on the surface water even though temperature or potential evapotranspiration (PET) did not significantly improve the fit of the model. In addition, vegetation in drylands typically shows a rapid increase in productivity in the few months following a large rainfall event (e.g., Veenendaal et al., 1996; McGrath et al., 2012); thus, runoff from subsequent events might be dampened through enhanced physiological (plant water) use, which is in turn consistent with the negative effect of F_{At-1} on flood area change (Table 1). We suggest that expected seasonal and interannual variation in temperature and/or PET were thus largely accounted for through the use of F_{At-1} and the constant *Interval* variables.

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3.2 Spatial and temporal patterns of inundations

Our monthly reconstruction reveals that the floodplains of the Fortescue Marsh have had extremely variable interannual severity of total flooded area (F_{Amax}) that in turn determined the duration of inundations for the last century (Fig. 3). Of the last 100 years (1912–2012), almost 25% were large flood years, i.e., years for which the maximum flood area (F_{Amax}) was over 300 km^2 (Fig. 3b). Large inundations typically occurred as a result of one to three-month long flood pulses in the austral summer (February–April). As described earlier, these flood pulses were mainly associated with regional hydroclimatic events such as TC occurring in the austral summer (January–March), and are major drivers of surface water expression at the Marsh for the last century. Following large floods, some level of inundation could be maintained for over 12 months in 7% of years (Figs. 6 and 7). Further, only large flood years generated substantial > 0.5m depth of surface water (Fig. 8a), which would also have the potential to completely submerge the vast chenopod community on the Marsh (Beard, 1975). These large flood years, their consequent supra-seasonal sustained inundations and their connectivity to the western sections (downstream) have been relatively frequent over the last century and reflect the natural variability in the hydroclimatic regime. On the other hand, > 800 km^2 flood years (only two in the past 100 yr, 1942 and 2000) are considered extreme, infrequent disturbances bringing exceptional volumes of freshwater to the system (Fig. 8b). The most striking effect of the interannual system memory was observed between 1999 and 2006, the period during which inundations extent and duration on the Marsh were above average and unprecedented for the last century. The longest period in the last 100 years that surface water was consistently present on the Marsh (i.e., $F_A > 0$ km^2) was from 1998 to 2002, including the largest yearly inundation for the entire century in March 2000 of $\sim$ 1000 km^2 (Fig. 3c).

In addition to the large flooding events described above, the majority of years (70–79 %) experienced at least one month of inundation resulting from smaller floods ($F_{Amax} < 40$–48 km^2) (Figs. 6 and 7) that in turn also influenced the distribution and connectivity of surface water within the different sections of the Marsh (Fig. 6). During large or severe inundation years, the entire floodplain became initially one (Fig. 6). Following such an event in 1934, pastoralists experienced the “Marsh becoming a [400 km^2] large lake” (Fig. 6; Aitchison, 2006). Going into the winter months, evaporation and the lack of significant input from rainfall events typically resulted in drying and progressive formation of disconnected pools mainly along the northern shore and eastern end of the Marsh (Fig. 6). Based on our 25 yr calibration period, similarly severe years resulted in spatially consistent patterns of interannual inundation during both wetting and drying phases (Fig. 6). While quite frequent, large flood years do not occur at regular intervals, conferring a poor predictability to surface water in the system. The lowest recurrence was prior to 1960, with up to 14 years between two events; post 1960, large events have occurred at intervals of seven years or less, which in turn has resulted in more severe and prolonged inundations e.g., between 1999 and 2006.

~~The increased flood severity and duration over recent decades relative to the previous 80 or so years observed in our flooding record is consistent with the increasing trend in heavier summer rainfall events recorded in the region for the same period (Shi et al., 2008; Taschetto and England, 2009; Gallant and Karoly, 2010; Fierro and Leslie, 2013). A simple linear regression between time and yearly duration of floods ($FA > 0$ km^2) further demonstrates slightly increased inundation length since the beginning of the century (p value= 0.046). However, the significance of this finding should be treated with some caution given the non-independence of the F_{Amax} (especially between two consecutive years) and the limited number of observations included ($n = 25$ flooding events).~~ The near yearly recurrence of severe and prolonged inundations over the 1999-2006 period in our record is unprecedented relative to the previous 80 or so years and consistent with the heavier summer rainfall events observed in the region over the recent decades (e.g. Shi et al., 2008; Taschetto and England, 2009; Gallant and Karoly, 2010; Fierro and Leslie, 2013). ~~The appraisal of multi-decadal trends in the hydrological regime could be improved by exploring the impact of cyclicity of known larger scale climatic drivers of (summer) rainfall in the northwest of Australia such as the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the Madden–Julian oscillation (MJO) – phasing of these different modes (Risbey et al., 2009)~~ However, rigorous analysis of periodicities would be required for the appraisal of potential multi-decadal trends in the hydrological regime against such a high background of variability (e.g., Kiem et al., 2003; Kiem et al. 2004; Verdon-Kidd and Kiem, 2010; Ishak et al. 2013). In fact, future investigations and risk analyses in the region should strive to assess the potential influence of known larger scale climatic drivers and their interaction of intraseasonal and interannual hydroclimate variability in the northwest of Australia (e.g., Kiem and Frank, 2004; Pui et al., 2011; Kiem and Verdon-Kidd, 2013), such as El Niño-Southern Oscillation, the Indian Ocean dipole, the Madden Julian oscillation and the southern annual mode (Risbey et al., 2009; Fierro and Leslie, 2013). The development and application of high-resolutions proxy indicators of past hydroclimatic changes for the arid zone could also provide more robust insights on multi-decadal trends and ecosystem vulnerability to these changes (e.g., Cullen and Grierson, 2007).

