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# Sindh water outlook: Impacts of climate change, dam sedimentation and urban water supply on irrigated agriculture

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*All CSIRO SDIP projects consider gender. In this report we have assumed that an improved, quantitative understanding of the impacts of climate change, dam sedimentation and urban water supply on irrigated agriculture in Sindh 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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# Acknowledgments

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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 Sindh, plus the Pat and desert canals in Balochistan that are supplied from the Guddu barrage in Sindh. The canal deliveries are the main supply of water into the canal commands, whereas the use of groundwater is insignificant, 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 relative change to the annual and seasonal (Rabi and Kharif) water balance from the historical baseline of projected (modelled) future rainfall, actual evapotranspiration, and canal deliveries as affected by climate change in the Upper Indus and in Sindh province, as affected by sedimentation in the main irrigation supply dams, and as affected by increasing the supply of water to Karachi from the Indus River. These changes were captured as a set of 12 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 flows on canal deliveries generally had the largest impact on the water balance, followed by the no dams scenario, then the sedimentation scenarios, then the climate change in Sindh scenarios, and lastly the scenarios of increased urban water supply to Karachi. While this is the general picture, in some seasons the order of the magnitude 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 results.

We conclude that water availability in Sindh may increase or decrease due to climate change in the Upper Indus Basin and due to local climate change in Sindh. Sedimentation of dam storages is projected to lead to 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. A greater future supply of water to Karachi could lead to small reductions in the overall availability of water for irrigation in Sindh (potentially of about 3 % of canal supplies, if all the future water is sourced from the Indus). In the Kharif season, the potential increases in water availability are generally larger than the potential decreases. Conversely, in the Rabi season, the potential increases in water availability are generally smaller than the potential decreases. The potential reductions in crop area in the Rabi season in response to lesser water availability are projected to amount to about 230 000 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 55 % of the wheat crop, 94 % of the fodder crop, or more than the area of sugarcane.

Several strategies will help deal with the impacts, including changing the areas of crops, changing the mix of crops to lower water using crops, finding alternative water sources for Karachi, improving the efficiency of water delivery via the canals, improving crop productivity, and controlling sedimentation in dams.

# 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 that while there is uncertainty in the absolute magnitude of terms in the water balance, we can be more confident about the likely relative changes to those terms under specific exploratory future 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 of 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. 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 are the implications for cropping of future water availability, which we summarise below, and outline the key messages.

The implications for cropping in the Kharif season differ from those in the Rabi season, and in both seasons vary according to the future scenario. Figure 1 and Figure 2 show the calculated change in the area that may be cropped under a range of exploratory future scenarios for three Kharif and three Rabi crops. The crops are major crops by both area and water use. 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 a 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. The exploratory future scenarios include: changes in future rainfall, actual evapotranspiration, canal deliveries, increased supply of water to Karachi from the Indus River and sedimentation in the main irrigation supply dams.

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.

### IMPLICATIONS OF FUTURE URBAN SUPPLY FOR CROP AREAS

The impact of possible future supply to Karachi is shown in the two 'Urban' box and whisker plots, in the light blue panel. The leftmost plot is based on an upper estimate of the possible supply in 2025 (labelled Karachi 2025) and the other is based on an upper estimate of the possible supply in 2050 (labelled Karachi 2050). The impact is greater in 2050, as expected with the continuing rise in population. If the reduction in the 2050 supply to irrigated cropping were to be accommodated solely by reducing the area of one Kharif crop and one Rabi crop, the maximum impact would be for cotton, with a reduction of about 9% of the cotton area or about 2% of the total cropped area in Kharif (based on 2013-14 areas). In Rabi, the corresponding maximum impact would be for sugarcane, with a reduction of about 27% of the sugarcane area or about 4% of the total cropped area. If the reduction in 2050 supply were accommodated by other crops, the impact would be less. However, future supplies for Karachi could be found from other sources such as desalination and recycling, and there might be no impact on irrigated cropping.

**KEY MESSAGE 2:** Even with an upper bound estimate on the impact of future water supplies to Karachi, the impact on cropping is unlikely to be greater than a reduction of 2% in the area of Kharif crops or 4% in Rabi crops. Alternative future water supplies to Karachi, such as desalination or recycling, might result in no impact on irrigated cropping.

