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Punjab water outlook: Impacts of climate change and dam sedimentation on water for irrigated agriculture

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Revision 17 March 2020

The report (originally published January 2020) has been revised to modify the y-axis scales on Figures 13 and 14 (which are replicated as Figures 1 and 2). This is a minor revision and has no impact on the results and key messages.

Copyright

Important disclaimer

Ethics

The activities reported herein have been conducted in accordance with CSIRO Social Science Human Research Ethics approval 011/17.

This report designed and implemented by CSIRO contributes to the South Asia Sustainable Development Investment Portfolio and is supported by the Australian aid program. Further details on CSIRO SDIP projects are available from http://research.csiro.au/sdip.

SDIP's goal is increased water, food and energy security in South Asia to support climate resilient livelihoods and economic growth, benefiting the poor and vulnerable, particularly women and girls

SDIP 2020 objective: Key actors are using and sharing evidence, and facilitating private sector engagement, to improve the integrated management of water, energy and food across two or more countries - addressing gender and climate change.

All CSIRO SDIP projects consider gender. In this report we have assumed that an improved, quantitative understanding of the water outlook for Punjab has the potential to benefit all, regardless of gender and other social factors. Excluding gender analysis, however, can lead to 'gender blind' tools, findings and decisions that reinforce existing gender inequities. This gap should be borne in mind when interpreting this report, and any application of its findings will need to integrate gender-specific and other social considerations to ensure benefits are distributed equitably.

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Executive summary

We used measured estimates of rainfall, actual evapotranspiration, canal deliveries and change in groundwater levels to assess the water balance of the canal commands in Punjab. The canal deliveries are the main supply of water into the canal commands. The use of groundwater is important, with a large volume of groundwater pumped for irrigation, though the net groundwater use (the difference between use and recharge) is a small component of the overall water balance, as evidenced by the change in groundwater levels. However, the sum of the measured water balance terms left a large residual of error or unknown water. There is also uncertainty in the assessment of evapotranspiration, and we used two remote sensing methods for assessing it.

We then assessed the change to the water balance from the historical baseline of projected (modelled) future rainfall, actual evapotranspiration, and canal deliveries under the 1991 inter-provincial water accord as affected by climate change in the Upper Indus and in Punjab province, and as affected by sedimentation in the main irrigation supply dams. We also assessed a 'no-dams' scenario in which it was assumed that there was no water storage in dams. These changes were captured as a set of 10 exploratory future scenarios. The study employed a simple approximate method for calculating the change in the area of crops required to use the available water.

The exploratory scenario analysis shows that the influence of changes to the local climate generally had the largest impact on the water balance, followed by the impact of flows on canal deliveries, then the no-dams scenario, and then the sedimentation scenarios. While this is the general picture, in some seasons the order of some effects is reversed. The analysis also showed that while the actual evapotranspiration estimated by two methods (ETLook and CMRSET) differed, the changes to the water balance were almost the same for the two methods. Therefore, the choice of method of actual evapotranspiration estimation made almost no difference to the assessment of impacts under the exploratory future scenarios.

We conclude that water availability in Punjab may increase or decrease due to climate change in the Upper Indus Basin and due to local climate change in Punjab. Sedimentation in the Tarbela and Mangla storages up to 2050 is projected to have a negative impact in the Rabi season particularly in conjunction with climate change. Complete loss of dam storage, such as might occur over the very long term, is projected to lead to much reduced water availability in the Rabi season, since there is a lesser volume of storage to supply Rabi crop demands, and increased availability in Kharif since there is a lesser volume of storage to capture the large Kharif river flows. In the Kharif season, the potential increases are generally larger than the potential decreases. Conversely, in the Rabi season, the potential increases are generally smaller than the potential decreases.

The Punjab could choose to accommodate changes in water availability and demand by adjusting the volume of groundwater use in fresh groundwater quality areas, though this is likely not to be sustainable in the long run. Alternatively, the current level of groundwater use could be maintained, and the area of crops adjusted. If the latter course is followed, the potential reductions in crop area in the Rabi in response to lesser water availability are projected for some crops to amount to an area equivalent to about 3 000 000 ha in several scenarios. The extreme case of loss of dam storage altogether (without the added impact of other scenarios) could amount to a loss of Rabi water availability equivalent to more than the area of the wheat crop.

Several strategies will help deal with the impacts, including changing the areas of crops, changing the mix of crops to lower water using crops, improving the efficiency of water delivery via the canals, and improving crop productivity. Although it does not seem to offer a short to medium term benefit, in the very long term controlling sedimentation in dams could also be beneficial.

Key results and messages

Water balance studies at large scale seldom agree closely with one another. Ahmad et al. (2019) describe the uncertainty in estimating the evapotranspiration in the irrigated areas of the Indus basin, and in this report we provide further evidence of the uncertainty in this major component of the water balance. However, we also show in this report that while there is uncertainty in the absolute magnitude of terms in the water balance, we can be more confident about the likely changes to those terms under specific scenarios. Since our concern is primarily with how the water balance might change in the future, and the implications of change for cropping, this leads to our first key message:

KEY MESSAGE 1: Reasonable confidence may be placed in the estimates of changes to the availability and evaporative demand for water for irrigation, and the implications for the areas of crops that may be planted, notwithstanding considerable uncertainty in the absolute magnitude of the availability and evaporative demand.

Irrigated cropping is currently by far the main user of water in the Punjab. The interest in future water availability and demand is mainly an interest in the implications for cropping (will there be a potential to grow more or less crops in the future?) and the economic consequences of growing more or less crops. We do not address the economic consequences in this report. The key results in this report are the implications for cropping, which we summarise below, and outline the key messages.

The implications for cropping in the Punjab depend on how the province responds to changed water availability and demand. Over the past few decades, areas of cropping in the Punjab have increased, with the use of ever greater volumes of groundwater. There is thus little association between the area cropped and the surface water availability. The Punjab could choose to offset future changes in surface water availability and demand by adjusting the volume of groundwater used. If surface water availability decreases, the implied offsetting increase in groundwater use would exacerbate what is already perceived as unsustainable use.

KEY MESSAGE 2: The Punjab could choose to accommodate changes to surface water availability and demand in the future by adjusting the volume of groundwater use. However, this would run the risk of exacerbating what is already perceived as unsustainable use.

Alternatively, the Punjab could choose to adjust the areas of cropping in response. Based on the assumption that the current level of groundwater use is maintained in the future, Figure 1 and Figure 2 show the adjustments that would be required of three Kharif and three Rabi crops (if the area of each crop were adjusted on its own). The adjustment in the Kharif season differs from that in the Rabi season, and in both seasons varies according to the future scenario. The calculated change in the area that may be cropped varies from year to year, with the range of variation shown using a ‘box and whisker’” plot. A box and whiskers that are small vertically indicates little year to year variation, whereas box and whiskers that are large vertically indicate much year to year variation. Further detail on interpreting box and whisker plots is given in Appendix A. The coloured panels in Figure 1 and Figure 2 indicate groups of similar scenarios.

In Figure 1 and Figure 2 the leftmost plot (white / non-coloured panel) is the current situation. By definition, there is no change in this scenario from the current position. This scenario is shown on the plots to help visualise the change in the other scenarios.

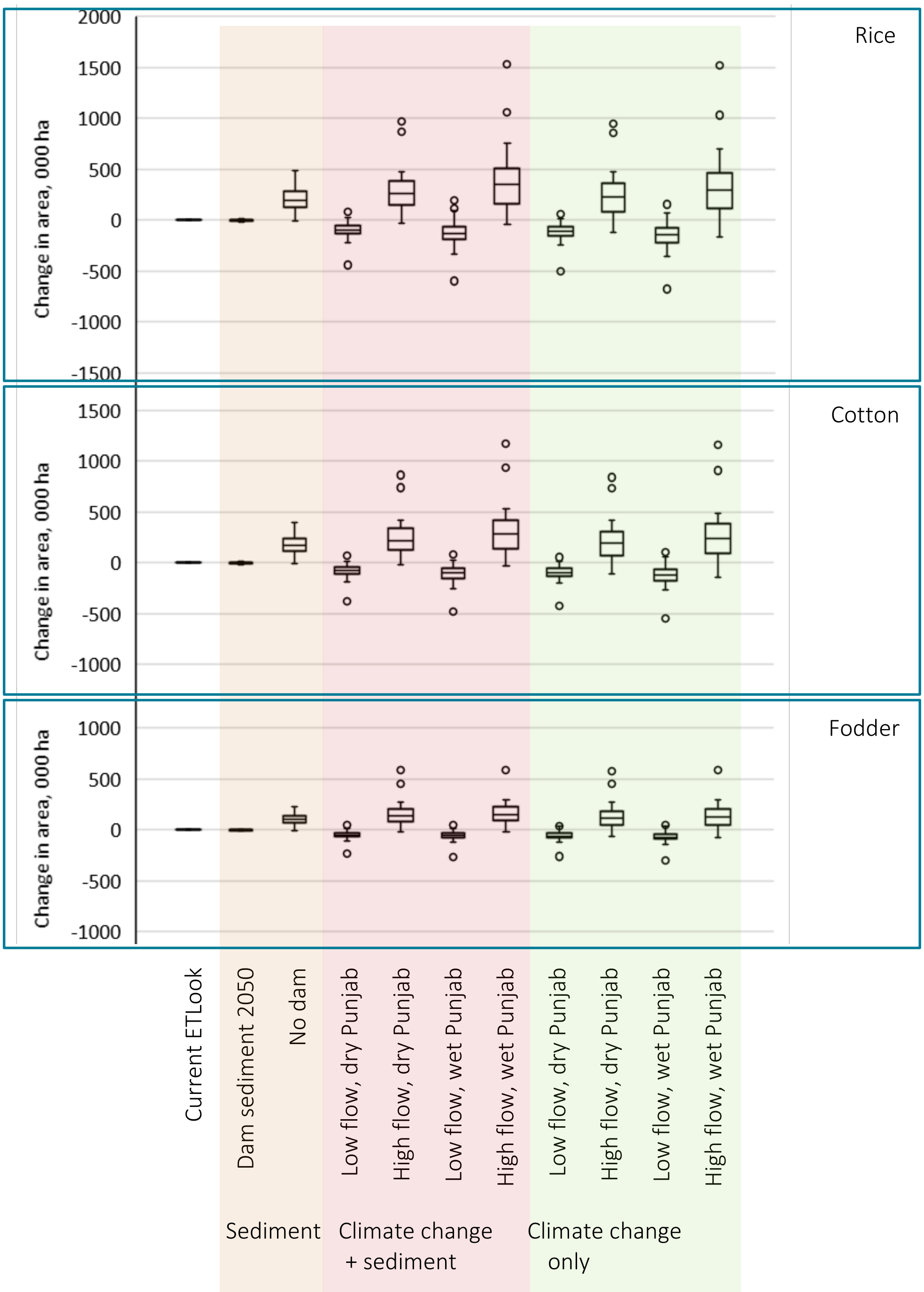


Figure 1 Range of change in areas of Kharif rice, cotton and fodder crops under the 10 exploratory future scenarios. The coloured panels show groups of similar scenarios

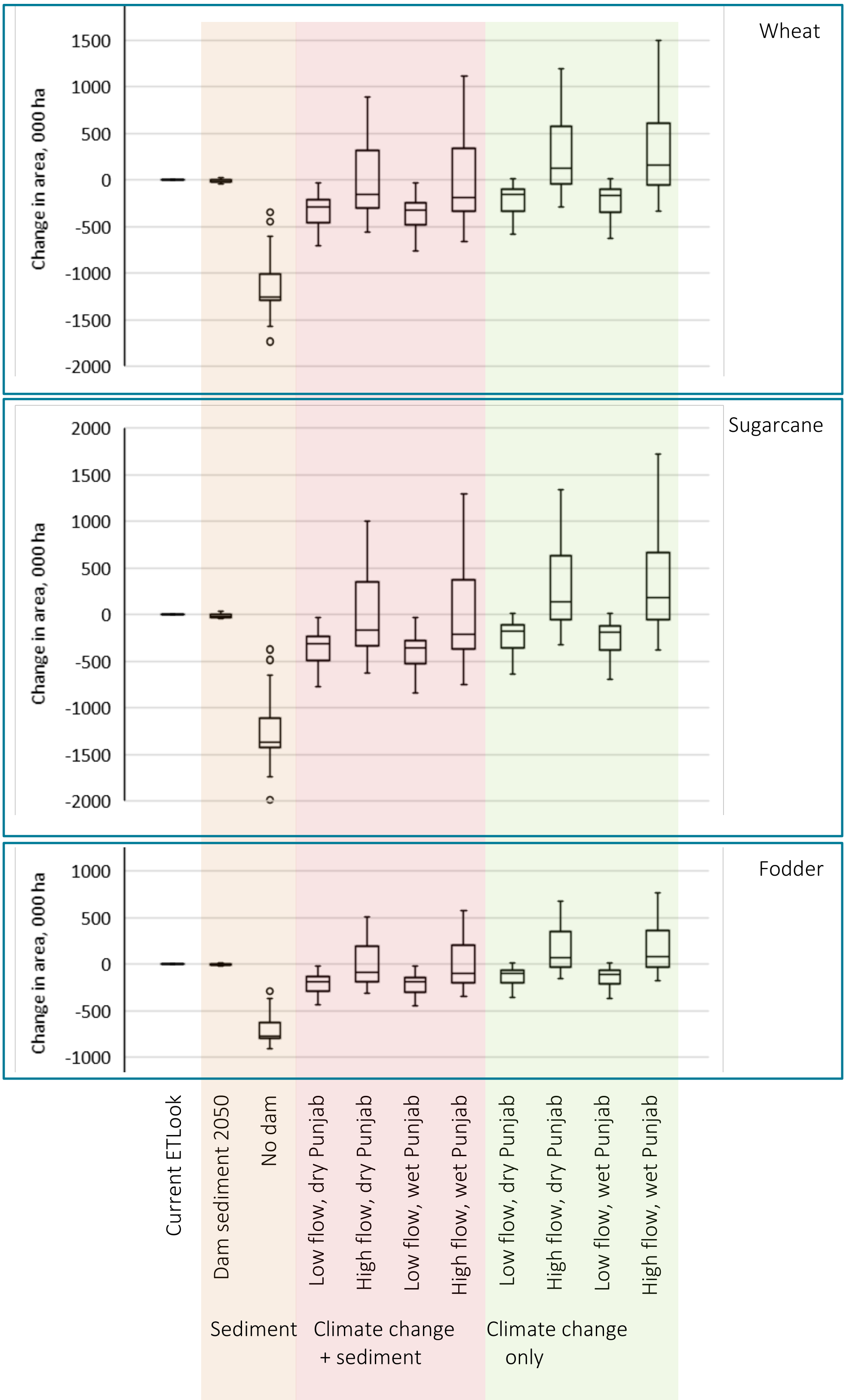


Figure 2 Range of change in areas of Rabi wheat, sugarcane and fodder crops under the 10 exploratory future scenarios. The coloured panels show groups of similar scenarios

Impacts of dam sedimentation for crop areas

The impact of possible future dam sedimentation (in Tarbela and Mangla) is shown in the two 'Sediment' box and whisker plots, in the light brown panels of Figure 1 and Figure 2. The leftmost plot is based on an estimate of likely dam sedimentation in 2050 (which extrapolates current sedimentation rates), and the other is based on an extreme scenario with a total loss of dam storage by 2050. The figures show that the 2050 sedimentation scenario results in little change in the Punjab; however, sedimentation plus climate change does reduce the areas that may be cropped in the Rabi season (see further discussion below). The no-dams scenario results in an increase in the area that might be irrigated for cropping in Kharif (Figure 1), and an expected reduction in irrigated crop areas in Rabi (Figure 2). This results from lesser storage to capture flows in Kharif, leading to greater flows and hence potentially greater canal deliveries in that season. Conversely, lesser storage leads to lesser volumes of water available for release and canal deliveries in Rabi.