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3.3 Significance of predictability and persistence of drought

Our reconstruction shows that the Fortescue Marsh floodplains have more often been dry (i.e., where no surface water is evident on the Marsh, or $F_A \leq 0$ km^2) than wet over the last century (Fig. 3c). Hydrological droughts (i.e., series of consecutive months where $F_A \leq 0$ km^2) of at least one year were frequent (21 %) between 1912–2012 (Figs. 3c d, and 7). The most recent drought that persisted for more than 2 years occurred between 1990 and 1993 (3.2 years). In contrast, particularly extended drought periods ~~(where no surface water is evident on the Marsh)~~ were more frequent between the late 1930's and early 1960's, with the longest supraseasonal drought on record lasting 4.3 years (between 1961 and 1965). In such water-restricted and remote environments, early pastoralists would have been the first to notice changes in the distribution and availability of freshwater. Reports of "bad drought" on Roy Hill Station in early 1939 and winter of 1940, where "no feed" for cattle was available (Aitchison, 2006) corroborate our reconstruction. Dramatic vegetation changes were also documented on the Marsh's floodplain during this dry period (1938–1940), which coincided shortly after with Marillana Station shifting from cattle to sheep farming (Aitchison, 2006). In our time series, this documented drought corresponded to ~~largely dry conditions~~ minimal surface water ($F_{Amax} < 150$ km^2) at the Marsh due to the occurrence of only minor flood events over these years (Fig. 3c). A 20 month period between 1918 and 1919 where F_A at the Marsh was reconstructed as less than 0 km^2 in our analysis also corresponds to a report by the Roy Hill Pastoral Company, one of the main pastoralist in the upper Fortescue River catchment, as a "severe drought" causing the installation of "10 new wells" in 1919 (Dept Land and Survey, 1919) (Fig. 3c).

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Overall, the eastern section of the Marsh experienced the least interannual variability by holding the most reliably inundated freshwater areas (Fig. 6), consistent with the presence of long-lived trees at 14 Mile Pool and Moorimoordinia Native Well (Beard, 1975). The September 1957 aerial photograph also shows these pools partially filled even though there was little summer rain that year, also corroborating our reconstruction of a dry period at that time. These more permanent, shallow water features were restricted to the floodplains at the mouth of the upper Fortescue River and other smaller tributaries draining the steeper slopes of the Chichester Range to the north (Fig. 6). These sections have thus been under a more localised and "high" inundation frequency regime from smaller events (Thomas et al., 2011; Fig. 6). These sequential, smaller events potentially maintain refugia for aquatic populations, which may facilitate recolonisation of other parts of the Marsh following the larger, less frequent flood disturbances that in turn effectively “reset” arid zone ecosystems (Leigh et al., 2010; Stendera et al., 2012). With such spatial variation in floods frequency, we can also expect vegetation communities on the Marsh to form mosaics tightly linked to their different water requirements and tolerances, as has been seen on other floodplains such as those of the Macquarie Marshes in central-eastern Australia (Thomas et al., 2011).

4 Conclusions

We developed a ~~robust~~ reliable model to predict and characterize the surface water response of a major regional wetland to hydroclimatic variability over the last century. Our approach is readily applicable to extend the temporal record to other ephemeral water bodies. Through greater understanding of system responsiveness to regional rainfall patterns, we also now have improved capacity to assess the long-term ecohydrological functioning of arid floodplains. For example, if current rainfall trends are sustained, increased flooding of the Fortescue Marsh will prolong the inundation period in the year, the connectivity between the different parts of the Marsh and the river network and increase the carry-over for the following year. The resulting enhanced persistence may in turn affect long-term hydrochemical and ecological processes of the system, e.g., by an increase in surface water salinity.

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Appendix A: Mapping the flood history

A1 Landsat archive/image selection

The flood history of the Fortescue Marsh was reconstructed using standard terrain corrected scenes for systematic radiometric and geometric accuracy (Level 1T) from the USGS EarthExplorer Landsat archive (http://earthexplorer.usgs.gov/). The Landsat archive has seasonal to monthly coverage of the Fortescue Marsh from 1972–1988 and fortnightly coverage from 1988–2012. We quantified water coverage, or total flooded area (*F*A) from a subset of 493 satellite images with the analysis of wavelengths sensitive to water reflectance (Xu, 2006), specifically the short wave (SWIR) or mid infrared (MIR) radiation bands 5 (TM, ETM) and 3 (MSS). All image processing was conducted using ArcGIS v.9.2 and ERDAS Imagine 2011. Pixel resolution was 30m x 30m (900m2) for the observation period (1988–2012).