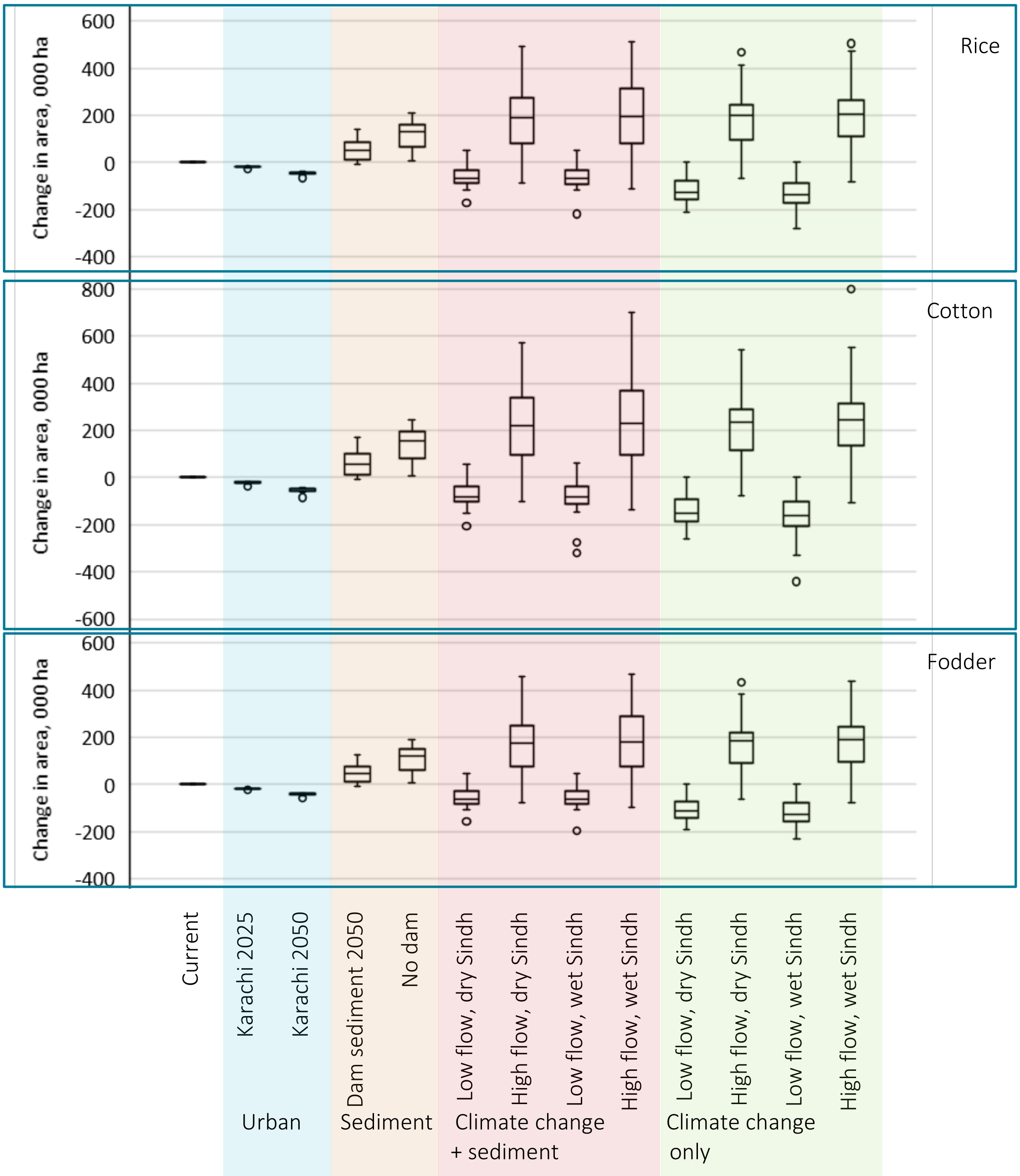


Figure 1 Range of change in areas of Kharif rice, cotton and fodder crops under the 12 exploratory future scenarios. The coloured panels show groups of similar scenarios

