Response to Reviewer 1

We are indebted to the reviewer for this insightful review of our discussion paper. As detailed below, we have made substantial improvements to analysis and presentation in response to reviewer comments.

General Comment 1

The first major shortcoming of the paper is to ignore the role of changes in infrastructure and agricultural practices that could be independent of, or resulting from, changes in climate and upstream infrastructure development. As the authors likely know, there are several proposals on the table in Sudan for new infrastructure projects, and agricultural expansion (particularly in sugar production) is a major objective of current irrigation development strategy in Sudan. In addition, reservoir operating rules and irrigators are not likely to take climate change "fully on the chin"; i.e., they will adapt by changing management.

Response:

The reviewer makes an excellent point. Indeed, we developed SHOM largely to provide a modeling tool for addressing these kinds of questions. We had initially withheld modifications in practice and infrastructure from the current paper because we wanted to present SHOM using present-day infrastructure, with the potential to apply the model to management and construction analysis in future studies. Upon reflection, however, we realize that we should include at least an indicative analysis of how the model responds to changes in management or infrastructure.

To do this we have considered the impact of agricultural intensification through the addition of a second cropping season. This pattern has already been observed in other parts of Sudan in which large upstream dams have been introduced (Professor Belay Simane, Addis Ababa University personal communication), so we consider it to be a realistic and likely management change in the presence of upstream control on the Blue Nile. Our analysis of this change in management proceeds as follows. Beginning with our upstream control scenario (i.e., the 3-month smoother; see response to General Comment 3 for more on this point) we add the option to divert water for irrigation in a second season in addition to the primary growing season included in the baseline model. This allows us to add four scenarios to our analysis:

1. A hydrology only analysis that includes upstream control and two cropping seasons but does not change the price of power or the treaty constraint (smooth2crop). This simulation can be compared to the original Smooth flow to isolate the impact of changing agricultural practices in the absence of other changes.
2. An analysis that includes double cropping and an estimate of less expensive power due to upstream production sold to Sudan (smoothPower2crop). This simulation can be compared to the original SmoothPower simulation to see

how double cropping might evolve under conditions of a lower electricity price.

3. A policy analysis that includes multiple cropping and the removal of the 1959 treaty constraint (Smooth2cropNA). This simulation is important because we found that the 1959 Nile Waters agreement placed a significant limitation on Sudan's ability to take advantage of multiple cropping seasons. Please see our response to Specific Comment 4 for more information on the treaty constraint.
4. A full analysis that includes multiple cropping, lower electricity price, and removal of the 1959 treaty constraint (SmoothPower2cropNA).