A2 Flood area delineation and error

Water features were relatively straightforward to extract using a simple automated thresholding method (Xu, 2006), owing to their very high contrast to the surrounding arid landscape. *F*A could not be estimated using our automated method when partial cloud cover was present in the satellite imagery, or for the ETM-SLC off series of Landsat 7 (169 images from a total of 493). Therefore, *F*A was estimated in these years by calculating the midpoint between the most recent "before and after" *F*A estimates. This approach also allowed us to capture the largest *F*A estimates as they were often partly obstructed by clouds.

To account for registration error across the temporal and satellite series, the *F*A estimate and its associated error (*estimation errors*) were obtained from three water features extracted for every image using a lower, mid and upper threshold of reflectance values. The three consecutive threshold values (either 10, 20, 30, 40, 50, or 60 value of reflectance) were selected to include the highest frequency distribution of water pixels while providing the smallest *F*A estimate error. We also calculated *resolution errors* in extracting *F*A to account for the use of 30m x 30m pixels values. Here, we applied a 15m buffer inside and outside the water-only polygon for all thresholds. Thus, *estimation* and *resolution errors* were largest when F_A was small owing to an increase in the "edge length" to 5 size ratio, and differences in F_A less than 6 km_2 should be considered with caution. A simple linear regression obtained between the automated F_A and its buffer was used to calculate the resolution error for these shapes. The *resolution error* for shape-estimated F_A was calculated using linear regression formulas obtained between F_A and inside buffer ($R_2 = 0.99$, p value < 0.001) and outside buffer ($R_2 = 0.99$, p value < 0.001). Strong congruency between elevation contours and the shape of flooded area estimates on the Fortescue Marsh indicate that our thresholding methodology accurately detected standing water. Neither *estimation* nor *resolution errors* were found to follow a seasonal or overall temporal trend. However, we cannot discount that areas of waterlogged ground also contributed to the estimates of flooded area (Castaneda et al., 2005).

Appendix B: Climate variables

While 17 meteorological stations have been intermittently recording daily rainfall data in the upper Fortescue River catchment, only six are currently still in operation, forming a too sparse and temporally inconsistent network for direct use in this study (Fig. 1; Table A2). Explanatory hydroclimatic variables were thus generated using monthly gridded datasets resolved at either 0.5 or 1" cell size weighted for their relative contribution to the upper Fortescue River catchment (Table A3). Total rainfall and mean temperature were obtained from the Australian Bureau of Meteorology (www.bom.gov.au/cgi-bin/silo/cli_var/area_timeseries.pl), the Climatic Research Unit (CRU) and the Global Precipitation Climatology Centre (GPCC) via the Koninklijk Nederlands Meteorologisch Instituut (KNMI) Climate Explorer (climexp.knmi.nl). Potential evapotranspiration (PET), calculated using Penman–Monteith parameterization and based on the actual vegetation cover, was from van der Schrier et al. (2013). The mean number of rain days/month (Rd) was calculated from daily rainfall records obtained from the four meteorological stations still in operation, located within or closest the upper Fortescue River catchment, relatively well spread in the vast geographic area and with the longest records (i.e., Noreena Downs, Bulloo Downs, Marillana and Mulga Downs) (Fig. 1; Table A2).

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Author contributions. A. Rouillard wrote the paper with input from P. F. Grierson, G. Skrzypek,

C. Turney and S. Dogramaci. A. Rouillard collected and processed the satellite imagery and conducted the statistical analyses. A. Rouillard and G. Skrzypek developed the modelling approach after discussion with co-authors. The study was conceived by P. F. Grierson, A. Rouillard, G. Skrzypek, S. Dogramaci and C. Turney.

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Table 1: Model parameter estimates and standardized statistics for the final linear model to reconstruct historical flood area on the Fortescue Marsh, NW Australia

Driver	β (km^2)	Effect	*p* value
R	144.729	+	< 0.001
R_d	−62.950	−	< 0.001
F_{At-1}	−29.157	±	< 0.001
Int	−7.650	−	0.070
Intercept	−8.040	−	0.816

Note: β = Weighted contribution; Effect = gain (+) or loss (−) effect of each variable on change in flood area (ΔF_A); R = total rainfall/month on the upper Fortescue; R_d = number of days with > 0 mm of rain/month; F_{At-1} = flood area of the previous month; Int = the time interval between observations; Intercept = equation intercept

Table A1: Temporal coverage of all official stream gauging stations in the Upper Fortescue River catchment and maximum recorded daily discharge

Site number	Stream Name	Name	Operational date	Last measurement	Max discharge (m^3 sec^{-1})	Total discharge (GL)
708001	Marillana Ck	Flat Rocks	15/08/1967	23/02/1983	1327	72
708006	Fortescue River	Goodiadarrie Crossing	01/12/1972	01/10/1986	*	*
708008	Fortescue River	Roy Hill	01/09/1973	29/09/1986	*	*
708011	Fortescue River	Newman	09/01/1980	Present	1730	78
708013	Weeli Wolli Ck	Waterloo Bore	30/11/1984	Present	4137	142
708014	Weeli Wolli Ck	Tarina	10/05/1985	Present	2100	62
708016	Weeli Wolli Ck	Weeli Wolli Springs	08/10/1997	14/07/2008	423	10

Note: * Only daily stage height available; location of stations marked on Fig. 1

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Table A2: Australian Bureau of Meteorology (BoM) rainfall stations (www.bom.gov.au/climate/data/) located within and nearby the upper Fortescue River catchment, NW Australia.