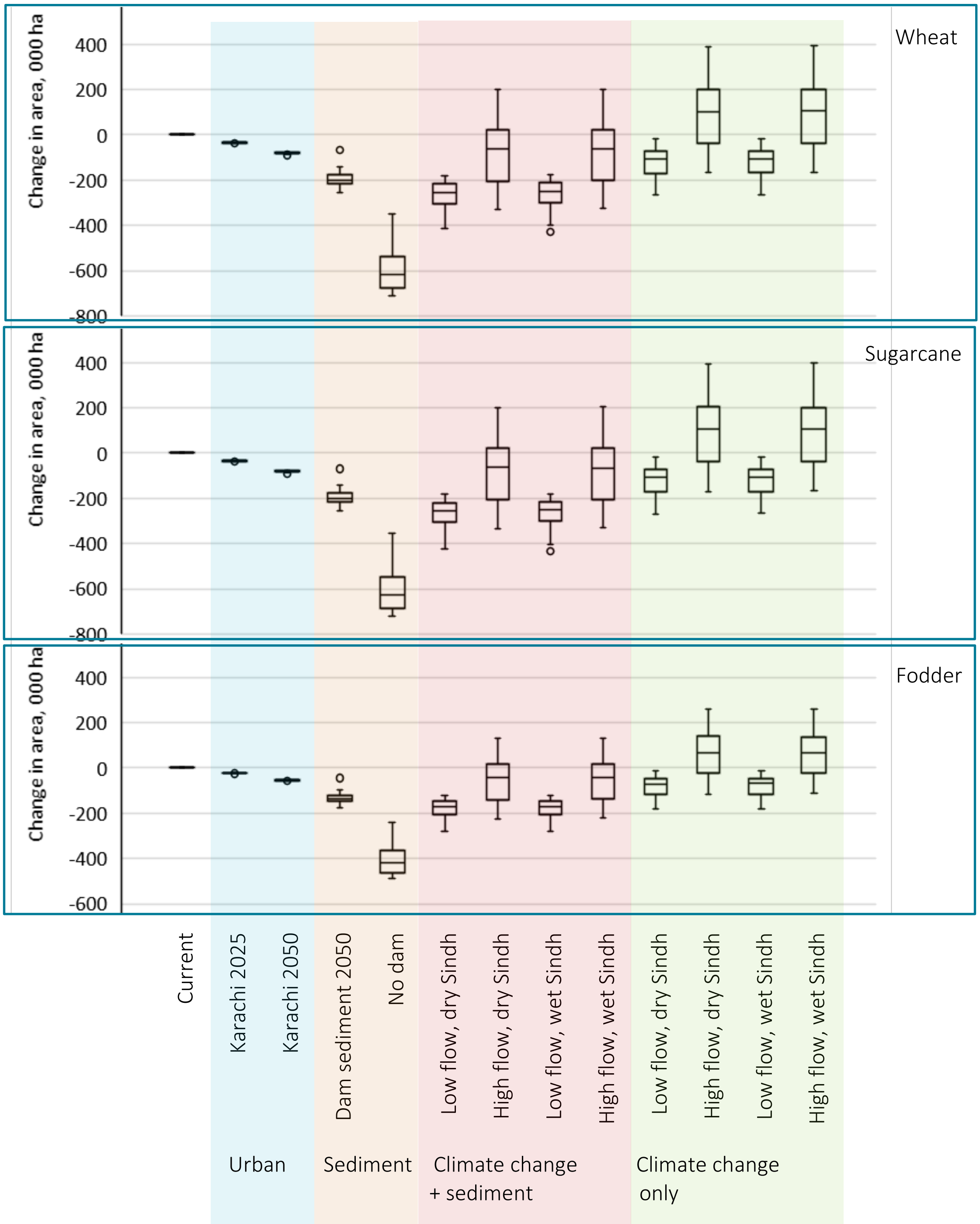


Figure 2 Range of change in areas of Rabi wheat, sugarcane and fodder crops under the 12 exploratory future scenarios. The coloured panels show groups of similar scenarios

### Implications of dam sedimentation for crop areas

The impact of possible future dam sedimentation (in Tarbela and Mangla dams) 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 ('No dam'). Under both scenarios, the result is an increase in the irrigated crop area in Kharif Figure 1), and a reduction in Rabi (Figure 2). The increase in Karif results from lesser storage to capture flows in Kharif, leading to greater flows and hence potentially greater canal deliveries in that season. Conversely, in Rabi, lesser storage leads to lesser volumes of water available for release and canal deliveries. The reduction in Rabi areas under the 2050 sedimentation scenario is equivalent to about 18% of the 2013-14 wheat area, or 68% of the sugarcane area, or 45% of the fodder area. The reduction in areas under the No dam scenario is about 55% of the 2013-14 wheat area, or 94% of the 2013-14 fodder area and is greater than the area of the sugarcane in that year.