> Key message 3: Dam sedimentation is projected to reduce the availability of water to the Punjab by 2050, and could further reduce supplies in the very long term. The area of irrigated cropping to accommodate the reduced canal deliveries in the very long term in Rabi is a substantial fraction of current cropped areas.

Implications of dam sedimentation + climate change for crop areas

The impact of possible future dam sedimentation combined with climate change in the Upper Indus Basin and in Punjab is shown in the four 'Climate change + sediment' box and whisker plots, in the light red panels of Figure 1 and Figure 2. The four climate change scenarios are based on the driest and wettest projected climates within Punjab (based on a subset of all model climate projections, as explained in greater detail later in this report), and the least and greatest flow projections resulting from climate change projections in the Upper Indus Basin (as explained later in this report and in the companion river modelling report by Stewart et al, 2020).

In the Kharif season, the low flow projections result in lesser canal deliveries which could be accommodated by modestly reduced areas of irrigated cropping (first and third box plots in the red group), whereas high flow projections lead to significantly increased areas of cropping (second and fourth plots in the red group).

In the Rabi season, even the high flow projections (second and fourth plots in the red group) result in a somewhat reduced area of cropping in most years and in the median year, whereas the low flow projections (first and third box plots in the red group) lead to a large decrease in the area.

The impact of climate change on rainfall and crop water demand within Punjab is significant, particularly in the Kharif season when it leads to increased areas that might be cropped, as seen by comparing the first and third plots (wet and dry projected climate in Punjab for projected low flows) in the red group for any crop, and by comparing the second and fourth plots (wet and dry projected climate in Punjab for projected high flows) in the red group for any crop.

> Key message 4: The impact of projected climate change in the Upper Indus Basin on flows and hence canal deliveries and cropping in Punjab is large, but its direction (increased or decreased area of cropping) is uncertain.

KEY MESSAGE 5: The impact of projected climate change on rain and crop water demand within Punjab is significant, with increased opportunities for cropping in the Kharif season.

IMPLICATIONS OF CLIMATE CHANGE FOR CROP AREAS

The impact of stopping all future dam sedimentation, so that the only effects are climate change in the Upper Indus Basin and within Punjab, is shown in the four 'Climate change only' box and whisker plots, in the light green panels of Figure 1 and Figure 2. The areas that can be planted in this set of scenarios are all greater than the corresponding climate change plus sedimentation scenarios in the red panel. Thus, sedimentation is projected to lead to lesser areas of cropping in future climate change scenarios.

In the following sections of this report we describe the methods, input data, scenarios and results that lead us to these key results and messages. We also discuss options for the Punjab to manage the potential impacts of dam sedimentation and climate change.

1 Introduction

The work described in this report forms part of CSIRO's Sustainable Development Investment Portfolio project on water resources in the Indus Basin of Pakistan. A companion report describes the water outlook for Sindh (Ahmad et al., 2020a). The purpose of this report is to present the results of a range of exploratory future scenarios for the Punjab assessing potential changes to the water balances of the canal commands (aggregated at the province level) due to:

- projected climate change impacts on the flows in the Indus and hence on canal deliveries in Punjab
- projected future storage reduction (through dam sedimentation) impacts on the flows in the Indus and hence on canal deliveries in the Punjab
- projected climate change impacts on the rainfall and potential evapotranspiration (and hence irrigation demand) within the Punjab.

Following this introduction, this report has three sections:

- Methods: Water balance and scenario assessment, including input data sources
- Scenario results
- Discussion, and opportunities for dealing with impacts.

Apart from obvious differences to diagrams and some changes to the text, this report largely repeats the structure and text of the Sindh report (Ahmad et al., 2020). This is deliberate. Either report can be read without reference to the other, and the reader can compare the Punjab and Sindh water balances with similar diagrams and other facts and figures in similar places in the two reports. The similarities and differences between the Punjab and Sindh are discussed in the results and discussion sections.

This report uses results from assessments of climate change and dam sedimentation impacts on projected canal deliveries to Sindh using the Indus River System Model (IRSM) (Stewart et al., 2020). While the Stewart et al. report describes results only for Sindh, the output of the model also included the projected canal deliveries to the canal commands of the Punjab. The canal delivery results are a major input to the water balance assessments described here.

1.1 Companion reports

This report is one of a suite of four reports. The first reports on assessments of climate change and dam sedimentation impacts on projected inflows to Sindh using the Indus River System Model (IRSM) (Stewart et al., 2020). The results described in that report are a major input to the water balance assessments described here.

Two other companion reports present the results for specific regions:

- Sindh province (Ahmad et al., 2020a) – publicly available.
- the Nara and Upper Nara canal commands (Ahmad et al., 2020b) – available on demand

1.2 Previous studies

Several other studies have estimated water balances in the Indus Basin. Many of these are for the whole basin, and do not separately identify the water balances for Punjab province. Whole-of-basin estimates include Hussain et al. (2011), Bastiaanssen et al. (2012), Cheema (2012), Karimi et al. (2013), Cheema et al. (2014), Kirby et al. (2017) and Young et al. (2019).

Zaidi et al. (2019) made a comprehensive study of the water balance of Sindh for the Rabi seasons of 2017-18 and 2018-19, and the Kharif season of 2018. Similar to the study we will report below, they used a remote sensing method to estimate actual evapotranspiration, included urban water supply, and also identified the water balances separately for each canal command in Sindh.

To the best of our knowledge, the results presented in this report are the most comprehensive available for impact of potential changes to water supply and demand on the canal commands of Punjab. In particular, we are not aware of any other study that links the impacts of potential changes in the flow regime due to climate change and sedimentation of reservoirs in the Upper Indus Basin in Pakistan with those that might occur within Punjab itself, while considering the inter-provincial water apportionment accords.

2 Methods: water balances, scenarios and crop area assessment

In this report, we describe results that arise from assessing province level time-series water balances of the canal commands in Punjab. While we will present results mainly at province level, the original calculations were all done at the canal command level. In a companion report (Ahmad et al., 2020) we described the results for Sindh. The water balances at canal command level were calculated as monthly time series from 1990 to 2013. We will present the results mainly as annual or seasonal totals.

This section is organised in subsections as follows:

1. Description of the basic water balance method.
2. Description of the historical data of inflows (rainfall, canal deliveries and change in groundwater) and outflows (evapotranspiration) in the water balance. We will show that two different remote sensing methods result in different actual evapotranspiration estimates and, further that the inflows generally do not match the outflows in any canal command (for either set of actual evapotranspiration estimates), implying considerable uncertainty in the water balance. We will further note that the uncertainty is not reconciled by water balance modelling. This establishes the case for assessing the likely impact of future scenarios (such as climate change) in terms of the relative changes to inflows and outflows, and hence whether there may be more or less water relative to future demand.
3. Description of the future water supply and demand scenarios, and the choice of input data for each scenario. The scenarios include sedimentation in the main water storage dams in Pakistan, climate change in the Upper Indus Basin and its effect on flows and hence canal deliveries, and climate change within Punjab which will affect rainfall and crop water demand.
4. Description of the assessment of changed cropping opportunities resulting from whether there is more or less water relative to future demand.

2.1 Water balance method

We used the surface water balance approach of Ahmad (2002) and Ahmad et al. (2005). Ahmad suggested that the net groundwater use in an irrigation area, I_{ngw}, could be computed as the deficit implied by a water balance of the land surface, given by:

$$I_{ngw} = ET_a - P_n - I_{cw} + dW / dt \quad (1)$$

where ET_a is the water lost by evapotranspiration of crops and other vegetation, P_n is the water gained from precipitation (considered as a net term, after losses to runoff), I_{cw} is the diversion of water into the area via canals, and dW / dt is the change in water stored in the area (in the soil, but also in other surface storages) over the period being considered.

The advantage of this surface water balance approach is that it does not require detailed groundwater modelling or assessment, and does not require information or assumptions about lateral groundwater flows.

Ahmad et al. (2005) applied the method to the Rechna Doab region of Pakistan, using spatially explicit estimates of ET_a derived from remotely sensed satellite data.

Here, we modify the idea slightly to look at a lumped canal command surface water balance given by:

$$0 = ET_a - P_n - I_{cw} - I_{ngw} + B \quad (2)$$

where B is a balance term that is the difference between the sum of the other terms (and thus forces equation (2) to sum to zero). The difference or balance term is a composite term that includes any unknown water flow (such as surface runoff), plus errors in all the other terms. If the balance terms across the canal commands are small relative to other terms, we probably have a reasonably confident estimate of the water balances.

In modifying equation (1) to derive equation (2), the soil water storage term, dW / dt, is absent, and is implicit in the difference or balance term, B. The change in the annual soil water storage is likely to be insignificant over the long term. There is likely to be a change in seasonal soil water storage (such as in the Rabi or Kharif seasons); the changes over the long term will average approximately to equal and opposite in Rabi and Kharif. The error introduced with this assumption will be seen in the balance term, which will be affected by an approximately equal and opposite amount in the two seasons. However, as we noted in the previous section and will show below, we are mainly concerned with how the balance term changes with scenarios (of climate change and so on); the change to the balance term is likely to be not much affected by the assumption that the change in soil water storage is zero. In a recent paper, Pena-Arancibia et al. (2019) showed that different assumptions about the size of the seasonal change in soil water storage in the districts of northwest Bangladesh affected individual water balance terms, but did not make much difference to conclusions about trends. All terms except the balance term are estimated directly from the input data.

The water balances in the canal commands of Punjab were assessed using monthly data for rainfall, actual evapotranspiration and canal deliveries, and the generally twice-yearly groundwater level data. The balance term B (equation 2) was then calculated for each month in each canal command. The input data values and the results of the balance term calculation were then aggregated to the province level using an area weighted average of the canal command values.

2.2 Canal command water balances – historical assessment

We first discuss the historical water balance of the canal commands, because this gives an idea of how they behave in water balance terms, and the uncertainties in the water balance. As we noted above, the uncertainties in the water balance establishes the case for assessing the likely impact of future scenarios (such as climate change) in terms of the relative changes to inflows and outflows, and hence whether there may be more or less water relative to future demand.

The canal commands of Punjab province receive only modest amounts of rainfall, and hence rely heavily on deliveries of canal water. The overall supplies of canal water have not changed greatly in the last few decades, but do show year to year variation resulting from inflows. However, cropping areas have increased greatly due to increasing use of groundwater (Figure 3).

We performed a water balance of the canal commands in Punjab over the period 1981 to 2013 based on the following:

- gridded rainfall generated from actual gauge data as part of the SDIP project being undertaken by CSIRO, sampled and aggregated to monthly totals for the canal command areas of Punjab
- remote sensing estimates of the actual evapotranspiration of the Punjab province based on the ETLook method (Bastiaanssen et al. 2012; Cheema 2012; Cheema et al. 2014), sampled and aggregated to monthly totals for the canal command areas of Punjab. The estimates are for 2007, and were extrapolated to other years by Ahmad et al. (2019)
- remote sensing estimates of the actual evapotranspiration of the Punjab province recently completed by CSIRO (Peña-Arancibia et al., 2020), based on the CMRSET method, sampled and aggregated to monthly totals for the canal command areas of Punjab. The estimates are for 2000 to 2018 and were extrapolated to earlier years using the same method as that for the 2007 estimates above
- canal deliveries based on information from Water and Power Development Authority (WAPDA) and Punjab Irrigation department
- groundwater depths from WAPDA, averaged for canal commands, and then fitted with a trend for the period of assessment (1981 – 2013). The groundwater level change is taken as that assessed from the trend over the period. The change in the groundwater component of the water balance is the groundwater level change multiplied by the specific yield (which accounts for the fact that groundwater occupies the pore space in the rocks, which is a modest fraction of the overall volume; more technically, specific yield is the ratio of the depth of groundwater level change for a unit depth withdrawal of water). The actual specific yield and its variation is not known for the canal commands, and we used a default (but reasonable) value of 0.1.