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No	Station name	BoM number	Lat (˚N)	Long (˚E)	Status	Year open	Year closed
	Mulga Downs	5015	−22.10	118.47	Open	1898	
	Bulloo Downs	7019	−24.00	119.57	Open	1917	
	Marillana	5009	−22.63	119.41	Open	1936	
	Noreena Downs	4026	−22.29	120.18	Open	1911	
1	Balfour Downs	4003	−22.80	120.86	Closed	1907	1998
2	Wittenoom	5026	−22.24	118.34	Open	1949	
3	Auski Munjina Roadhouse	5093	−22.38	118.69	Open	1998	
4	Kerdiadary	5047	−22.25	119.10	Closed	1901	1910
5	Warrie	5025	−22.40	119.53	Closed	1927	1964
6	Bonney Downs	4006	−22.18	119.94	Open	1907	
7	Poondawindie	4063	−22.20	120.20	Closed	1930	1938
8	Sand Hill	5064	−22.78	119.62	Closed	1971	1984
9	Roy Hill	5023	−22.62	119.96	Closed	1900	1998
10	Ethel Creek	5003	−22.90	120.17	Closed	1907	2003
11	Packsaddle Camp	5089	−22.90	118.70	Closed	1989	2002
12	Rhodes Ridge	7169	−23.10	119.37	Open	1971	
13	Rpf 672 Mile	4065	−22.70	121.10	Closed	1913	1947
14	Billinnooka	13029	−23.03	120.90	Closed	1960	1974
15	Jigalong	13003	−23.36	120.78	Closed	1913	1991
16	Minderoo	7172	−23.40	119.78	Closed	1913	1931
17	Newman Aero	7176	−23.42	119.80	Open	1971	
18	Capricorn Roadhouse	7191	−23.45	119.80	Open	1975	
19	Murramunda	7102	−23.50	120.50	Closed	1915	1949
20	Sylvania	7079	−23.59	120.05	Open	1950	
21	Prairie Downs	7153	−23.55	119.15	Open	1968	
22	Turee Creek	7083	−23.62	118.66	Open	1920	
23	Mundiwindi	7062	−23.79	120.24	Closed	1915	1981
24	Rpf 561 Mile	13013	−23.90	120.40	Closed	1913	1947
	Newman	7151	−23.37	119.73	Closed	1965	2003

Table A3: Climate variables used in the development of a linear model to reconstruct historical flood area on the Fortescue Marsh, NW Australia

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Interval	Variable	Res.	Location	Period	Source
d	*R*		Bulloo Downs	1917-2012	www.bom.gov.au/climate/data/
d	*R*		Marillana	1936-2012	www.bom.gov.au/climate/data/
d	*R*		Mulga Downs	1907-2012	www.bom.gov.au/climate/data/
d	*R*		Noreena Downs	1911-2012	www.bom.gov.au/climate/data/
m	*R*	1°	UF	1900-2012	www.bom.gov.au/cgi-bin/silo/cli_var/area_timeseriespl
m	*R*	0.5°	UF	1901-2012	GPCC V6 rain gauge precipitation dataset
m	*R*	0.5°	UF	1901-2009	CRU time-series (TS) version 3.10.01 (land)
m	*T*	1°	UF	1910-2012	www.bom.gov.au/cgi-bin/silo/cli_var/area_timeseriespl
m	*T*	0.5°	UF	1901-2009	CRU TS 3.10 (land)
m	PET	0.5°	UF	1901-2009	(Schrier et al., 2013)

Note: Res. stands for the resolution of gridded data, d is daily weather station rainfall data, m is monthly gridded climate data, *R* is total rainfall (mm), *T* is mean temperature (°C) and PET is Penman-Monteith potential evapotranspiration index. *UF* is the upper Fortescue River catchment (31,000 km^2).

Table A4: Pearson correlation matrix of the variables included in the final linear model to reconstruct historical flood area on the Fortescue Marsh, NW Australia

	R	R_d	F_{At-1}	Int
R	1	-	-	-
R_d	0.8518 $p<0.001$	1	-	-
F_{At-1}	-0.0361 $p=0.6507$	-0.0313 $p=0.6943$	1	-
Int	0.0703 $p=0.3767$	0.0089 $p=0.9108$	-0.0162 $p= 0.8388$	1

Note: R = total rainfall·month^{-1} on the upper Fortescue (mm); R_d = number of days with > 0 mm of rain·month^{-1} (days); F_{At-1} = flood area of the previous month (km^2); Int = the time interval between observations (days)