KEY MESSAGE 3: Continuing dam sedimentation will lead to an increase in Kharif canal deliveries to Sindh, and a reduction in deliveries in Rabi season. The reduction in the area of irrigated cropping to accommodate the reduced canal deliveries 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 Sindh 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 Sindh (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 must be accommodated by modestly reduced areas of irrigated cropping (first and third box plots in the red panel Figure 1), whereas high flow projections lead to significantly increased areas of cropping (second and fourth plots in the red panel Figure 1). In the Rabi season, even the high flow projections (second and fourth plots in the red panel Figure 2) result in a somewhat reduced area of cropping, whereas the low flow projections (first and third box plots in the red panel Figure 2) lead to a large decrease in the area. This combination of results shows that in the Kharif season in Sindh, the sedimentation effect of increased areas (outlined above) is enhanced (even larger areas of cropping) under climate change scenarios with high flows; and diminished or even reversed (lesser areas of cropping) under low flow scenarios. Conversely, in Rabi, the sedimentation effect of reduced areas is enhanced under low flow scenarios (even more reduced areas of cropping) and diminished but not reversed (except in a few individual years) under high flow scenarios (somewhat reduced areas of cropping).

The impact of climate change on rainfall and crop water demand within Sindh is small, as seen by comparing the first and third plots in the red panel (wet and dry projected climate in Sindh for projected low flows ) for any crop, and by comparing the second and fourth plots in the red panel (wet and dry projected climate in Sindh for projected high flows) 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 Sindh is large, but its direction (increased or decreased area of cropping) is uncertain.

**Key message 5**: The impact in Rabi season of projected high flows (should they occur) resulting from projected climate change in the Upper Indus Basin is not sufficient to reverse the impact of dam sedimentation leading to reduced flows and canal deliveries.

**Key message 6**: The impact of a projected changed climate within Sindh on rain and crop water demand within Sindh is smaller than either the potential impact of sedimentation or the potential impact of climate change on flows in the Upper Indus Basin.

### 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 Sindh, is shown in the four box and whisker plots in the light green panels of Figure 1 and Figure 2. The removal of the sedimentation effect leads to both Kharif and Rabi seasons having similar potential for increased cropping under high flow scenarios (second and fourth box plots in the green panel), and similar potential for decreased cropping under low flow scenarios (first and third plots in the green panel). This reinforces Key message 3.

In the following sections of this report we describe the methods, input data, scenarios and results that have led us to these key results and messages. We also discuss options for Pakistan to manage the potential impacts of dam sedimentation, projected climate change and potential changes to the supply of Indus water to Karachi.

# 1 Introduction

The province of Sindh in Pakistan requires an assessment of the impacts of climate change, population growth and changes to cropping patterns on the water balance of canal commands in the province. CSIRO's role in this work is to:

- undertake initial water balance modelling and scenario assessments, including exploratory climate change impact assessments, on projected inflows to Sindh using the Indus River System Model (IRSM)
- provide more detailed modelling assessments on the Nara Canal water balance
- advise on the framework for a Sindh Hydro-informatics Program to maintain and leverage water data in Sindh.

The purpose of this report is to present the results of a range of exploratory future scenarios for Sindh exploring 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 Sindh
- projected future storage reduction (through dam sedimentation) impacts on the flows in the Indus and hence on canal deliveries in Sindh
- projected climate change impacts on the rainfall and potential evapotranspiration (and hence irrigation demand) within Sindh
- projected changes to the urban water supply to Karachi with supply augmentation from the Indus River and population growth.

In addition, general implications of the scenarios for potential changes to the areas of some major irrigated crops have been assessed.

Following this introduction, this report has three sections:

- Methods: Water balance and scenario assessment, including input data source
- 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 Punjab report (Ahmad et al., 2020b). 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.

## 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:

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

## 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 water balances for Sindh 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 report herein, 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.

The major difference between the study reported here and that of Zaidi et al. (2019) is that we assess the water balances for the canal commands alone, whereas they assessed the overall water balance for Sindh, including the Indus river water balance and its discharge to the sea. (The water balance of the Indus River is implicit in the IRSM modelling (Stewart et al., 2020) and is not discussed in this report.) On the other hand, we make a comprehensive assessment of the impact on the future water balance of projected changes to river flows, rainfall change and change in evaporative demand. We also assess the implications of these changes for the area that can be planted to various crops. Zaidi et al. (2019) do include some future projections, but they are less detailed than those we make and do not consider the full range of processes that we consider.