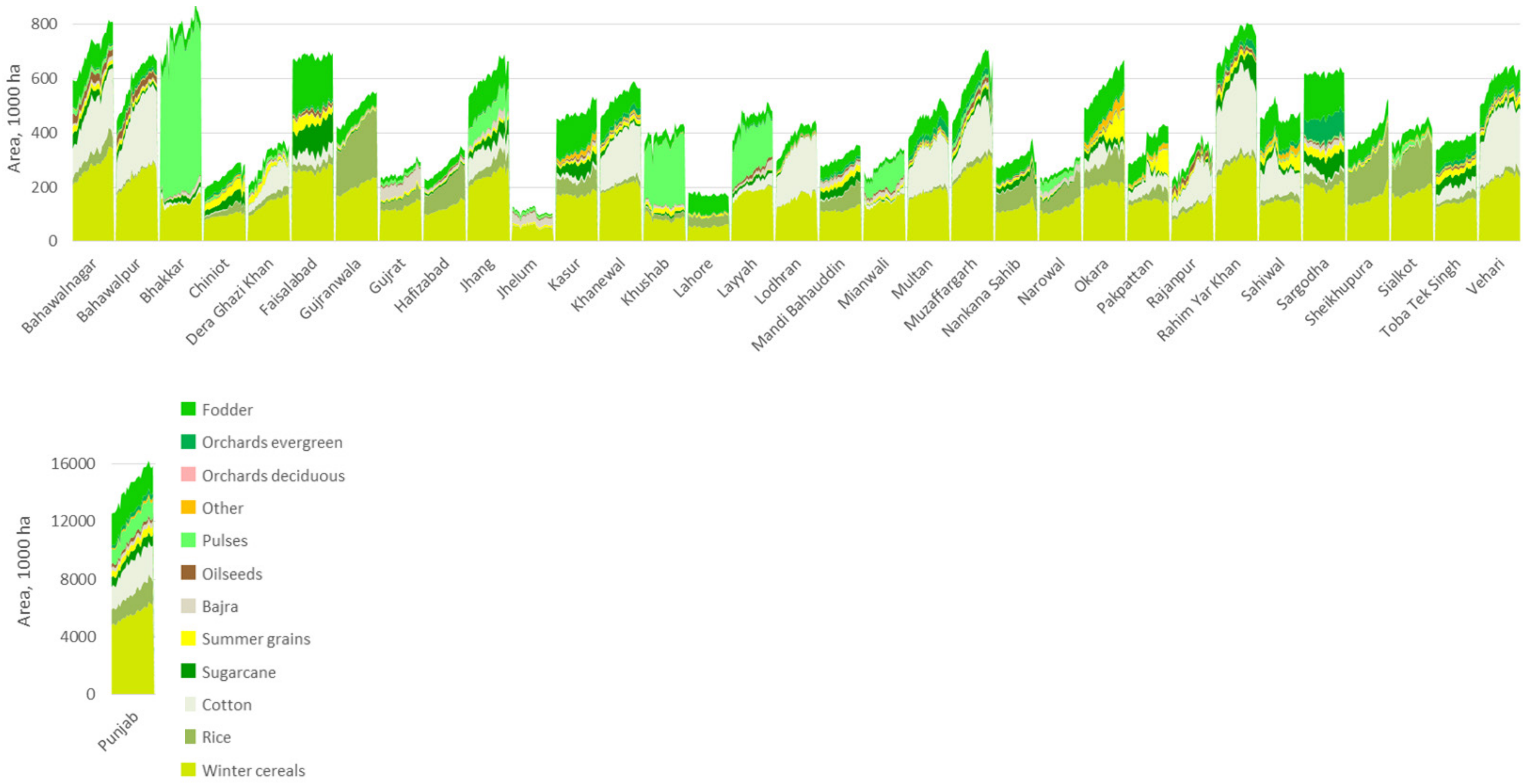


Figure 3 Crop areas from 1981-2 to 2011-12 in the districts of Punjab and for the whole province [Source: Pakistan crop statistics, collated by Kirby and Ahmad (2016), Ahmad et al., 2019 and further updated]

Figure 4 shows the components of the water balance for both estimates of actual evapotranspiration. Some key features of the water balance are:

- The change in groundwater is a small component of the overall water balance. In some cases it is too small to be visible on the plots in Figure 4, though it can be seen in the case of the Bahawal, CBDC, CRBD, Forwah and other canal commands. Any plausible specific yield value in place of the one we assumed would not change this result.
- The main water supplies are rain and canal deliveries, with canal deliveries generally being somewhat the larger of the two. Rain is the larger component for the Upper Jhelum Canal (UJC). This has implications for climate change scenarios, inasmuch as we might expect changes to canal deliveries and the local climate to have a similar impact on future water supply, with perhaps a slightly greater impact from canal deliveries. We shall examine this suggestion when assessing the climate change scenarios.
- The difference between inflows and outflows – the balance term - varies from canal command to canal command, but is generally smaller than the rain, canal deliveries or actual evapotranspiration (Figure 4). It is larger than rainfall some canal commands, and much larger than the groundwater contribution in nearly all canal commands. These large balance terms, required to close the water balance, are part of our reason for using the approach outlined above for water balances, rather than constructing models for the missing processes. Such models would require untestable assumptions to invoke processes to account for the balance term and close the water balance. The balance term is also negative in most canal commands when the ETLook estimate of evapotranspiration is used, meaning that there are more inflows estimated than outflows, and additional outflows are required to make the system balance. For the CMRSET estimate, the balance term is positive in most canal commands, meaning that there are less inflows estimated than outflows, and additional inflows are required to make the system balance.
- The two estimates of actual evapotranspiration are different.

We investigated the use of water balance models to help understand the monthly water balances in each canal command. In particular, we hoped that a time-stepping, monthly model might help resolve the uncertainties in the water balance – for example, by showing that an equation for the presumed additional outflows and inflows mentioned above would consistently account for the difference between inflows and outflows. We could find models and model parameter sets that fitted the historical data reasonably well, but we encountered two problems with the models.

The first problem was that many models and parameter sets fitted more or less as well as one another. For example, a model in which the presumed additional outflows were satisfied by an overland flow process fitted as well as a model in which they were satisfied by a groundwater flow process. Furthermore, the models fitted the ETLook evapotranspiration values more or less as well as they fitted the CMRSET evapotranspiration values, with a small change to model parameters. Thus, fitting models was little more than a statistical exercise, and did little or nothing to reduce the uncertainty in our understanding of the process operating.

The second problem with the models was that when applied to future scenarios, in some scenarios and canal commands, the groundwater was projected to be rapidly depleted. While groundwater depletion is a feature in some areas of the Punjab, the rate of projected depletion was too great to be credible.

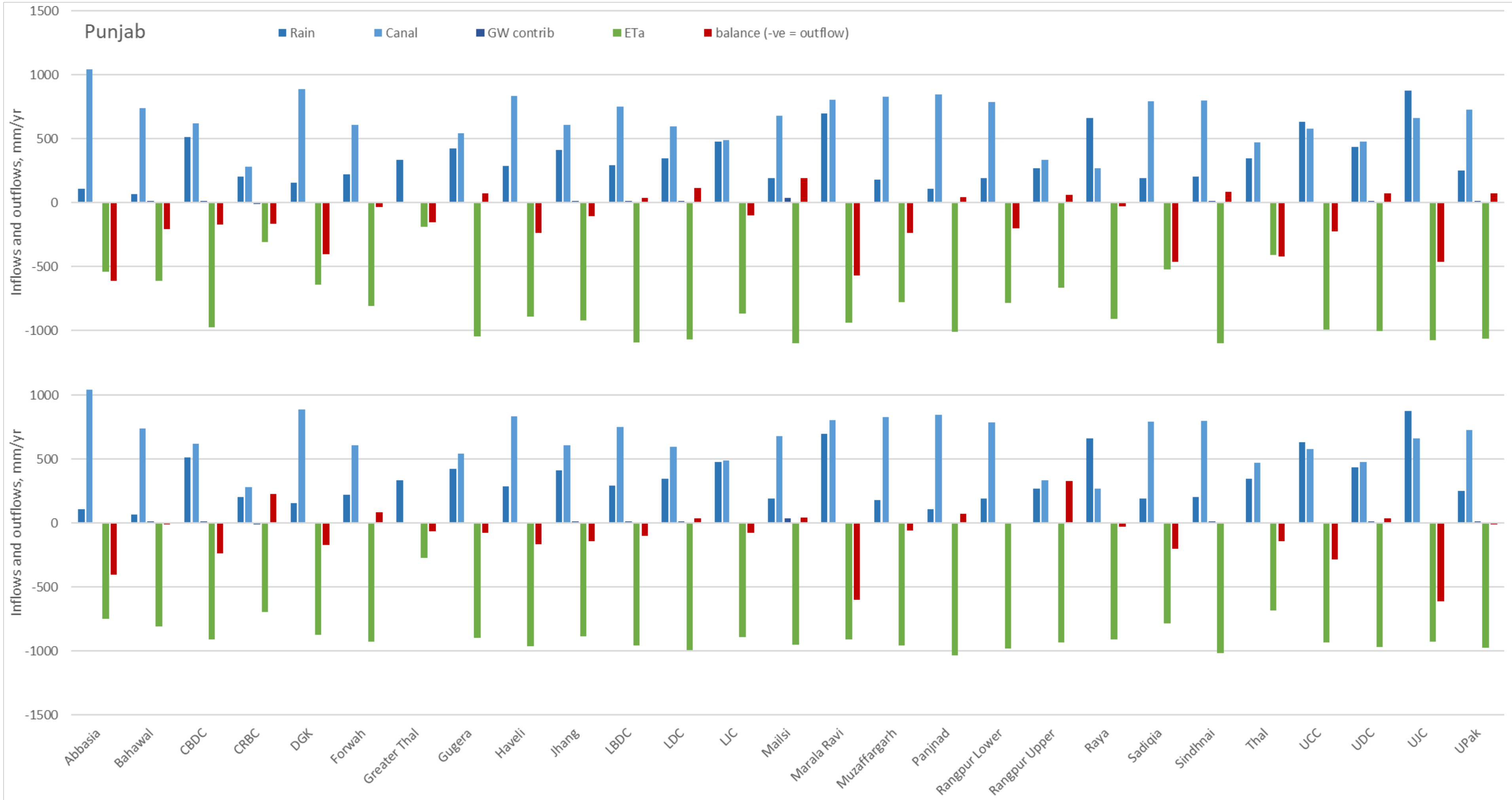


Figure 4 Measured historical (1981–2013) water balance terms for the canal commands of Punjab. The top plot is for the ETLook actual evapotranspiration assessment, whereas the bottom plot is for the CMRSET assessment. The rainfall, canal deliveries and groundwater terms are the same in the two plots

We therefore abandoned the use of models. We focussed instead on relative changes to inflows and outflows, and hence whether there may be more or less water relative to future demand. For example, if in a future scenario the inflows to a canal command are projected to increase by 200 million cubic metres (mcm) in a year, and evapotranspiration demand is projected to increase by 100 mcm, we conclude that there is an additional 100 mcm which potentially might be used for increased cropping. Alternatively, the additional water could offset the use of groundwater, and hence slow the rate of groundwater depletion in some areas of the Punjab. Conversely, if the inflows are projected to decrease by 200 mcm, and evapotranspiration demand to increase by 100 mcm, we conclude that there is 100 mcm less water than currently, which would lead to decreased cropping. Alternatively, the lesser water could be offset by the use of groundwater, and hence increase the rate of groundwater depletion in some areas of the Punjab.

2.3 Canal command water balances – scenario assessment

In this section we describe first our general approach to the choice of scenarios. We then define the scenarios in terms of the specific data inputs in the subsections to this section. The general approach to the choice of scenarios is outlined in Table 1. The scenarios are designed to address the following questions:

- Comparing 3 and 4 with 2 answers the question "how will I be affected (if I do nothing)?" for the case of dam sedimentation (3), loss of dam storage (4). Note: in this context, business-as-usual (do-nothing) retains current crop areas.
- Comparing 6 with 5 and 3 with 2 answers the question "what can I do about it – will fixing the sedimentation issue make much difference?"
- 7 answers the question "what can I do about it – how much must I change crop areas to satisfy the change in water supply and crop water demand?".

Table 1 The general approach to the scenarios: historical and current, and exploratory future scenarios of changes in Tarbela sedimentation and climate change. The specific scenarios are given in Table 3

Scenario name	IRSM modelling	Water balance modelling
1. Historical experience	Measured canal deliveries (not from IRSM modelling)	Historical data, from 1981 to 2013 CMRSET and ETLook *ETa*
2. Current conditions	Historical inflow sequence Current infrastructure Sedimentation in Tarbela set at 2019 levels	Historical climate CMRSET and ETLook *ETa*
3. Tarbela sedimentation impacts	Historical inflow sequence Current infrastructure Sedimentation in Tarbela set at 2050 levels	Current climate CMRSET and ETLook *ETa*
4. Impacts of no dams	Historical inflow sequence Complete loss of storage	Current climate CMRSET and ETLook *ETa*
5. Combined climate change and Tarbela sedimentation impacts	Historical inflow sequence scaled to account for climate change Current infrastructure Sedimentation in Tarbela set at 2050 levels	Future climate CMRSET and ETLook *ETa* (projected)
6. impact of managing Tarbela sedimentation	Historical inflow sequence scaled to account for climate change Current infrastructure Sedimentation in Tarbela set at 2019 levels	Future climate CMRSET and ETLook *ETa* (projected)
7. impact of changed supply and demand on crop areas that may be grown	For all of the above scenarios, assess the change in crop areas and hence crop water use that are equivalent to the change to water inflows and crop water demand	

2.3.1 Current conditions scenario

This scenario acts as a base case. In the other scenarios (of climate change, etc.), we will assess the change from current conditions in the water inflows (rain and canal deliveries) and crop water demand (crop evapotranspiration demand). The current conditions are given by the same inputs as the historical case, except that modelled canal deliveries are used in place of the measured canal deliveries. In the future scenarios, the canal deliveries are all modelled. Thus, when we compare a future scenario with modelled future canal deliveries to the current scenario, we will be comparing like with like – modelled future canal deliveries to modelled current canal deliveries.

2.3.2 Sedimentation and no dam scenarios

The two scenarios are defined by Stewart at al. (2020) and impact the canal deliveries to the canal commands in Punjab.