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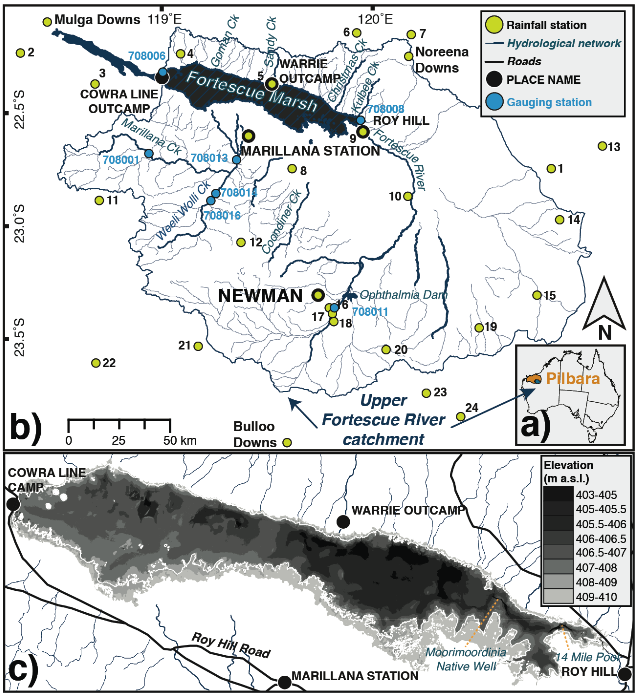

Figure 1: The **a)** Pilbara region in northwest Australia, **b)** Upper Fortescue River catchment and river network (blue lines; DoW, 2014), including the Fortescue Marsh's floodplain area used in this study (black hatched section; < 410 m a.s.l. extracted from a 1 sec DEM-H, Geoscience Australia, 2011), stream gauging stations (blue circles, see full list in Appendix A, Table A1; WIN, 2014) and meteorological stations (green circles, see full list in Appendix A, Table A2; www.bom.gov.au/climate/data/) and **c)** elevation of the study area (0.1 m vertical accuracy (RMS) LiDAR Survey DEM; Fortescue Metals Group Ltd, 2010) with roads and place name (black lines and circles; Geoscience Australia, 2001). *Generated in ArcMap v. 9.2.*

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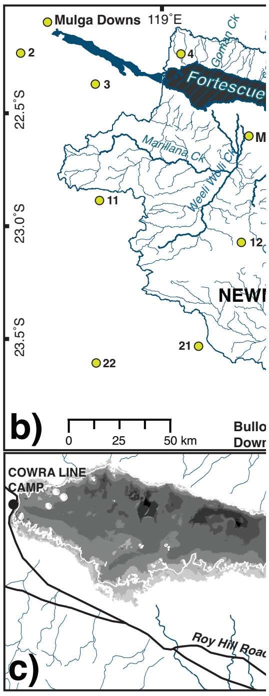

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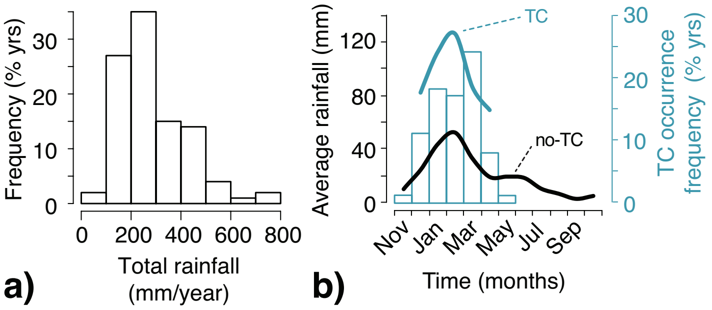

Figure 2: The upper Fortescue River catchment 1912-2012 hydroclimate with **a)** frequency distribution of total yearly rainfall and **b)** average monthly rainfall for months recording at least one tropical cyclone (TC) within 500 km radius of the upper Fortescue River catchment (blue line) and without TC recorded (black line), with the number of years (frequency) where TC occurrence was recorded for each month of the water year (blue columns); only one occurrence of TC was recorded in Nov and May for the last century and thus rainfall averages for these months were not included. Source: www.bom.gov.au/cgi-bin/silo/cli_var/area_timeseriespl & www.bom.gov.au/cyclone/history/.