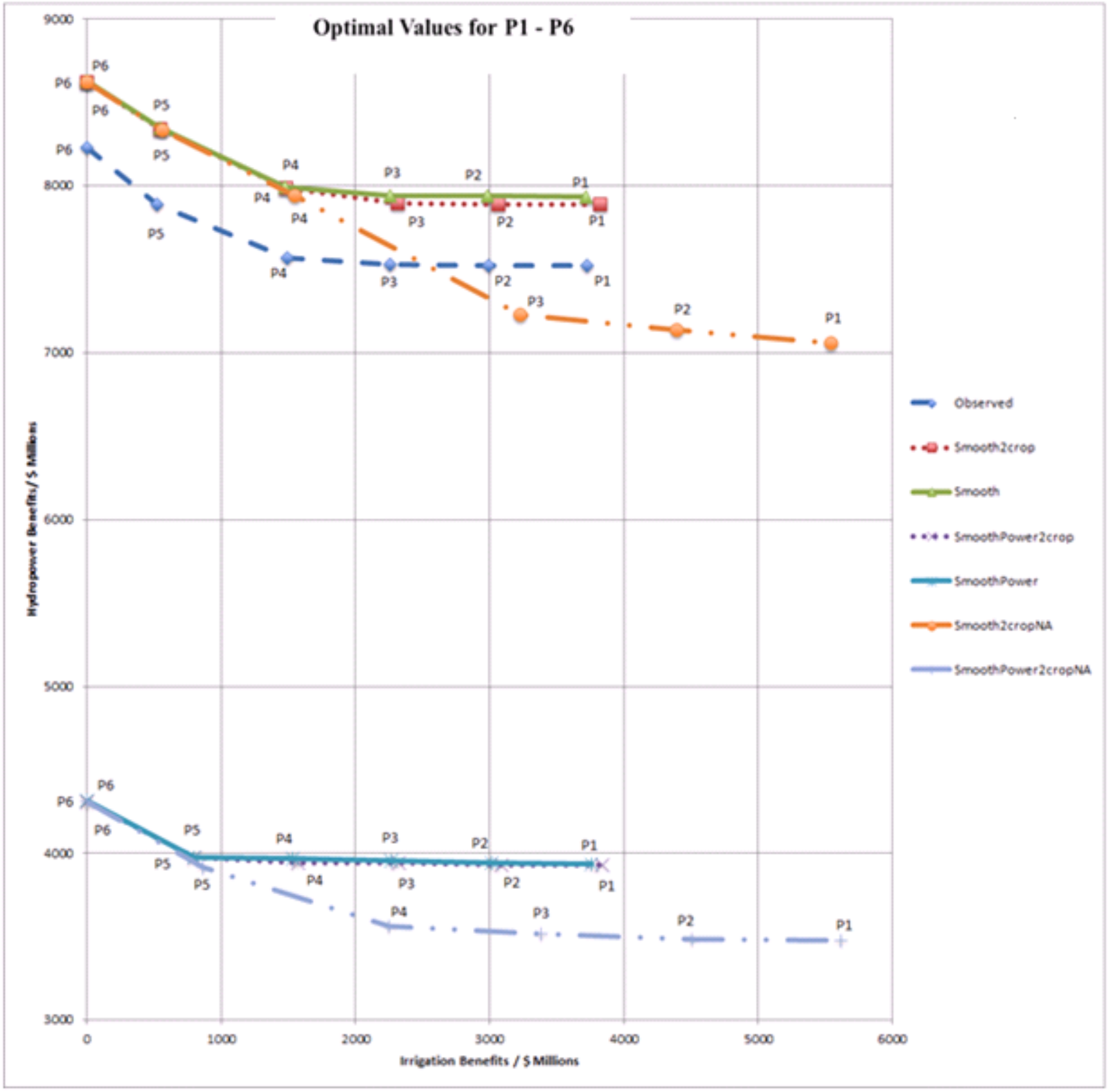
For each scenario we performed simulations for a range of marginal water values to test sensitivity across a range of agricultural returns (see General Comment 5 for more on this topic). These values are presented in Table 1. As the marginal value of water for each crop increases the model tends towards larger irrigation withdrawals.

Table 1: Marginal Value of water calculated for each crop

	Marginal value of water ($/m3)					
	P1	P2	P3	P4	P5	P6
Cotton	0.287	0.118	0.036	0.008	0.001	0.00001
Wheat	0.062	0.025	0.008	0.002	0.000	0.000
Groundnut	0.083	0.034	0.011	0.002	0.000	0.000
Sorghum	0.017	0.007	0.002	0.000	0.000	0.000

The results of these simulations are presented in Figure 1, which has also been added to the paper (new paper Figure 9).

Figure 1: Hydropower vs. irrigation benefits in simulations that include double cropping. Simulation names are described in the text. The "Observed" flow simulation is included for comparison.



In this figure we see that the Smooth and Smooth2crop scenarios both lie above the Observed scenario for all sets of marginal water values. This indicates that an upstream control that smoothes Blue Nile flows results in increased hydropower production in Sudan even when an additional cropping season is allowed in the model. Somewhat surprisingly, there is very little increase in irrigation benefits in Smooth2crop relative to Smooth, even for high agricultural marginal water values (e.g, P1-P3). This suggests that the value of hydropower and/or hydrological or treaty constraints limit the attractiveness of an irrigation driven pathway in this scenario.

One might also expect that a reduction in electricity price (any of the Power scenarios) would push Sudan strongly towards irrigation. Some tendency in this direction can be seen in Figure 1, but the effect is modest and only applies for specific marginal values of water (P5, P4), and not every case. In fact, the "SmoothPower2crop" scenario actually produces more KWH power than

"Observed," albeit with lower total benefit on account of the lower price of power in this scenario. This is true even for high marginal values of irrigation (P5 and P6).

The "NA" simulations shown in Figure 1 suggest that these counterintuitive results are in large part a product of the treaty constraint. As Figure 1 shows the nature of the 1959 agreement constraint within The 1959 Agreement constraint in the equation below guarantees at least three times more water passing through Merowe (the largest dam in the model) than to be used in irrigation and for losses due to evaporation. Hence Sudan's irrigation potential is limited by the 1959 agreement.

$$\sum_{l,m}(\, i_{l,m,y}\,) + \sum_{l,m}(\, e_{l,m,y}\,) \leq\ 0.28 * \sum_{m}(\, r_{3,m,y}\,)$$

"Smooth2cropNA" and "SmoothPower2cropNAPower" removes this constraint, and for larger marginal values there is a substantial increase in irrigation benefits.