2.3.3 Urban water scenarios

In the Sindh study, we considered the impact of the water supply to Karachi (Ahmad et al., 2020a). Karachi's water supply is mostly sourced from the Indus. The water leaves the river basin and does not return, so it affects the overall availability of water for other irrigation in the canal commands. In that study, we showed that much of Hyderabad's water supply, by contrast, remains in the basin. Although we do not have actual data for cities in the Punjab, in general urban development results in less evapotranspiration and more runoff than the natural landscape (Oke et al., 2017). The water inflows to the city are therefore mostly returned to the environment, albeit at an often degraded quality, and are available for use in irrigation (Young et al., 2019). In the case of the Punjab, all water supplied to urban centres remains in the basin. It therefore does not much impact the water balance at the province level. We therefore do not consider urban water use in this report.

2.3.4 Climate change scenarios

Cropping opportunities and the water balance in the canal commands will depend on the water availability from rain and canal deliveries, and by the evaporative demand. These will all change with climate change.

Climate change in the Upper Indus Basin

The canal deliveries will be affected by climate change in the Upper Indus Basin. Several climate change scenarios were evaluated using the Indus River System Model (IRSM), and described in the companion report (Stewart et al. 2018, 2020). For the water balance study reported here, we used the scenarios that resulted in the greatest and least flows to Punjab, and hence the greatest and least canal deliveries to the canal commands in Punjab.

Climate change in Punjab

The water balance and cropping opportunities will be affected by climate change within Punjab. For the water balance study reported here, we used climate change scenarios that resulted in a dry and a wet climate in Punjab. We used a three-stage process to select the climate change scenarios. In the first stage, we screened for GCM models that seemed adequately to model the climate of Punjab. In the second stage, from amongst the screened set we selected five GCM models that showed the range of projected future changes to rainfall and potential evapotranspiration. In the third stage, from amongst the five we selected the two that gave the wettest and driest projected climate.

We developed projections of changed climates for the period 2046 to 2075, for the canal commands based on an empirical downscaling or change-factor approach (Zheng et al., 2018). We did not apply the approach to all GCMs, since some appear to simulate rainfall in Punjab poorly, and downscaling the results for future scenarios appeared to give unreasonable results. We therefore applied the approach to five sets of GCM (general circulation model) outputs that appear to give reasonable projections, as outlined in Appendix B. The five were chosen to give a contrasting changes in rainfall and potential evapotranspiration in Pakistan: average change in rainfall with average change in potential evapotranspiration; most negative (or least positive) change in rainfall with average change in potential evapotranspiration; most positive change in rainfall with average change in potential evapotranspiration; average change in rainfall with most negative (or least positive) change in potential evapotranspiration; and, average change in rainfall with most positive change in potential evapotranspiration. The projected potential evapotranspiration calculated with this procedure was combined with the estimates of actual evapotranspiration to calculate projected actual evapotranspiration according to:

$$ETa\ (month, scenario) = ETa\ (month, historical) * ETo\ (month, scenario) / ETo\ (month, historical) \quad (3)$$

This scaling approach was used by Ahmad et al (2019) to derive the extrapolated historical time series of actual evapotranspiration, and is adapted here to derive projected climate change time series.

The average rainfall of the canal commands, averaged for Punjab province, is shown in Figure 5, for the historical period of 1981–2013, and for the five climate change scenarios. (Note: these figures were calculated from monthly totals. The early Kharif rainfall was calculated as April + May + June / 3. The late Kharif rainfall was calculated as June x 2 / 3 + July + August + September. The Rabi rainfall was calculated as the sum of the remaining months.) Figure 5 shows the projected rainfall of the scenarios as a ratio with historical period, for the early Kharif, late Kharif and Rabi seasons, and for the annual total. Figure 5 shows that the annual rainfall is projected to increase in three of the five climate change scenarios, and decrease in two. The total annual rainfall for the canal commands over the historical period was 353 mm, and the projected annual totals vary from 362 (using ccsm4, and 382 using miroc-esm) to 518 mm (using fgoals-s2).

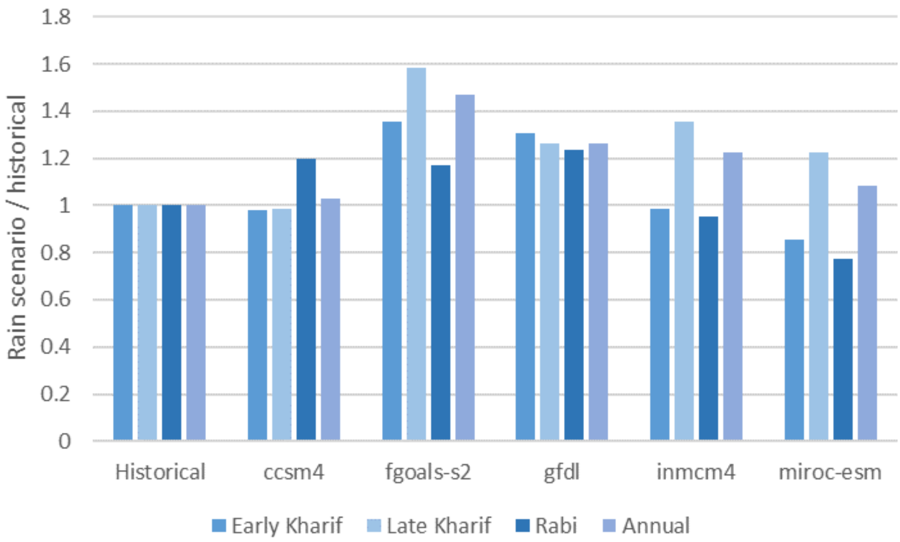


Figure 5 Average rainfall of the canal commands, averaged for Punjab province, for the historical period of 1981–2013, and that projected for five climate change scenarios in 2046–2075 as a ratio of the rainfall in the historical period

The ratios of potential evapotranspiration of scenarios to that in the historical periods were calculated in the same manner as that for rainfall, and are shown in Figure 6. The annual potential evapotranspiration for the historical period was 1950 mm. The variation amongst climate change scenarios is less than that with rainfall, and the differences amongst seasons is also less. The projected annual potential evapotranspiration in all scenarios is greater than that for the historical period, and varies in the scenarios from 1846 (inmcm4) to 1937 (fgoals-s2) mm.

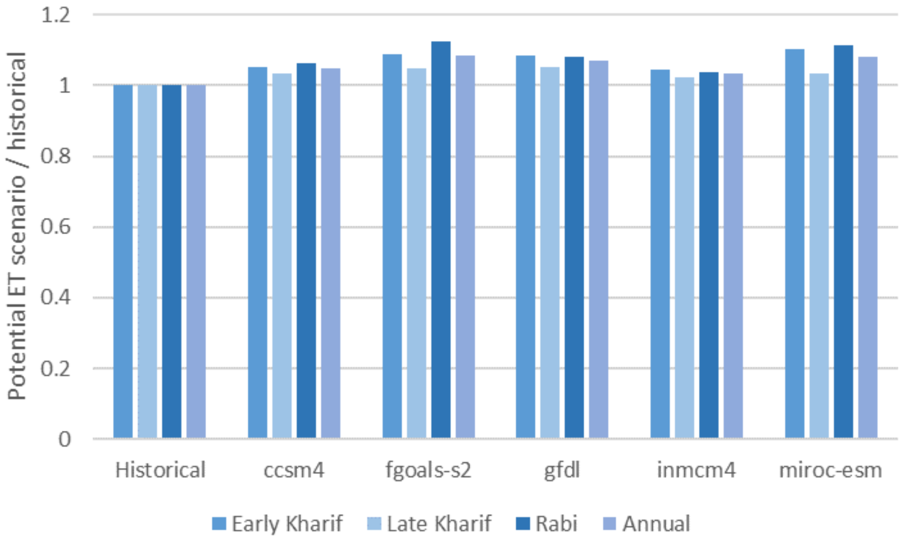
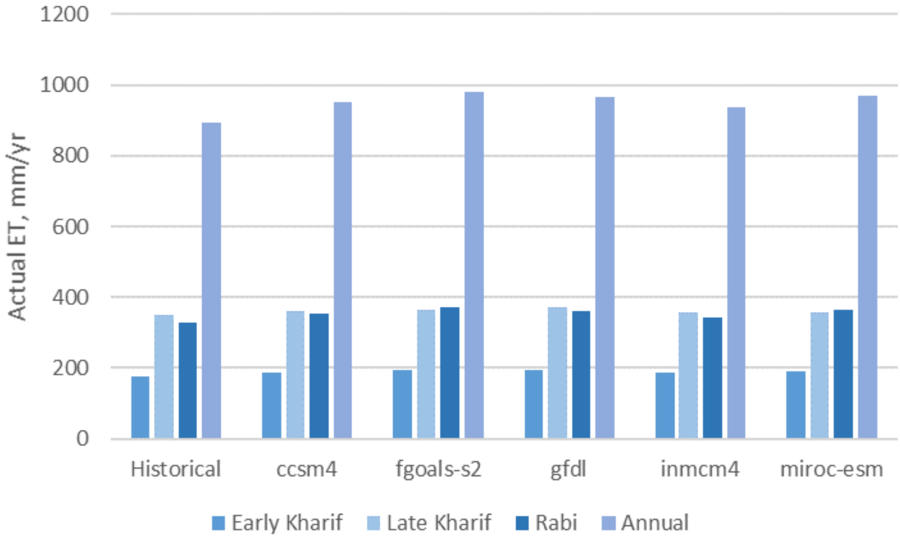


Figure 6 Average potential evapotranspiration of the canal commands, averaged for Punjab province, for the historical period of 1981–2013, and that projected for five climate change scenarios in 2046–2075 as a ratio of the potential evapotranspiration in the historical period

It was shown above in Section 2.2 and Figure 4 that the two methods of estimating actual evapotranspiration resulted in different values. Figure 7 shows the projected actual evapotranspiration (as totals rather than ratios with historical) averaged for Punjab, for the two estimation methods. The two methods give similar projected annual totals, but the CMRSET method results in higher Rabi evapotranspiration and lower Late Kharif evapotranspiration than does the ETLook method.

For the assessment reported here, we further reduced the five climate change scenarios described above to a consideration only of the scenario which (across all canal commands) gave the greatest increase in rainfall (using the fgoals-s2 model to give a 'wet' scenario) and that which gave the least increase or greatest decrease. The least increase was given by the ccsm4 model, but we used the miroc-esm model as the 'dry' scenario, since this was used in the Sindh part of the study. As noted above, the miroc-esm model gives only a slightly greater rainfall than the ccsm4 model.



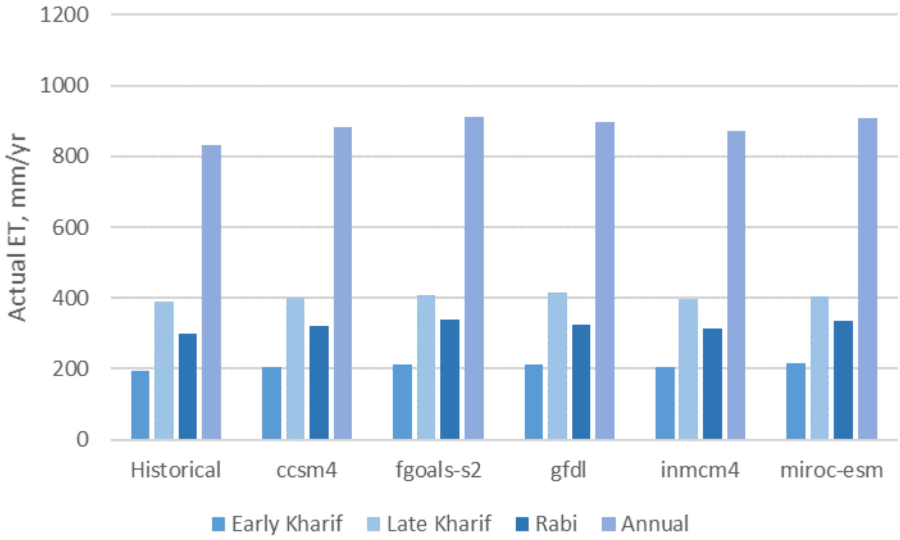


Figure 7 Average actual evapotranspiration of the canal commands , averaged for Punjab province, for the historical period of 1981–2013, and that projected for five climate change scenarios in 2046–2075 as a ratio of the potential evapotranspiration in the historical period. The CMRSET based method is shown in the top plot, and the ETLook based method is shown in the bottom plot

2.3.5 Groundwater behaviour in the scenarios

In assessing the future water availability, we assume that future groundwater levels will behave much as they do currently. As shown in section 2.2, groundwater levels are a small component of the water balance. Measurements show that they are declining at a rate of 110 mm (equivalent to 11 mm depth of water using an assumed specific yield of 0.1), averaged over the area of the canal commands. Canal deliveries have remained approximately the same over recent decades, whereas the area under crops has increased, which has resulted in declining groundwater. We assume that this rate of decline will be maintained. The province of Punjab could change water management such that the rate of decline increases or decreases. However, we do not speculate on potential future management choices.

2.3.6 Specific water balance assessment scenarios

We examined 22 scenarios, comprising 11 based on the ETLook actual evapotranspiration assessment and 11 on the CMRSET assessment.

The first five scenarios for each of the ETLook and CMRSET actual evapotranspiration assessments are for current climate and inflows to the headwaters of the Indus. The first two assess the impact of changed storages in the dams – increases sedimentation at 2050 and no storage in dams.

The next eight scenarios for each of the ETLook and CMRSET actual evapotranspiration assessments are for projected future climate and inflows to the headwaters of the Indus. We also used the scenarios which (across all canal commands) resulted in the highest annual inflows and that which resulted in the lowest. These climate change – inflow scenarios were taken for the two storage cases, current and future storage (the latter being a reduced storage due to continuing sedimentation in the dams).

The complete set of 22 scenarios is shown in Table 3. For each of these scenarios, the components of the water balance in equation (2) were calculated, with the assumption that the year-to-year groundwater level would not change. As discussed in Section 2.2, the groundwater is not much used, and year-to-year groundwater levels at canal command level have generally varied little over the historical period. Thus, the monthly rainfall, canal deliveries, and actual evapotranspiration were taken, and the monthly balance term, B, was calculated for each canal command; all quantities are shown as the equivalent depth of water averaged over the canal command. The canal deliveries, assessed in terms of volumes in the IRSM river modelling (Stewart et al. 2020, companions report), were divided by the canal command areas to give the results in depth of water.