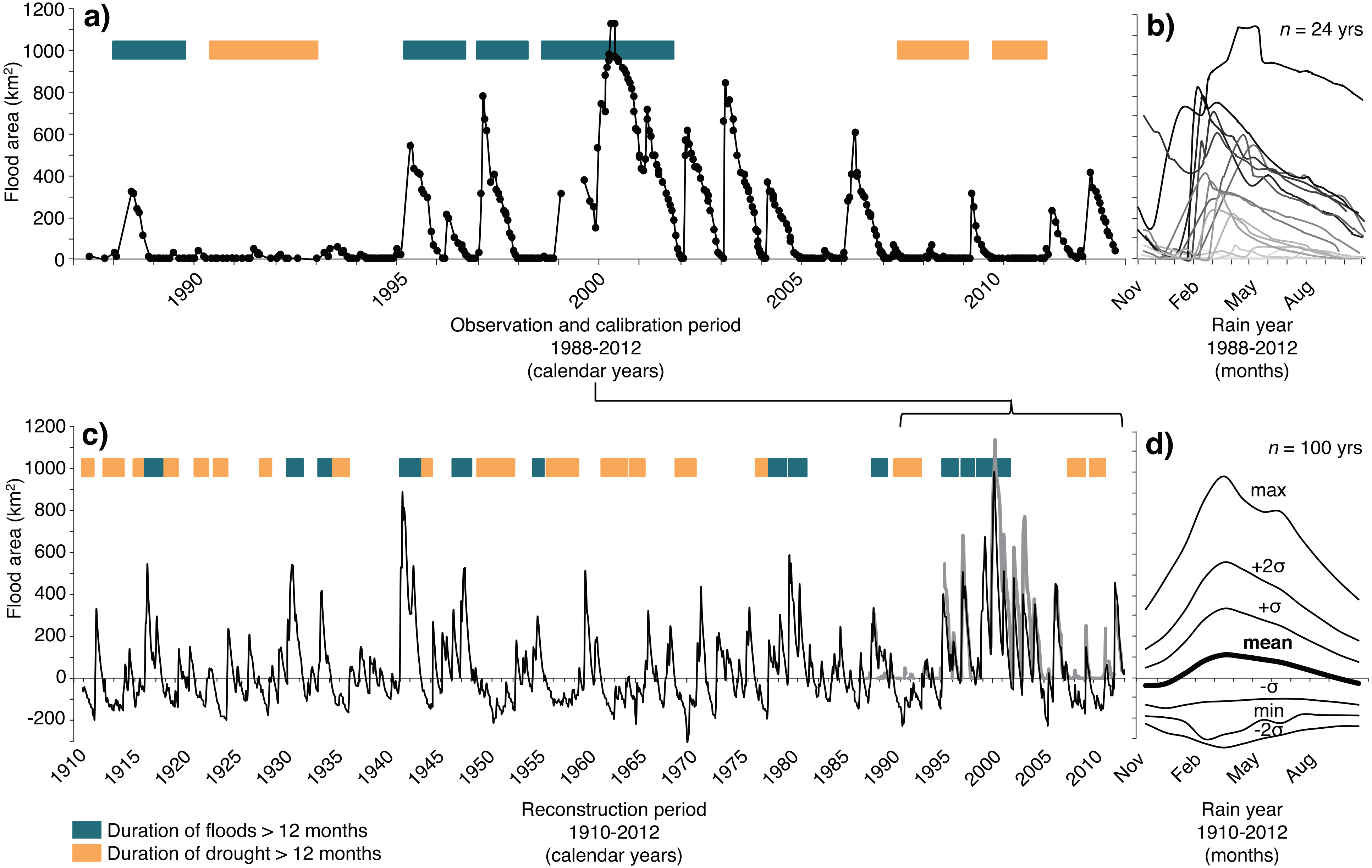
a)
b)
c)
d)
Flood area (km²)
1200
1000
800
600
400
200
0
-200
1990
1995
2000
2005
2010
Observation and calibration period
1988-2012
(calendar years)
n = 24 yrs
Nov
Feb
May
Aug
Rain year
1988-2012
(months)
n = 100 yrs
max
+2σ
+σ
mean
-σ
min
-2σ
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
Reconstruction period
1910-2012
(calendar years)
Rain year
1910-2012
(months)
Duration of floods > 12 months
Duration of drought > 12 months

Figure 3: 1988-2012 **a)** flood area observation and calibration dataset (solid black line with dots for each observation; monthly E_{RMSP} of $\Delta F_A = 56$ km^2) and its **b)** timing of seasonal change over the rain year ($n = 24$ yr); 1912-2012 **c)** flood area reconstruction (solid black line) with the observation dataset plotted for the 1988-2012 period (solid grey line) for comparison and **d)** monthly mean, minimum (min), maximum (max) and 1 and 2 σ ranges of variation over the rain year for the reconstructed period ($n = 100$ yr). Overlaid on a) and c) time-series are the supraseasonal dry and wet periods, where F_A was either < 0 km^2 or > 0 km^2 for over 12 consecutive months.

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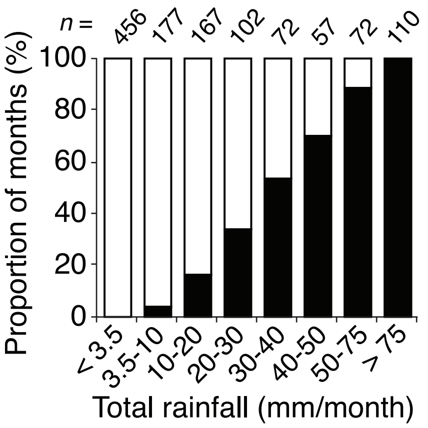

Figure 4: Total monthly rainfall in the upper Fortescue River catchment (Total rainfall) causing an increase in surface water area measured as the proportion of months with net change in flood area or $\Delta F_A > 0$ km^2 (black columns) at the Fortescue Marsh (1912-2012).