Additional changes in infrastructure and management—for example, additional dams in Sudan or development of new irrigation initiatives—are left for future analysis. The matter of adaptive reservoir management is an interesting problem. We acknowledge that, we would need a more realistic and data-informed representation of reservoir operation to provide a fully meaningful analysis of adaptive reservoir management under climate change.

General Comment 2

The second major shortcoming of the paper is the fact that it ignores the White Nile and the Atbara rivers completely. The problem with these omissions is that the water management situation in those rivers is dynamic and not insignificant (contrary to what the authors assert). In the White Nile, there are a range of changes underway between Gebel el Aulia and Khartoum, as well as long-standing plans related to the Sudd, a discussion that includes South Sudan. And changes in the Atbara and White Nile could both affect the negotiation of allocations under climate change. The paper must either be given a new title or the model expanded; at the moment it does not apply to the entire "Sudanese Nile."

Response:

Agreed. Rather than attempt a drastic expansion of the model for the current paper we have changed our title to:

The Question of Sudan: a hydroeconomic optimization model for the Sudanese Blue Nile.

Reviewer 1 General Comment 3

The third issue is the treatment of the effect of upstream infrastructure. The authors *do not provide sufficient justification for their temporal smoothing assumption, which is surprisingly ad-hoc given that they would appear to be able to model a new large dam in Ethiopia. Why not simply include such a project, optimized from Ethiopia's perspective? The other advantage of this is that it would allow for more realistic representation of the energy system, since a likely target for Ethiopian hydropower would be the Sudanese market. Because of the way the analysis has been structured, the model may overstate the tradeoff between hydropower and irrigation because it assumes no hydropower from Ethiopia will go to Sudan (this is acknowledged on p.11585 but the solution is again ad-hoc). I would urge a rethinking of the analysis along these lines.*

Response:
We agree with the reviewer that expanding the model across the border to model the GERD would lead to a more realistic simulation. However, we are not sure that adding a GERD optimized from Ethiopia's perspective in the context of a connected grid is really a simple addition to the current model. Just as an example, it is highly likely that the GERD and Roseires will be managed in some kind of reregulating fashion in order to supply peaking power to Khartoum. We've begun to work through this problem, but we are not ready to formalize it within the model.

For this reason, we have used the observed monthly flows averaged across 3 months purely as an illustrative example of how upstream flow regulation impacts Sudan. This is, indeed, a simplified approach. But it is not a trivial adjustment, given the fact that the high variability of Blue Nile flows has been identified as a key development limitation for Sudan for many years. Our simplified "GERD" (i.e., smoothing) allows us to examine this issue in an idealized manner. In the future we do intend to expand the model in a number of ways, including the addition of an optimally managed GERD.

General Comment 4
The description of previous work in the Nile basin covers the existing hydro-economic optimization models well, but says little about important simulation work that has been used specifically to consider climate change implications, which seems very relevant. See Jeuland (2010) in Water Resources Research and Jeuland & Whittington (2014). Note that the supplementary materials for the latter also include updated water demands for Sudan, compared to those used in the paper.

Response:
We thank the reviewer for noting these studies. A description of related hydroeconomic tradeoff simulations within the Nile basin as detailed in Jeuland (2010), Jeuland and Whittington (2014) were all added to the section 1.2 of the updated version of the manuscript.

General Comment 5

Model: I question the choice of valuing the irrigation benefits using agricultural profit margins (in the objective function). The problem is that this assumes that all profits are attributable to irrigation, which may not be the case. What the authors need instead is a marginal product of water in irrigation. Given this approach, I find it hard to interpret the tradeoff curves, which do not reflect the marginal contribution of water to agriculture profits.

Response:

We acknowledge that our application of AGM was poorly framed. To address this shortcoming we have replaced AGM with a marginal value of agricultural water, an approach that has been used in previous studies (e.g., Whittington 2005, Arjoon 2014). Noting that agricultural data from the region is extremely limited, these authors used a flat demand curve with a constant marginal value of water at 0.05$/m^3 for all agricultural areas.