For presentation, the results were aggregated to the whole of Punjab province, and also aggregated to annual, early Kharif, late Kharif, and Rabi seasons.

Table 2 Details of the 22 water balance assessment scenarios. The final two columns give the description used in this report to identify each scenario

Punjab climate	Indus inflows	Dam storage	ETLook 2007 *ETa*	CMRSET 2000-2013 *ETa*
Historical	Historical	Current	Current ETLook	Current CMRSET
Historical	Historical	Future	Dam sedimentation 2050	
Historical	Historical	No Dams	No Dam	
Future, dry (miroc)	Future, low inflows	Future	Low flow, dry Punjab	Climate change + sediment
Future, dry (miroc)	Future, high inflows	Future	High flow, dry Punjab	Climate change + sediment
Future, wet (fgoals)	Future, low inflows	Future	Low flow, wet Punjab	Climate change + sediment
Future, wet (fgoals)	Future, high inflows	Future	High flow, wet Punjab	Climate change + sediment
Future, dry (miroc)	Future, low inflows	Current	Low flow, dry Punjab	Climate change only
Future, dry (miroc)	Future, high inflows	Current	High flow, dry Punjab	Climate change only
Future, wet (fgoals)	Future, low inflows	Current	Low flow, wet Punjab	Climate change only
Future, wet (fgoals)	Future, high inflows	Current	High flow, wet Punjab	Climate change only

All data were spatially averaged for each canal command. The various terms in the water balance were temporally averaged to give average annual, Kharif and Rabi water balances.

2.3.7 Changed cropping resulting from the scenarios

As discussed in Section 2.2 and as shown in Figure 3, crop areas in Punjab generally have generally increased over recent decades, using groundwater to make up for any deficiencies in canal deliveries. We assume that future cropping in Punjab will continue to access groundwater and that groundwater levels will continue to fall at the current rate. Under this assumption, to keep the rate of groundwater decline unchanged, crop areas must increase or decrease according to the change in water availability and demand. This can be stated in an equivalent form: that the change in crop areas will be such as to keep the difference or balance term, B, in equation (2) at its current level. This leads to a simple, approximate means of assessing the change in crop areas.

For several assumed cropping scenarios discussed below, the change in crop area required to restore the balance term to its current level was calculated. The required change in area was calculated for each of the 23 years in the scenarios. The future cropping scenarios are shown in Table 4. Wheat grows into the early Kharif season (Ullah et al., 2001), but we assume that most of the irrigation requirement (including an initial wetting up of the soil) takes place in the Rabi period. The modest amount of water required for sugarcane in the Rabi season is due to the assumed growing season from February to about November, with little growth in December and January, based on the crop calendar in Ullah et al. (2001). This growing season combined with the lower potential evapotranspiration in the Rabi season results in most of the water requirement of sugarcane occurring in the Kharif season; however, we assumed some additional water is required in the Rabi season for initial wetting of the soil.

Table 3 Cropping scenarios: the crops in the table are those for which the change in area required to restore the water balance term, B, is calculated

Crop	Season
1. Rice	Kharif
2. Cotton	Kharif*
3. Fodder	Kharif*
4. Wheat	Rabi
5. Sugarcane	Rabi
6. Fodder	Rabi#

* Some crops, of which cotton and Kharif fodder are examples, may be currently planted from early Kharif onwards. We here assess the change in area required to restore the balance for Kharif as a whole. In some places and in some years, the early Kharif supplies calculated in the scenarios may not be adequate for the assumed area; in such cases, we assume that there will be shift in the planting time.

Sugarcane grows throughout the year but, as we will show, the Rabi season water balance is the most impacted by the various scenarios. Thus, a requirement to change the area of sugarcane to restore the Rabi water balance will determine how much sugarcane is grown throughout the year.

The change in area of crops required to restore the balance to the current level is calculated from the change in canal deliveries and the crop water requirement:

$$\Delta A = \frac{A_{cc}\left(I_{cw,scen} - I_{cw,base}\right)}{\left(\left(\frac{ET_{o,scen}}{ET_{o,base}}\right) CWR_{crop} - P_{scen}\right)/IE} \tag{4}$$

in which $I_{cw,scen}$ and $I_{cw,base}$ are the canal deliveries in a scenario and in the base case, $ET_{o,scen}$ and $ET_{o,base}$ are the potential evapotranspiration in a scenario and in the base case, CWR_{crop} is the current crop water requirement of the crop under consideration (calculated as *ETww* using a crop coefficient approach with the crop coefficients based on Ullah et al., 2001), P_{scen} is the rainfall in a scenario, and *IE* is the irrigation efficiency – the fraction of diverted water that reaches the plants and contributes to the crop evapotranspiration. The term A_{CC} ($I_{cw,scen} – I_{cw,base}$) is the volume of additional canal deliveries. ($ET_{a,scen}$ / $ET_{a,base}$) CWR is the crop water requirement corrected for future demand, and (($ET_{a,scen}$ / $ET_{a,base}$) CWR – P_{scen}) is then the crop water requirement after rainfall is accounted for.

The irrigation efficiency is generally regarded as low in Pakistan in general and in Punjab in particular. The major part of the water is lost from the canals and field channels though evaporation or seepage. However, estimates of the actual value of irrigation efficiency vary widely; most are for the Indus basin as a whole, with few specific to Punjab. (It should also be noted that literature estimates use various bases for assessing irrigation efficiencies, sometimes including river losses. Here we are concerned with the losses in the canals and fields from the diversion point to the point of use of the crops – ie the root zone.) Azad et al. (2003) quote a value for Punjab province of 35 % from the canal head to the crop root zone. Hussain et al. (2011) quote a similar value for the Indus basin as a whole, but this includes the losses in the rivers; excluding the river component of their calculation leads to an irrigation efficiency of about 50 % from the canal head to the root zone. Qureshi (2011) quoted a figure of around 35 to 40 % (whole basin). Bhutta and Smedema (2007) suggested that losses from canals and fields (whole basin) are around 30 to 40 %, implying an irrigation efficiency of 60 to 70 %. Yu et al (2013, their Table 5.1) give watercourse (ie river), canal and field efficiencies for each province of Pakistan; the figures imply a canal-to-rootzone efficiency of 64 % for Punjab.

In the companion report on Sindh (Ahmad et al., 2020), we estimated the irrigation efficiency from the measured changes in crop area and canal deliveries. The method cannot be used in the case of the Punjab because much of the water used for irrigation comes from groundwater.

We therefore used a figure of 65 % for the irrigation efficiency, consistent the figures from the literature noted above.

The calculation in equation (4) does not return the whole of the canal command balance to the current level; it deals only with the irrigated area within a canal command. We assume that the rest is “self-adjusting”, in the sense that if rainfall reduces, then evapotranspiration of non-irrigated areas will also reduce, whereas if rainfall increase, so too will evapotranspiration – or, with groundwater levels close to the surface, there will be runoff to remove the excess water.

3 Water balance scenario results

In this section of the report, we outline the results of the water balance scenario assessments. We show the water balance terms for the Punjab province, given as equivalent depth in mm per year or mm per cropping season. The results are given as annual water balances and for the Kharif, early Kharif, late Kharif and Rabi seasons. After a brief description of the rainfall, actual evapotranspiration and canal delivery results, we will focus particularly on how the difference between the supply of water and evapotranspiration demand is changed by the various scenarios in the different seasons. (This may be alternatively stated as how the balance term changes with the scenarios.) We also assess which scenario effect has the greatest impact on changes in the balance term, using the logic of Section 2.2 to examine the differences amongst scenarios. Finally, we describe the change in crop areas required to adjust the water use to match the change in the supply and demand for water.

In what follows, we shall for brevity show mainly only the results for the scenarios using the ETLook method for assessing actual evapotranspiration. The CMRSET method led to different values for actual evapotranspiration. However, the manner in which the actual evapotranspiration changes from scenario to scenario is very similar for the two methods. For comparison of the two methods, we show the results for the base case (current conditions) of the ETLook and CMRSET methods, but we do not show the other scenario results for the CMRSET method.

Note that in what follows, there are repeat effects in the presentation of the scenarios. For example, the first three scenarios all have current climate. The values for rainfall and actual evapotranspiration will therefore be identical in these scenarios; other values will show repeats in other scenarios.

3.1 Rainfall

The annual and seasonal rainfalls in the various scenarios are summarised in Figure 8. (The interpretation of box and whisker plots used in this section is given in Appendix A.) The median annual rainfall from 1990 to 2013, averaged across the canal commands of the Punjab, was 331 mm, with the wettest year of 484 mm in 1997 and the driest of 192 mm in 1999. (The whole period from 1999 to 2002 was exceptionally dry, with an average annual rainfall of 247 mm.) The median annual rainfall in the wet scenario increased to 538 mm, with a corresponding wettest year of 723 mm, and increased to only 368 mm in the dry scenario with a corresponding wettest year of 560 mm.

3.2 Actual evapotranspiration

The annual and seasonal actual evapotranspiration in the various scenarios are summarised in Figure 9. The median annual actual evapotranspiration from 1990 to 2013, averaged across the canal commands of the Punjab, was 877 mm using the ETLook method. For ETLook, the maximum year was 916 and the minimum was 826. The median annual actual evapotranspiration in the wet scenario increased to 963 mm, with a corresponding maximum year of 1007 mm, and to 956 mm in the dry scenario with a corresponding maximum year of 999 mm. Using the CMRSET method, the medians were 885 for the current scenario, 974 for the wet scenario and 967 for the dry scenario. The difference between ETLook and CMRSET was 8 mm and 11 mm for the wet and dry scenarios.

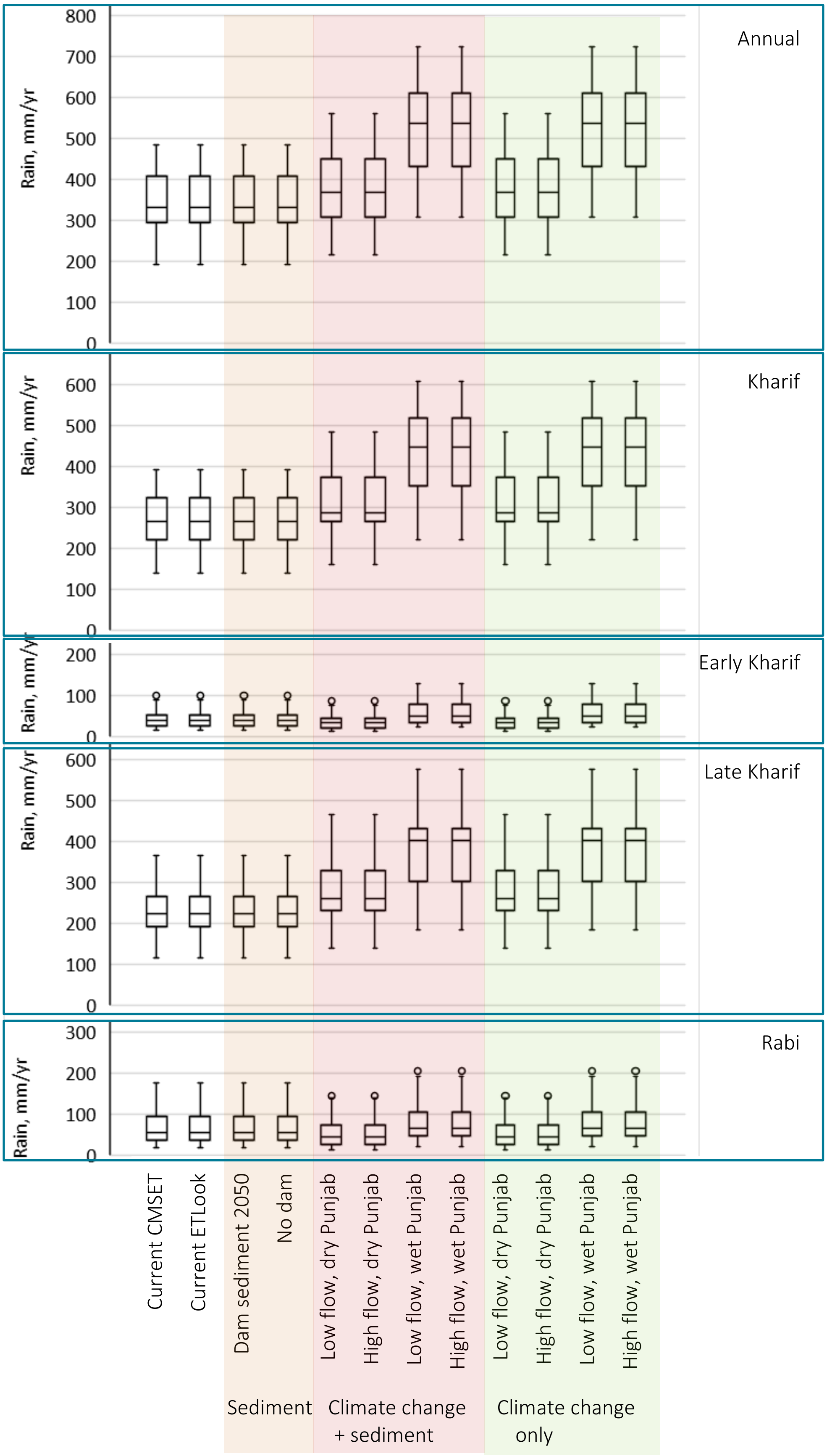


Figure 8 Rainfall in the scenarios; annual (top), Kharif (2nd plot), early Kharif (middle), late Kharif (4th plot), Rabi (bottom). The coloured panels show groups of similar scenarios