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 Sindh. 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 Sindh itself, while considering the inter-provincial water apportionment accords.

# 2 Methods: water balances, scenarios and crop area assessment

This report presents the results of assessing province level time-series from aggregated water balances of the canal commands in Sindh. The Pat Feeder and Desert canal commands in Balochistan are included as they are supplied by the Guddu barrage in Sindh that supplies several of the Sindh canal commands. Results are presented mainly at province level; however, the underlying calculations were at canal command level. In a companion report (Ahmad et al., 2020a) we present the results for the Upper Nara and Nara canal commands. While these water balances at canal command level were calculated as monthly time series from 1990 to 2013, results are presented mainly as annual or seasonal totals.

This section is organised into four subsections:

1. Description of the basic water balance method
2. Description of the historical data of inflows (rainfall, canal deliveries and change in groundwater, noting that the latter is effectively zero in Sindh) 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 the future water supply to Karachi from the Indus River, 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 Sindh 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, 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:

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

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:

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

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 - the smaller the balance terms across the canal commands are relative to other terms, the higher the confidence in the 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, Peña-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 Sindh (plus the Pat Feeder and Desert canal commands of Balochistan) 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 Sindh 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. Cropping areas have therefore not changed greatly except for an increase in Jaffarabad and Nasirabad (in Balochistan, where the Pat Feeder and Desert canal commands are situated), but do show year to year variation (Figure 3).

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

- gridded rainfall generated from actual gauge data as part of the Sustainable Development Investment Portfolio (SDIP) project being undertaken by CSIRO, sampled and aggregated to monthly totals for the canal command areas of Sindh
- remotely sensed estimates of the actual evapotranspiration of the Sindh 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 Sindh. The estimates are for 2007, and were extrapolated to other years by Ahmad et al. (2019)
- remotely sensed estimates of the actual evapotranspiration of the Sindh 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 Sindh. 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 monthly and ten-daily data for the Sindh barrages and canals, from Water and Power Development Authority (WAPDA) and Sindh 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 are not known for the canal commands, and we used a default (but reasonable) value of 0.1.

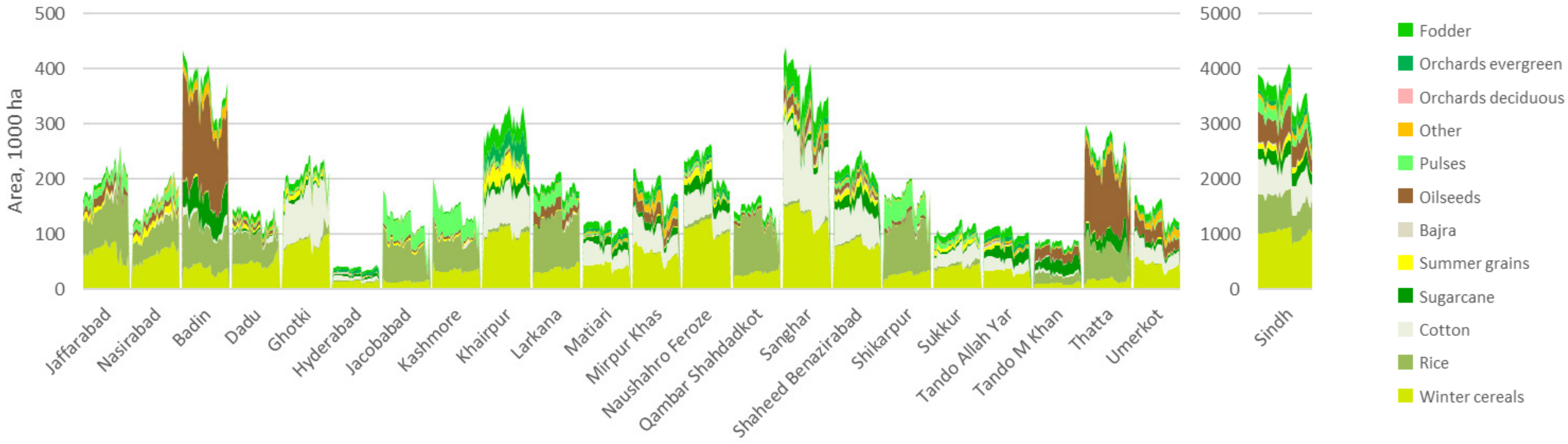


Figure 3 Crop areas from 1981-2 to 2011-12 in the districts of Sindh and for the whole province [Source: Pakistan crop statistics, collated by Kirby and Ahmad (2016), Ahmad et al., 2019 and further updated]