For this paper we have followed the approach of using a flat demand curve, but we have applied crop-specific marginal water values and performed a sensitivity analysis on the parameter. Six different combinations of marginal water value were tested, as listed in the table below. The ratio of the marginal values for each crop was calculated based on the producer price (P, $/ton), yield (Y, ton/m^2) and water content (W, m^3/m^2).

PY/W will give the $/m3 for each crop, thus a ratio of marginal value of water for each crop. Varying the values based on this ratio gives the table below. Sources: P (FAOSTAT website), Y (Ghezae, 1998 taken from a Rahad Research Station for potential yield values), W (Plasquelle 1990, takes into account initial irrigation and penman evap from Wad Medina)

	Marginal value of water ($/m^3)					
	S1	S2	S3	S4	S5	S6
Cotton	0.287	0.118	0.036	0.008	0.001	0.00001
Wheat	0.062	0.025	0.008	0.002	0.000	0.000
Groundnut	0.083	0.034	0.011	0.002	0.000	0.000
Sorghum	0.017	0.007	0.002	0.000	0.000	0.000

Additionally, we would like to clarify that the marginal values presented here as well as the power pricing of 8 cents/KWh are chosen for illustrative purposes only. They are intended to assess the sensitivities of the model and are **not** meant to reflect an optimal estimate of current agricultural or energy market prices. This will be added in section 2.2.1 of the manuscript.

General Comment 6

A final (and difficult) issue I would raise is that the valuation must clearly be presented as a country-specific one. Despite the legal regime, Egypt has been releasing more than 55.5 bcm per year from the High Aswan Dam, because Sudan has not used her full *allocation. This means that the true economic benefits of Sudan consuming more water thus must include the reduced water available in Egypt, where it is being used productively. If the paper is really about optimal economic use of water, it must explain and handle this issue clearly.*

Response:
Agreed. The larger benefits accrued by increased consumption of water in the analysis of this paper is restricted to the Sudan only. This analysis does not factor the effect of the decrease in upstream water supplied to Egypt, thus an increase in benefits to Sudan does not necessarily equate to a basin-wide increase in net benefits. This is now noted in the paper in Section 4. Our model does not address the question of what an increase in Sudan's consumption would do to basin wide benefits. Past studies (Whittington and Blackmore) have shown that decreases in inflows to Aswan Dam would lower water levels in the dam and decrease the total amount of water lost to evaporation, thus increasing basin-wide benefits.

Specific Comment 1
In the introduction p. 11567, the relevance of changing silt loads is not properly explained (lines 25-26).

Response:
Development upstream of Sudan will decrease silt loads thereby having multiple effects. Silt deposited accumulate over time in the reservoir and reduce the volume of reservoir. This affects hydropower production, reduces the available water for irrigation, incurs dredging costs, as well as reduces flood control capabilities. We have added text explaining this to the relevant passage of the introduction.

Specific Comment 2
I would advise the authors to update somewhat their data sources. In the introduction, based on a now dated study by Blackmore and Whittington, it is said that Sudan consumes 13.5 bcm/yr of water, which is likely on the low side, and does not include evaporation losses from the reservoirs behind the heightened Roseires Dam and the Merowe Dam, the latter of which should be included in Sudan's 18.5 bcm/yr allocation (e.g., the 10 bcm in the 1959 agreement is evaporation from behind Lake Nasser). Also, how evaporation from Roseires should be handled is ambiguous since the heightening was not written into the treaty.

Response:
Agreed. Jeuland (2010) uses a baseline demand target for Sudan of 16.1 Billion cubic meters (Bcm). This is corrected in the revised version of the manuscript.

Specific Comment 3
Please review the equations section. Some terms (e.g. "Water") are not defined, and it is unclear how little "i" relates to big "I". I think the problem is that the water requirements of different crops have not been clearly explained.

Response:
Water in the irrigation equation is defined as the crop water requirement, the total amount of water (m^3) required by 1 m^2 area of the crop. We apologize for the confusion and restated the irrigation constraint as:
Total water withdrawn for irrigation location (l) at month (m) in year (y):

$$i_{l,m,y} = \sum_{c} (effi * Water_{c,l,m,y} * Area_{c,l,m,y})$$

The total water used for irrigation is calculated by multiplying the area cultivated, the crop water requirement and the irrigation efficiency. The total benefits are derived by multiplying the total water used and the marginal value of the water. Therefore the total irrigation benefits for each month (m) at year (y):

$$bi_{m,y} = \sum_{c,l} (effi * v_c * Water_{c,l,m,y} * Area_{c,l,m,y})$$

where v_c is the marginal value of water for each crop. With these changes, big "I" has been removed from the irrigation constraint. This updated constraint has now been included in section 2.1.3.