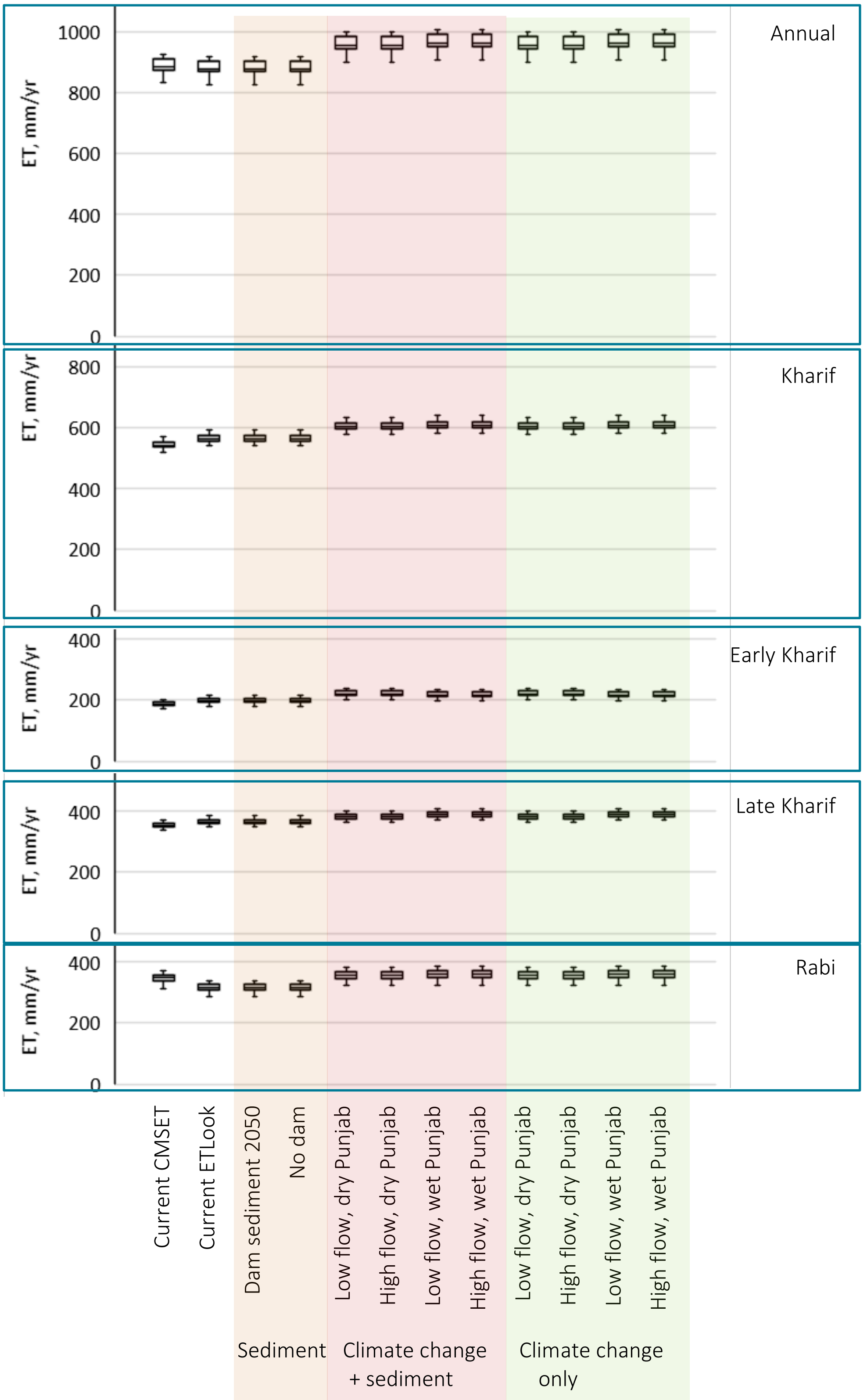


Figure 9 Actual evapotranspiration in the scenarios; annual (top), Kharif (2nd plot), early Kharif (middle), late Kharif (4th plot), Rabi (bottom). The coloured panels show groups of similar scenarios. Note that the scale for the annual plot (top) does not start at zero

3.3 Canal deliveries

The canal deliveries in the various scenarios are summarised in Figure 10. The deliveries were taken from the companion report (Stewart et al., 2020), where they are reported in terms of percent change from the baseline. Note that in the water balance climate change scenarios we have used only the inflow scenarios that resulted in the greatest and least canal deliveries in the IRSM canal delivery modelling in the companion report (Stewart et al., 2020). Here we show the actual volumes delivered (shown as a depth equivalent), since this is what is used in the water balance. The median depths delivered annually vary from 373 mm (low inflows with no sedimentation) to 398 mm (high inflows with sedimentation).

Sedimenting of the storages, leading to loss of dams altogether, results in annual total deliveries somewhat lower than the corresponding no-sedimentation scenario (as shown by the right-hand box plot in the light brown panel in Figure 10). However, the impact of 2050 sedimentation is small. Canal deliveries from no dams are somewhat higher in Kharif (and in early Kharif), but much lower in Rabi. The higher canal deliveries in Kharif result from the lack of storage with the loss of dams, and hence Kharif flows cannot be captured and stored; they therefore flow on past the dams. Conversely, in Rabi, no water is stored in the dams to augment Rabi flows and canal deliveries.

The climate change impacts in the upper Indus result in somewhat decreased annual and seasonal deliveries in the low flow scenarios (first and third box plots in the light red and light green panels), and somewhat increased annual and seasonal deliveries in the high flow scenarios (second and fourth box plots in the light red and light green panels).

3.4 Impact of scenarios on the change in water availability and demand

We described in Section 2 that the assessment of the likely impact of future scenarios (such as climate change) is to be made in terms of the relative changes to inflows and outflows, and hence whether there may be more or less water relative to future demand. This is equivalent to assessing the change in the balance term in equation 2. Figure 11 shows the change in the balance term, annually and seasonally. As discussed in the previous section, the balance term in the Kharif and Rabi seasons included the effect of ignoring the changes in seasonal soil water and groundwater storage. However, this effect is largely eliminated in the change in the balance term.

The change in the balance term varies from negative to positive in different scenarios. A negative change in balance means reduced water availability to satisfy the anticipated actual evapotranspiration, whereas a positive change in balance means increased water availability to satisfy the anticipated actual evapotranspiration. The 2050 sedimentation scenario shows little change from the base case. The no dams scenario shows a negative change in the balance annually and in the Rabi season, but positive in Kharif. This is due to the change in canal deliveries, which are greater in Kharif if there is no dam storage to fill, hence reducing Kharif flows. The climate change impacts (both the climate change in Punjab and the climate change consequences on flows in the Indus and hence canal deliveries) vary from a negative change in balance to a positive; changes in Kharif, especially late Kharif are generally more positive, whereas those in Rabi are generally negative. While the 2050 sedimentation scenario showed little change from the base case, there is a difference between the climate change plus sedimentation scenarios and the climate change only scenarios; in Rabi, there is reduced water availability in the sedimentation plus climate change case, showing that the 2050 sedimentation does have an impact. Thus the general expectation resulting from the scenario projections is that there may be more water to satisfy the anticipated actual evapotranspiration in Kharif and less in Rabi. However, in both seasons, the opposite is possible though less frequent in the projections.

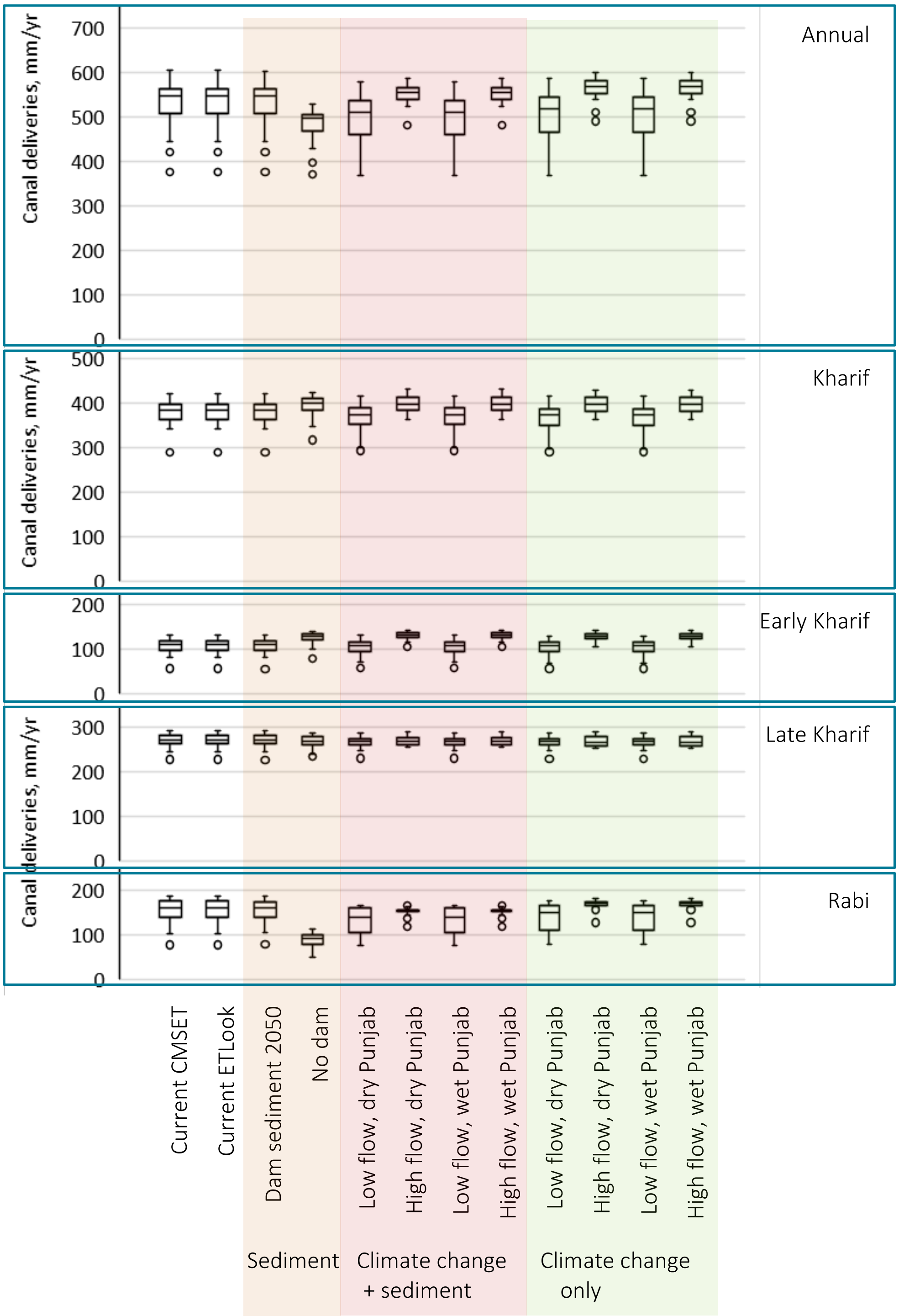


Figure 10 Canal deliveries in the scenarios ; annual (top), Kharif (2nd plot), early Kharif (middle), late Kharif (4th plot), Rabi (bottom). The coloured panels show groups of similar scenarios. Note that the scale for the annual plot (top) does not start at zero

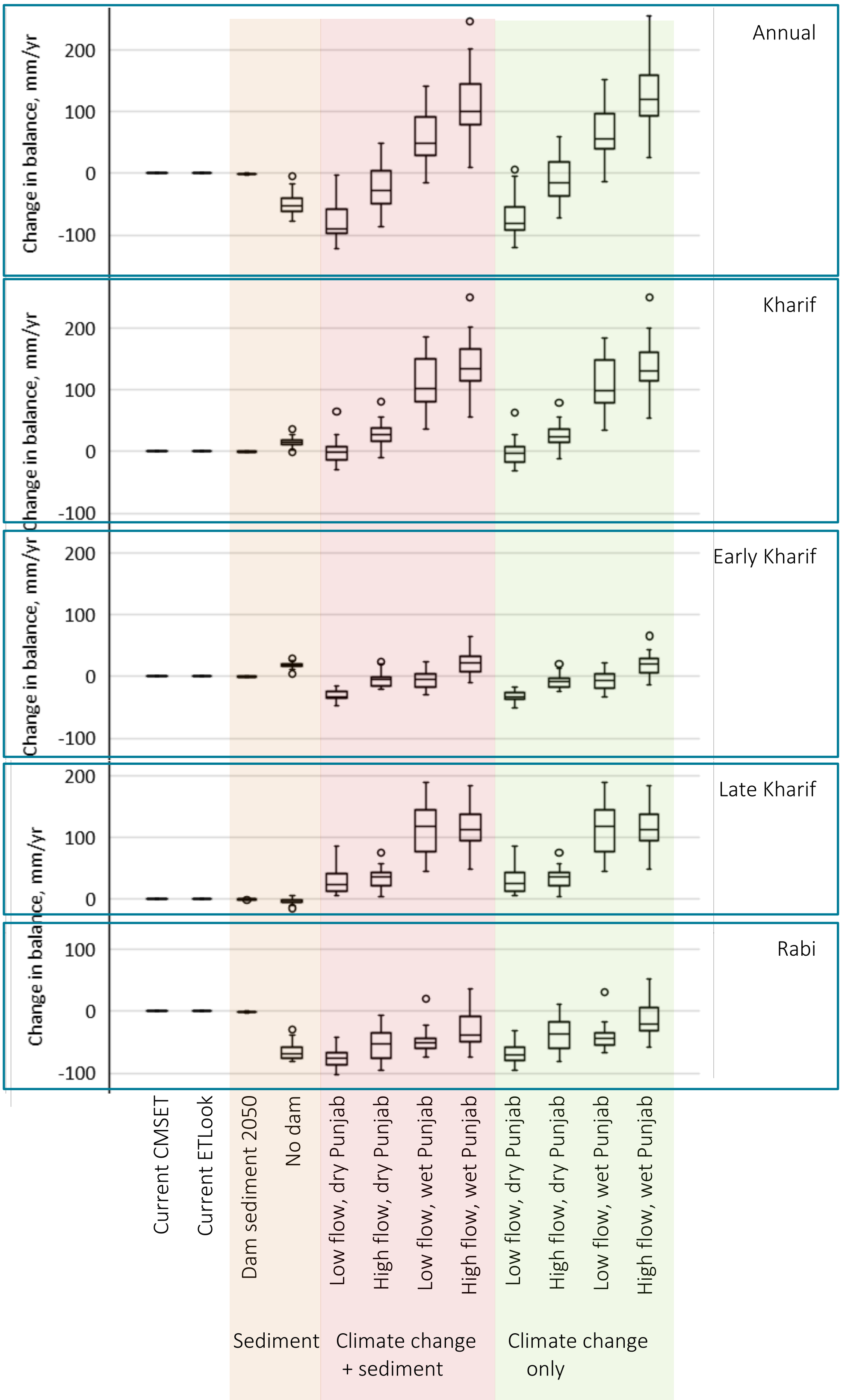


Figure 11 The change in the balance term, B (equation (2), in the scenarios ; annual (top), Kharif (2nd plot), early Kharif (middle), late Kharif (4th plot), Rabi (bottom). The coloured panels show groups of similar scenarios

3.5 Magnitude of different scenarios components

The scenarios were developed in a way that allowed separation of the individual effects of dam sedimentation, climate change in Punjab, and climate change in the Upper Indus as it affects river flows and canal deliveries. They also allow a comparison of the consequences of using the ETLook method and the CMRSET method of estimating actual evapotranspiration.