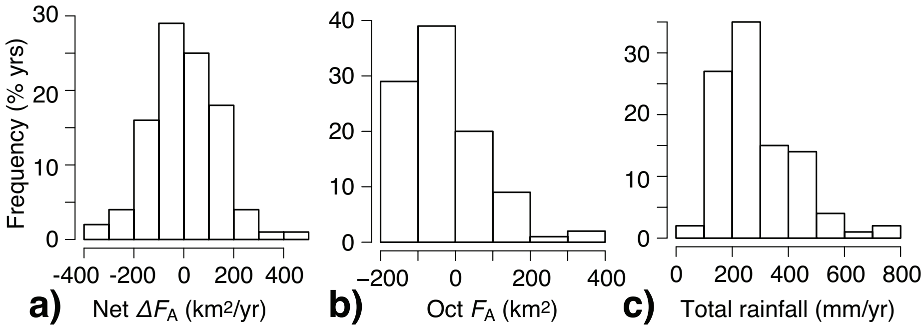

Figure 5: 1912-2012 frequency distributions of yearly **a)** net change in flood area (ΔF_A), **b)** end-of-the-year flood area (Oct F_A) and **c)** yearly maximum flood area (F_{Amax}; km^2), $n = 100$ yr.

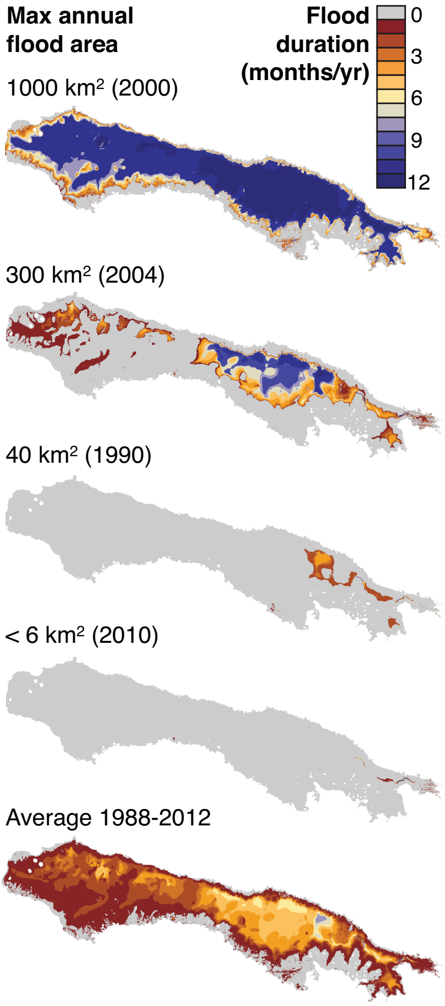

Figure 6: Maps of the Fortescue Marsh floodplain including flood duration isohyets over the rain year (Nov-Oct) representing examples of the main connectivity thresholds: wettest year observed in 2000 ($F_{Amax} \sim 1000$ km^2); a very large flood year in 2004 ($F_{Amax} \sim 300$ km^2); the long-term mean flood year in 1990 ($F_{Amax} \sim 40$ km^2) and a dry year in 2010 ($F_{Amax} < 6$ km^2) and the 1988-2012 average.

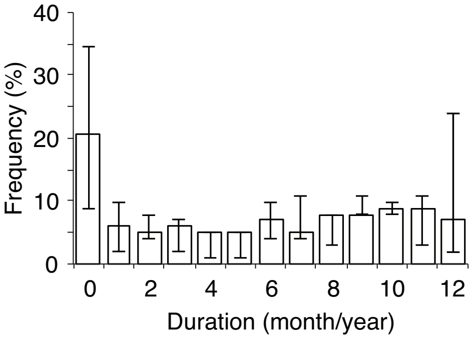

Figure 7: Frequency distribution of drought duration per annum (i.e. consecutive month with $F_A < 0$ km^2), with error bars representing the variation in the distribution when threshold for drought duration is defined as $F_A < \pm 56$ km^2 for the last century ($n = 100$ yr).

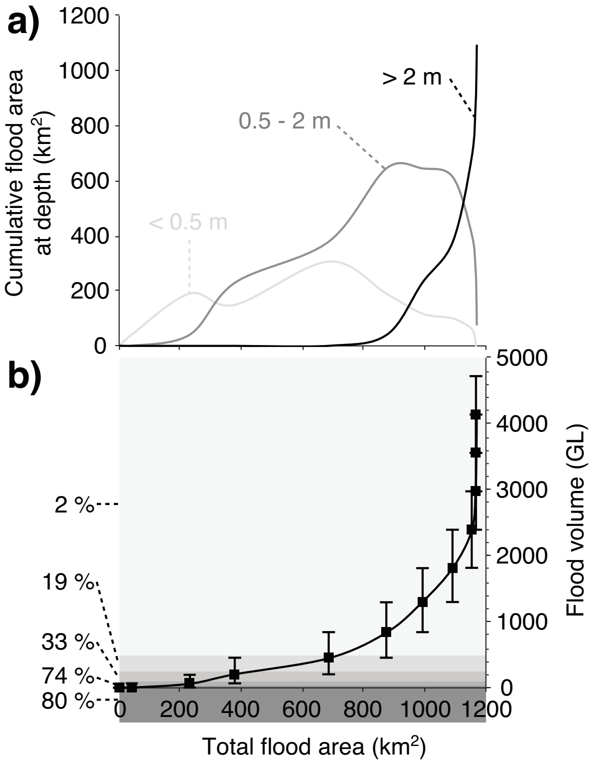

Figure 8: Total flood area at the Fortescue Marsh and **a)** its proportion occupied by water depth shallower than 0.5 m (light grey), between 0.5 and 2 m (dark grey) and deeper than 2 m (black) and **b)** the volume of surface water (black line) with century frequencies (% yr) at which different thresholds (grey shading) were attained.