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 very small component of the overall water balance. Indeed, it generally is too small to be visible on the plots in Figure 4, though it can just be seen in the case of the Desert canal command. (The groundwater levels in the Pat Feeder and Desert canal command areas – in Balochistan, but fed from the Guddu barrage in Sindh – rose during the early part of the historical period following their establishment as new irrigation areas.) Any plausible specific yield value in place of the one we assumed would not change this result.
- The main water supply is canal deliveries, with rain being a minor component, as discussed above. This has implications for climate change scenarios, inasmuch as we might expect changes to canal deliveries to have a greater impact on future water supply than changes locally to the rainfall. We 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; however, it is generally smaller than the canal deliveries or actual evapotranspiration (Figure 4). It is, nevertheless, a larger term than rainfall for most of the canal commands, and much larger than the groundwater contribution in 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 mostly negative, meaning that in most canal commands we have measured more inflows than outflows, and additional outflows are required to make the system balance.
- The seasonal patterns of the two estimates of actual evapotranspiration are similar, but the magnitudes are different and mixed (one estimate can be either generally higher or lower than the other depending on the canal command).

We investigated the use of water balance models to help understand the monthly water balances in each canal command. In particular, we anticipated that a time-stepping, monthly model could help in resolving the uncertainties in the water balance – for example, by showing that an equation for the presumed additional outflows 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 in the canal commands.

The second problem with the models was that when applied to future scenarios, in some scenarios and canal commands, groundwater was projected to be rapidly depleted. This is not credible for Sindh.

We therefore abandoned the use of models. We focussed instead on <u>relative changes</u> 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. 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.