Making this separation is done using the change in balance term results shown in Figure 11. For each scenario effect, the assessment is done as follows:

- For the no dams effect the scenario impact is simply the change in balance in the scenario minus the base case, or in other words (No dams - Current ETLook).
- For the sedimentation effect, the scenario impact is the average change in balance in scenarios with dam sedimentation minus the corresponding scenarios without dam sedimentation.
- For the effect of climate change within Punjab, the scenario impact is the average change in balance in wet climate scenarios minus the corresponding dry climate scenarios. Note that unlike the impact of sedimentation, this is the magnitude of the range of climate effects from wet to dry, not the change from the current climate to a future climate.
- For the effect of change of canal deliveries to Punjab, the scenario impact is the average change in balance in high flow scenarios minus the corresponding low flow scenarios. Note that this is the magnitude of the range of flow effects from high to low, not the change from the current flows to future flows.
- For the impact of the method of actual evapotranspiration estimation is the average of all the ETLook scenarios minus the average of the corresponding CMRSET scenarios.

The magnitude of scenario impacts resulting from the calculations are shown in Figure 12. Annually and seasonally, the impact of the local climate (rainfall plus evapotranspiration demand in the Punjab) is the largest, followed by the impact of flows on canal deliveries, then the no dams scenario, and then the sedimentation scenarios. While this is the general picture, in some seasons the order of the magnitude of some effects is reversed.

The picture in the Punjab differs somewhat from that in Sindh. The climate change in Sindh generally had the least impact on the change in the balance term (Ahmad et al., 2020a). The rainfall averaged across the canal commands in Sindh is about half that for the canal commands in the Punjab, so changes to the rainfall have a smaller impact than in the Punjab. Because of the greater importance of rainfall and also the use of groundwater, the impacts of 2050 dam sedimentation are smaller in the Punjab than in Sindh.

It is particularly notable that the choice of method of actual evapotranspiration estimation makes almost no difference. This repeats the observation in section 3.2 that while the actual evapotranspiration estimated by the two methods differs, the difference between any corresponding pair of scenarios was the same. This was also found in the Sindh study (Ahmad et al. 2020a).

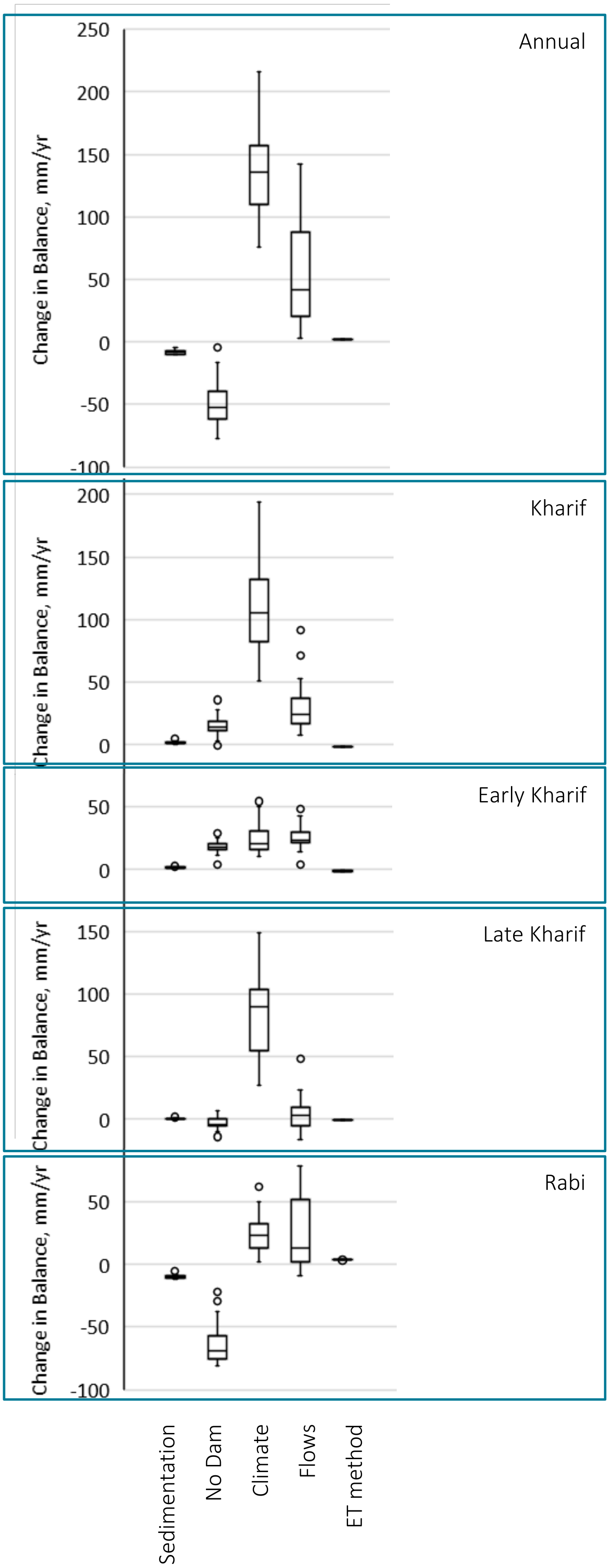


Figure 12 The magnitude of scenario impacts; annual (top), Kharif (2nd plot), early Kharif (middle), late Kharif (4th plot), Rabi (bottom

3.6 Changing crop areas

As discussed in Section 2.3.7, the crop areas in Punjab have historically increased with the use of greater quantities of groundwater. We calculated the change in crop areas that would result in a change in water use equivalent to the changes in water availability and evapotranspiration, which would represent an increase or decrease in area from the currently cropped area. We emphasise that this is an approximate calculation. The Punjab could choose to carry on increasing the area at the same rate as in the last few years, and adjust the use of groundwater accordingly. Based on the findings of many studies, this would continue an already unsustainable water use. Alternatively, to ensure sustainability, further use of groundwater could be capped, which would limit the further expansion of cropped areas (though this appears unlikely based on past performance). Under such scenarios, our calculations below are irrelevant. The calculations are therefore merely indicative of the areas of cropping that can be viewed as equivalent to the changes in water availability and demand. They are not predictions or projections of what might happen.

The required change in area of the three Kharif crops (rice, cotton and fodder) is shown in Figure 13, with the three Rabi crops (wheat, sugarcane and fodder) shown in Figure 14.

In the Kharif season, the greater canal deliveries plus increased rain in some scenarios lead to an opportunity to plant a greater area of crops, generally of up to about 3 000 000 hectares more. (The figures quoted here and below are the approximate median areas.) However, in scenarios with low flows and a dry future climate there is a decline in the area that may be planted of up to about 1 500 000 hectares. The changed areas could be by planting a different area of just one of the crops, or of all three (or other) crops in combination. For comparison, the areas planted to rice, cotton and fodder in 2013-14 were respectively 1 809 000, 2 199 000 and 1 835 000 hectares, or in total 5 843 000 hectares. With other Kharif crops, the total Kharif area in 2013-14 was around 7 928 000 hectares.

In the Rabi season, the lesser canal deliveries plus decreased rain and increased evapotranspiration requirement in some scenarios generally lead to a reduction area of crops that can be planted, generally of up to about 3 000 000 hectares, though more in the case of the no dam scenario. In the companion report on river flows and canal deliveries (Stewart et al., 2020), it was shown that the no dam scenario leads to about a 35% reduction in canal deliveries in Sindh in the Rabi season, which leads to a large reduction in crop areas in this scenario. In scenarios with no dam sedimentation and increased canal deliveries, there may be an opportunity to increase areas of crops by up to about 1 500 000 hectares. The changed areas could be by planting a different area of just one of the crops, or of all three (or other) crops in combination. For comparison, the areas planted to wheat, sugarcane and fodder in 2013-14 were respectively 6 925 000, 757 000 and 1 835 000 hectares, or in total 9 517 000 hectares. With other Rabi crops, the total Rabi area in 2013-14 was around 11 206 000 hectares, greater than the total area of Kharif crops. However, the Rabi areas are province totals and include areas of rainfed wheat and pulses. Some crops such as sugarcane, fodder and tree crops grow in both seasons. The no dam scenario leads to greater reductions, equivalent to more than the total area of wheat. In the climate change plus sedimentation case, the areas of crops that can be planted are all less than in the base case, whereas with climate change only, greater areas of crops can be planted in the wet future climate scenarios. 2050 sedimentation thus has a negative impact on projected future cropping.

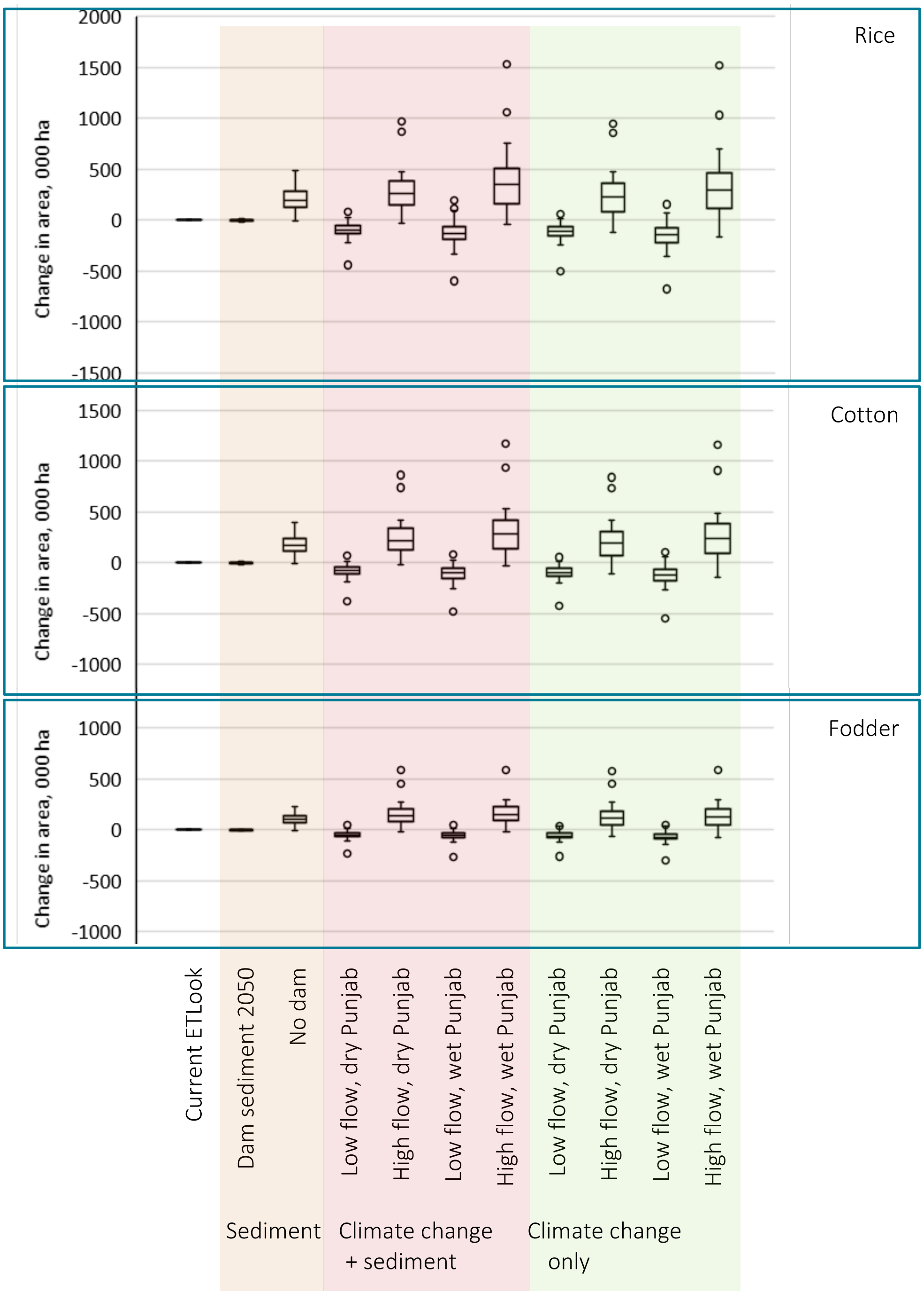


Figure 13 Range of change in areas of Kharif rice, cotton and fodder crops under the 10 exploratory future scenarios. The coloured panels show groups of similar scenarios