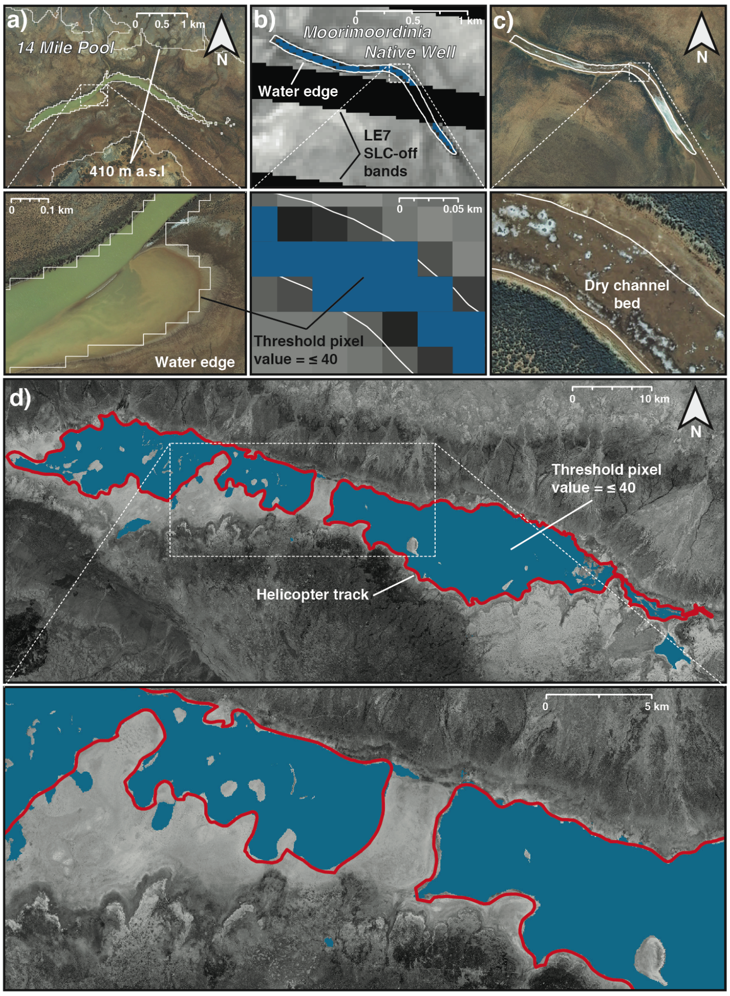

Figure A1: Validation and groundtruthing of standing water on the Fortescue Marsh, including: **a)** standing water on the 14 Mile Pool extracted from Level 1T Landsat image (Jul 2010; solid white line = threshold pixel value ≤ 40; LT5; USGS) and close up against a 40-cm resolution ortho-photo (Jul 2010); delineation by GPS route tracking while walking along the water edge (1-2 m distance from standing water; solid white line) and close up against **b)** a Level 1T Landsat image of Moorimoordinia Native Well (Nov 2012; blue fill = threshold pixel value ≤ 40; LE7-SLC-off, USGS) and **c)** a RGB image showing the extent of the dry channel bed (Dec 2006; SPOT-5); **d)** delineation of standing water by GPS route tracking during a low altitude helicopter survey

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along the water plume of the Fortescue Marsh (2012 Feb 12; solid red line) and close up against standing water extracted from Level 1T Landsat image (2012 Feb 14; blue fill = threshold pixel value ≤ 40; corrected LE7-SLC-off; USGS), overlain on a 2.5 m resolution RGB image taken during dry season (Dec 2006; SPOT-5).

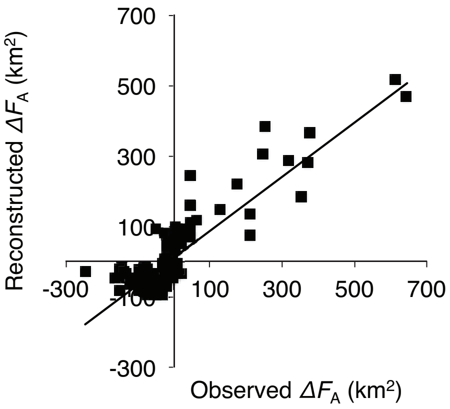

Figure A2: Observed against reconstructed monthly ΔF_A values ($n = 160$) for the 1988-2012 calibration period ($R^2_{adj} = 0.79$; $p\text{-}value < 0.001$).

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