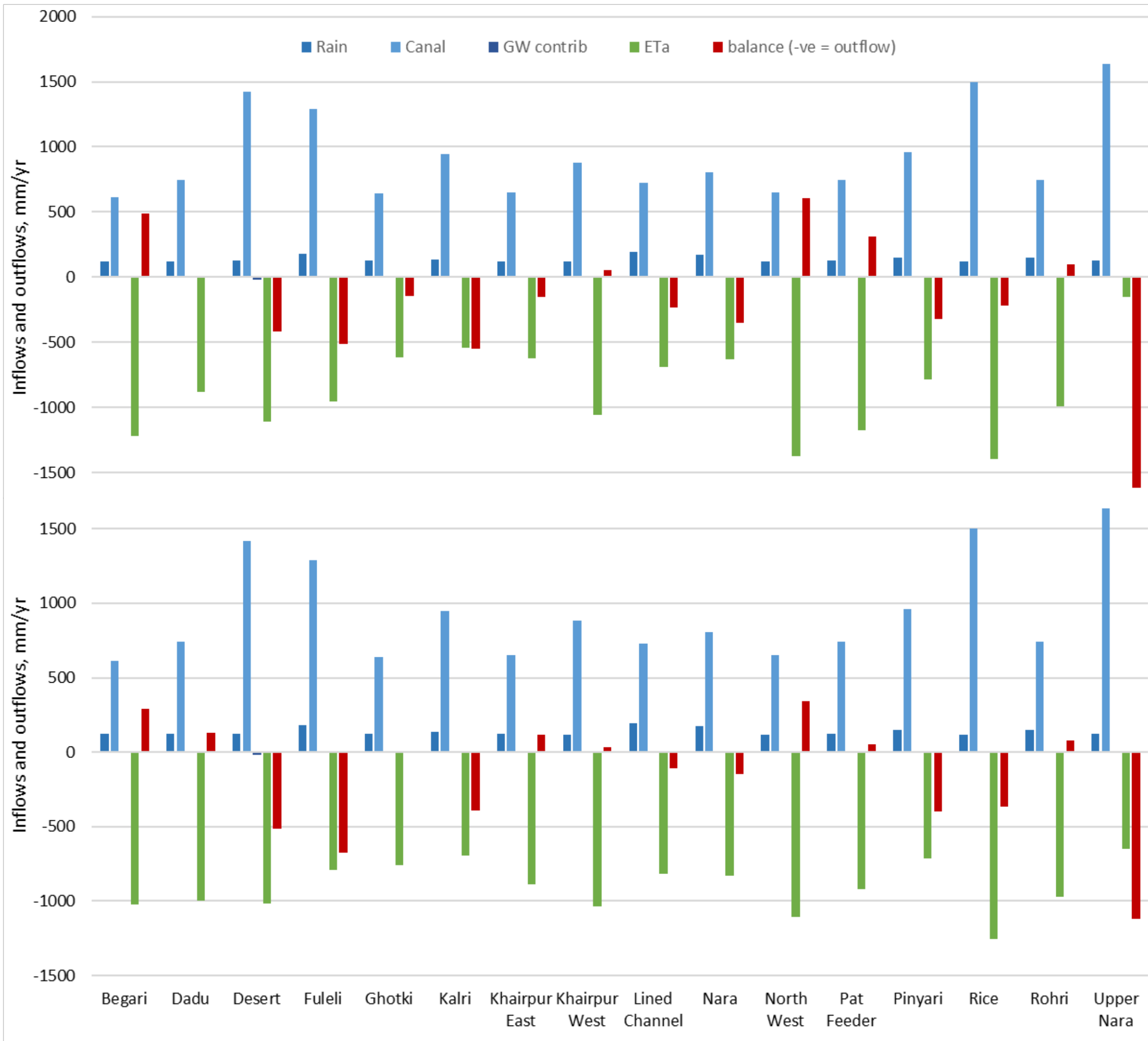


Figure 4 Measured historical (1981–2013) water balance terms for the canal commands of Sindh (plus Balochistan). The top plot is for the ETLook actual evapotranspiration assessment, whereas the bottom plot is for the CMRSET assessment. The rainfall, canal deliveries and groundwater terms are the same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

## 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 scenarios 3, 4 and 5 with scenario 2 answers the question “How will I be affected (if I do nothing)?” for the case of dam sedimentation (4), loss of dam storage (5) or increased urban supply to Karachi (3). Note: in this context, business-as-usual (do-nothing) retains current crop areas (they haven’t changed much in Sindh over the last 30–40 years, except going up and down a bit in response to supply).
- Comparing 7 with 6 and 4 with 2 answers the question “What can I do about it – will fixing the sedimentation issue make much difference?”.
- 8 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 Karachi water supply, 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 climate, from 1981 to 2013<br>CMRSET and ETLook *ETa* |
| 2 Current conditions | Historical inflow sequence<br>Current infrastructure<br>Sedimentation in Tarbela set at 2019 levels | Historical climate<br>CMRSET and ETLook *ETa* |
| 3 Impacts of increased water supply to Karachi | Historical inflow sequence<br>Current infrastructure<br>Sedimentation in Tarbela set at 2019 levels | Current climate<br>CMRSET and ETLook *ETa*<br>Increased supply of Kalri canal flows to Karachi city |
| 4 Tarbela sedimentation impacts | Historical inflow sequence<br>Current infrastructure<br>Sedimentation in Tarbela set at 2050 levels | Current climate<br>CMRSET and ETLook *ETa* |
| 5 Impacts of no dams | Historical inflow sequence<br>Complete loss of storage | Current climate<br>CMRSET and ETLook *ETa* |
| 6 Combined climate change and Tarbela sedimentation impacts | Historical inflow sequence scaled to account for climate change<br>Current infrastructure<br>Sedimentation in Tarbela set at 2050 levels | Future climate<br>CMRSET and ETLook *ETa* (projected) |
| 7 Impact of managing Tarbela sedimentation | Historical inflow sequence scaled to account for climate change<br>Current infrastructure<br>Sedimentation in Tarbela set at 2019 levels | Future climate<br>CMRSET and ETLook *ETa* (projected) |
| 8 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 exploratory future scenarios, we 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 are comparing like with like – modelled future canal deliveries to modelled current canal deliveries.

### 2.3.2 Urban water supply scenarios

We considered the two largest urban centres in Sindh, Karachi and Hyderabad. Other centres are too small to have a significant impact on the water balance. In any event, many small centres may be implicitly accounted for in the assessment. Their supply will be from groundwater or canal water which is part of the measured inputs to the water balance. Any evaporation from house blocks will appear in the actual evapotranspiration but is in any event likely to be small, as will any discharge of water back into the canal command and consumed as evapotranspiration. We therefore do not consider small urban or rural centres.