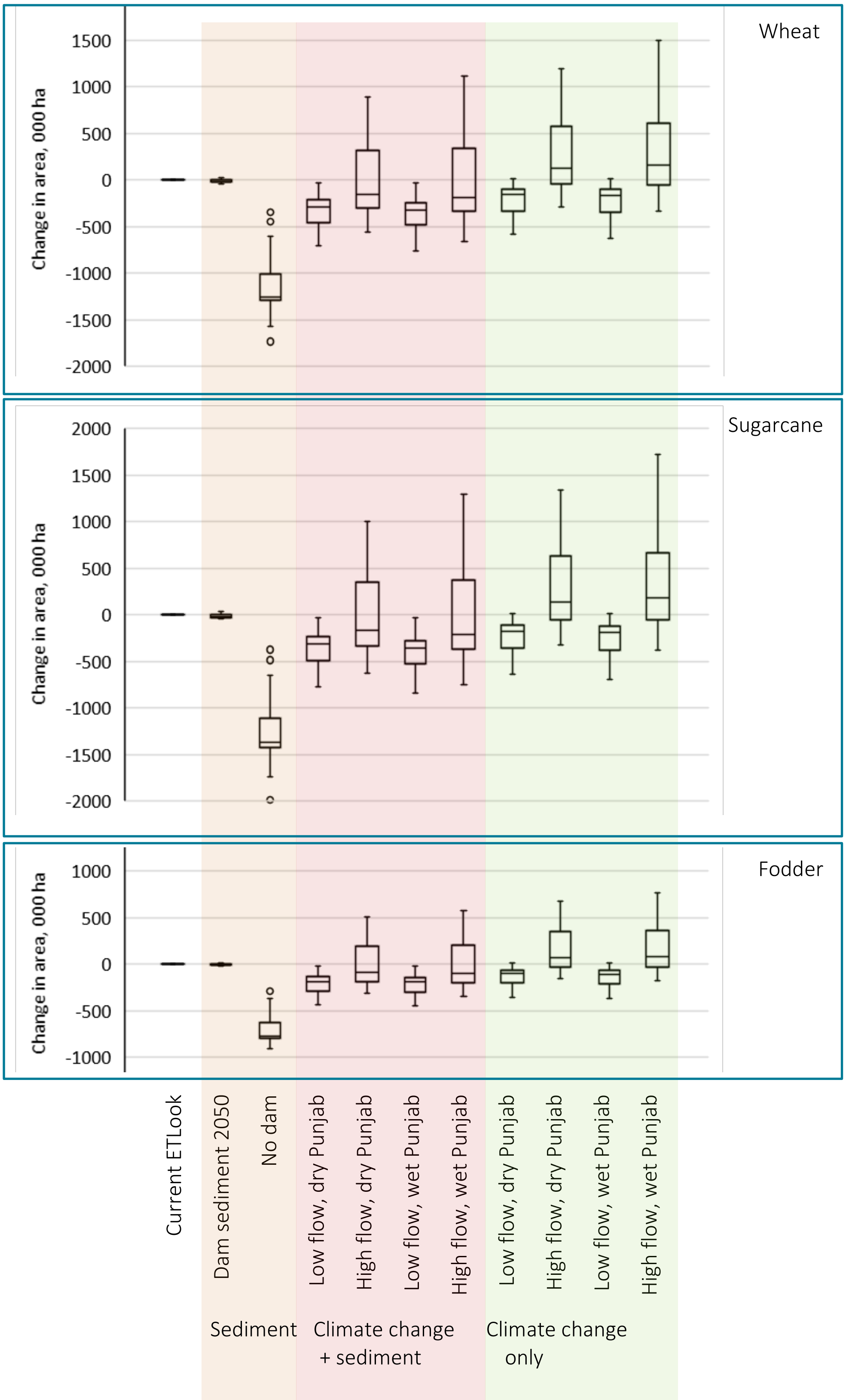


Figure 14 Range of change in areas of Rabi wheat, sugarcane and fodder crops under the 10 exploratory future scenarios. The coloured panels show groups of similar scenarios

4 Discussion: opportunities for dealing with the impacts

The scenario results described in the previous section show that the water availability for irrigated agriculture in Punjab may increase or decrease due to climate change in the Upper Indus Basin, due to local rainfall in Punjab, and due to sedimentation of dam storages. The impacts of the various scenarios suggest that, if the current level groundwater use is to continue, the area that may be planted to crops will change in the future, with increased areas and decreased areas both possible. However, groundwater use in the Punjab could change to offset the impacts of changed water availability and demand. Water availability and food security in Pakistan are very challenging, though there are options for meeting the challenges (Kirby et al., 2017). The potential decreases in water availability and adverse impacts on the water balance will increase the challenges, and make more urgent the implementation of potential opportunities.

In this section we discuss some alternative opportunities for dealing with the impacts.

4.1 Canal conveyance efficiency

As discussed in Section 2.3.7, we used estimates of the losses from fields, canals and other water conveyance infrastructure of 35%. Literature estimates vary from about 65% losses to about 30% losses. Water will be lost primarily as evaporation from canals and shallow in-route storages and as seepage from the canals into the groundwater. The groundwater is fresh in some places, particularly in the Punjab and saline in others. Where it is fresh, the seepage recharges groundwater and thus is available to be pumped for irrigation or other uses. Where it is saline, as is the case in some parts of the Punjab and much of Sindh, the seepage cannot be reused (Ahmad et al., 2014). If these losses to saline areas can be reduced, for example by better lining of canals, more water will be made available to irrigation.

However, it should be noted that the water lost as seepage is not actually lost; it must go somewhere. It will add to the groundwater where it will either be used in the local environment, contributing to evapotranspiration some of which might be from local salt tolerant vegetation, or it will flow underground back to the Indus. If the losses are reduced, there may be some impacts on the local non-crop vegetation, and there may also be impacts on the flow of the Indus.

4.2 Crop productivity

Crop yields in Pakistan generally, and Punjab in particular, are low by world standards, and low by comparison with potential yields (Lashari and Mahesar, 2012; Aslam, 2016, Kirby et al., 2017). Some of this is due to choice of crops; Basmati rice (which is favoured in Pakistan), has lower productivity than other rice varieties and, due to its longer growing period, may also impact on timely sowing and hence productivity of a following crop. Some of it is due to less favourable conditions, particularly the more saline groundwater.

Notwithstanding the reasons for some lesser crop productivity, there appear to be opportunities to increase yields generally (Lashari and Mahesar, 2012; Watto and Mugera, 2014; Kirby et al., 2017). In Sindh there are opportunities to increase yields by dealing with problems of waterlogging and shallow saline groundwater (van Steenbergen et al., 2015), though this is less important in the Punjab.

4.3 Crop choices

Pakistan generally, in both the Punjab and SIndh, use a considerable portion of the available irrigation water on crops with high water requirements, particularly rice, cotton, and sugarcane. About half of Pakistan's rice and much of the cotton are exported. In contrast, low water using and high value pulses and oilseeds are largely imported (Kirby, et al., 2017). Changing the mix of crops could result in less water use (Qureshi et al., 2010) and less importation of high value pulses and oilseeds. However, as pointed out by Ahmad and Farooq (2010), domestic food production in Pakistan is regarded as fundamental to economic development, poverty reduction and national security. Therefore, changing to a different mix of crops will require careful economic evaluation and policy development (Vanzetti et al., 2017).

4.4 Water storage maintenance and sedimentation control

The results in the companion report on flows in the Indus river, and in the previous section, indicate that declining water storage volumes due to sedimentation are likely to have a significant impact on the quantity and reliability of irrigation water in Sindh, particularly in the Rabi season. However, the results presented here suggest that the continuation of sedimentation at the current rate will not by 2050 make much difference to water availability in the Punjab. However, long term loss of storage altogether will reduce quantity and reliability of irrigation water in the Punjab. Water storage maintenance and sedimentation control seems therefore not to be as high a priority for the Punjab as it is for Sindh, but may become so in the longer term.

4.5 New storages

Similar to the previous point about water storage maintenance, building storages would seem to be a priority for the Punjab only in the longer term. New storages might be built at multiple scales including on farm, in-route river storage, managed aquifer recharge, and identification and construction of large dams.

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Appendix A Interpreting box and whisker plots

Figure A-1 shows an example box and whisker plot, with the features labelled.

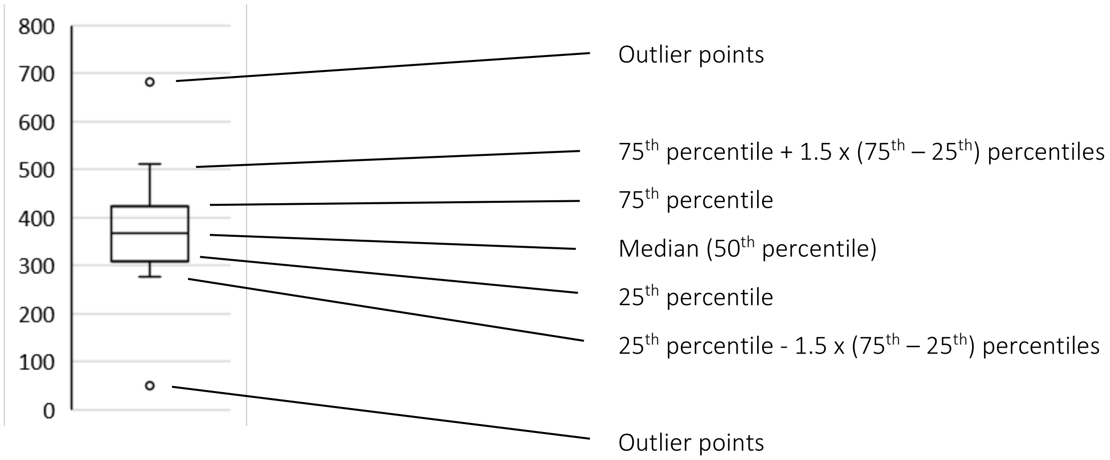

Figure A-1 Interpreting a box and whisker plot

A box and whisker plot is very useful for showing the range of variation. A box and whiskers that are small vertically indicates little variation in the y-axis variable (e.g. crop area), whereas a box and whiskers that are large vertically indicate more variation.

Appendix B Selection of GCMs for use in the study

The results of 37 GCMs were available at the time of the study. However, some of them appeared to give unreasonable rainfall results for Sindh and southern Punjab. In the scaling factor approach used by CSIRO, some months in some locations would be assigned large (sometimes very large) scaling factors. The large scaling factors resulted from dividing a future projected rainfall by a near zero rainfall in the month and location in question. The large scaling factors when applied to the historical data in some cases would in turn lead to unreasonably large rainfalls in that month in other years, when there was a year with a large rainfall in that month. We ignored all GCMs for which this problem occurred. (An alternative approach would have been to make arbitrary manual adjustments to the scaling factors. The 'best' adjustments and the overall consequences of such an approach were not clear, and we deemed the approach not worth pursuing in the time available.) This resulted in a list of 11 GCMs (Table B-1).

Table B-1 List of Global Climate Models (GCMs) selected for use in this study

GCM	Colour circle indication in Figure B-1
bnu-esm_r1i1p1_r45-ave.csv	Blue
cesm1-cam5_r1i1p1_r45-ave.csv	Green
gfdl-cm3_r1i1p1_r45-ave.csv	Purple
fgoals-s2_r1i1p1_r45-ave.csv	
fio-esm_r1i1p1_r45-ave.csv	
noresm1-me_r1i1p1_r45-ave.csv	
miroc-esm-chem_r1i1p1_r45-ave.csv	
cesm1-bgc_r1i1p1_r45-ave.csv	
inmcm4_r1i1p1_r45-ave.csv	Red
ccsm4_r1i1p1_r45-ave.csv	Yellow
miroc-esm_r1i1p1_r45-ave.csv	

The annual rainfall and evapotranspiration scaling factors were selected based on their performance in Sindh, where the results were most problematic. The resulting list of 11 GCMs were plotted for the northern, central and southern parts of Sindh, as shown in Figure B1. Five GCMs were selected such that four covered the range of rainfall and evapotranspiration scaling factors, and one (ccsm4, indicated by yellow in Figure B1) was close to the median rainfall and evapotranspiration scaling factors.

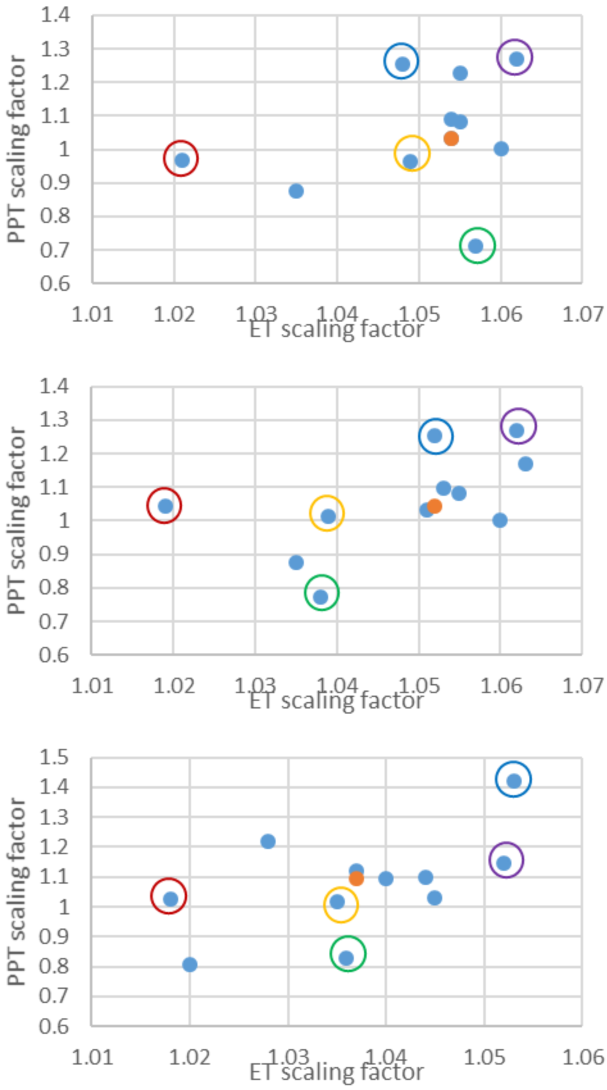

Figure B-1 Rainfall and evapotranspiration scaling factors for northern (top), central (middle) and southern (bottom) Sindh for the 11 selected GCMs indicated by blue points. The coloured circles indicate the GCMs noted in Table B-1. The orange point is the median value of the scaling factors (which in the case of northern Punjab coincides with one of the GCM points)

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