Specific Comment 4
Looking at constraint in equation 5, is it correct that the model allows Sudan to withdraw more or less than 18.5 in a given year so long as the total balances out? That seems problematic since Sudan would likely be tempted to take more water in drought years and Egypt would clearly not allow this. The other reason that this formulation is problematic is because the discounting will necessarily front-load demands.

We thank the reviewer for noting these important concerns. We have attempted to address the drought problem as follows. In order to ensure Egypt's water allocation, Sudan's total use of water for the year should be less than or equal to 0.28 of the total release downstream of Merowe (i.e Egypt's share). This prevents Sudan's large intake during drought years by guaranteeing Egypt's fractional share during those years.

$$\sum_{l,m} (i_{l,m,y}) + \sum_{l,m} (e_{l,m,y}) \leq 0.28 * \sum_{m} (r_{3,m,y})$$

0.28 = 18.5 / (55.5 +10) = Sudan's share / (Egypt's share + evaporation at Aswan).

With this additional constraint incorporated, we tested our model for front-loading. Results displayed below show the difference between two identical models, the first "Dis" includes a discount rate of 5%, the second model "No Dis" removes the discount rate.

$$Objective\ function = \sum_{m,y} (D_y * bi_{m,y}) + \sum_{m,y} (D_y * bh_{m,y})$$

As the table indicates, front loading is not a significant phenomenon in the model once the drought year constraint is included. The largest change in any year is an increase of approximately 4% in benefits for the first year for both irrigation and hydropower.

	Bi			bh		
	Irrigation Benefits			Hydropower Benefits		
Year	Dis	No Dis	%Diff	Dis	No Dis	%Diff
1	41.420	39.830	3.992	549.241	526.077	4.403
2	47.985	47.985	0.000	951.687	975.899	-2.481
3	47.985	47.985	0.000	992.416	993.895	-0.149
4	45.323	45.323	0.000	963.910	959.026	0.509
5	47.985	47.985	0.000	990.561	995.715	-0.518
6	47.985	47.985	0.000	963.039	963.039	0.000
7	18.312	18.312	0.000	956.764	951.440	0.560
8	47.985	47.985	0.000	899.781	900.426	-0.072
9	40.527	40.527	0.000	880.719	885.905	-0.585
10	1.053	1.053	0.000	885.186	883.670	0.172
11	47.985	47.985	0.000	900.973	900.541	0.048
12	47.985	47.985	0.000	975.185	975.899	-0.073
13	47.985	47.985	0.000	992.416	993.895	-0.149
14	45.323	45.323	0.000	959.026	959.026	0.000
15	47.985	47.985	0.000	995.715	995.715	0.000
16	47.985	47.985	0.000	963.039	963.039	0.000
17	18.312	18.312	0.000	954.264	951.440	0.297
18	47.985	47.985	0.000	899.346	900.426	-0.120
19	40.527	40.527	0.000	884.726	885.905	-0.133
20	1.090	1.090	0.000	975.216	976.027	-0.083

Both the updated constraint and a statement on front loading are now included in the text, in sections 2.1.3 and 2.2.2, respectively.

Specific Comment 5

Model II: Random bootstrapping of flows will not maintain the autocorrelation in the hydrological time series. The authors should comment on the implications of this and whether it is likely to be an important shortcoming.

Response:

The reviewer makes a good point: our bootstrapping method does retain the seasonal structure of flows, but any autocorrelation between hydrologic years is lost. To check whether interannual autocorrelation is significant in the available 70 year discharge record we calculated autocorrelation for total and average annual flows lagged for 1 to 50 years. The lag-1 autocorrelation was 0.165, which is not statistically significant. For other time lags the largest correlation value was 0.175 and the lowest -0.215. These low values show minimal autocorrelation on annual scales thus minimizing the distortive effects of bootstrapping. We now note this in the text in section 2.2.4.

P.11567, line 27: "analytical tools" not "analysis tools".

Response: Changed

P.11568, line 5: "For the purposes of..."

Response: Changed

Gezira – as in the irrigation scheme, is misspelled in different ways in different places (as Gezeira, Gezeria, etc.)

Response:

P.11575. line 16: The model does not maximize I. The objective function includes both agricultural profits and hydropower.

Response: Irrigation constraints and the objective function have been updated