Karachi, with a population variously put at between about 15 million and perhaps approaching 20 million, is currently supplied with about 630 million US gallons/day, or about 870 mcm/year (unattributed Word document supplied to the project). This is well short of the requirement, based on an assumed demand of 40 US gallons/person/day. About 35% of the water is lost during conveyancing (which we understand does not include losses in the Kalri Canal and Kinjhar Lake). Of the total supply, about 100 million US gallons/day, or about 138 mcm/year, is supplied from the Hub river[1], leaving about 732 mcm/year as the supply from the Indus. The Indus supply is via the Kalri Canal and the Kinjhar Lake. The document referred to above anticipates an augmentation of supply by 2025 with additional pumping (roughly doubling the supply) and reducing the losses. It appears that the Hub supply is highly unreliable, and some current schemes are planned to take water from Kinjhar Lake[2].

We assume here two scenarios that represent the greatest likely impact on the Indus. Both scenarios assume that all additional future water supplies come from the Indus via the Kalri Canal and Kinjhar Lake. The first scenario is for 2025, based on doubling the supply and reducing the losses from the current 35% to 27%. We assumed that the supply would serve a population of 23 million by 2025. The second scenario is based on a population of 40 million in 2050, based on upper estimates of the current population, and assuming a doubling (Hoornweg and Pope (2016) project that Karachi's population will double to 2050). We also assumed that the population would receive the same level of supply as a fraction of demand as that in the 2025 scenario. In both the 2025 and 2050 scenarios, we assumed that the Hub would continue to supply 138 mcm/year. We understand from the Government of Sindh (personal communication) that the planned increase in supplies to Karachi may now be less than stated in the document supplied to the project, and further that future planned supplies are reduced generally due to a reduced estimate of the Karachi population. Therefore, the scenario we use represents upper limits of what might occur. The Karachi urban supply scenarios are summarised in Table 2. For comparison, Table 2 also shows the average measured supply to the Kalri Canal for the period 1990 to 2013.

Table 2 Details of the Karachi water supply 2025 and 2050 scenarios

| | Annual average supply, mcm/yr |
|---|---|
| 1. Measured supply to Kalri Canal 1990–2013 | 3392 |
| 2. Current supply from Kalri Canal and Kinjhar Lake to Karachi | 732 |
| 3. Karachi 2025 | 1414 |
| 4. Karachi 2050 | 2323 |

Based on personal communication with Sindh Irrigation officials, we assumed that the day-to-day supply to Karachi is constant. In some months, this results in a supply that is greater than the flow in Kalri Canal. We assume that such periods are managed by drawing on the storage in Kinjhar Lake, and that lake is refilled in other months when the flow in the canal is greater than the supply to Karachi.

Hyderabad, with a population approaching 2 m, is supplied with about 60 million US gallons/day, or about 83 mcm/year (Jabeen, 2018). Some of this water comes from the River Indus near the diversion point for the Pinyari and Lined Channel canals. However, approximately the same volume of water flows back into the Pinyari canal, affecting its quality (Mahessar et al., 2015). It appears therefore that the city does not reduce canal water supplies. Unless different water supply and disposal infrastructure with different supply and disposal locations is built, future growth of the city may also not reduce canal water supplies, though the impact on the quality could increase. We therefore did not include Hyderabad in the canal command water balances.

[1] http://www.wapda.gov.pk/index.php/projects/water-sector/o-m/hub-dam/item/111-hub-dam-canal-system

[2] https://www.fwo.com.pk/projects/ongoing-projects/dams-watersupply/451-karachi-bulk-water-supply-k-iv

### 2.3.3 Sedimentation and no dam scenarios

The two scenarios are defined by Stewart et al. (2020) and impact the canal deliveries to the canal commands in Sindh. In brief, the sedimentation scenario is for the year 2050, and assumes that current sedimentation rates in Tarbela and Mangla continue to 2050. The no dams scenario assumes that there is no storage at all.

### 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 Sindh, and hence the greatest and least canal deliveries to the canal commands in Sindh.

**Climate change in Sindh**

The water balance and cropping opportunities will be affected by climate change within Sindh. For the water balance study reported here, we used climate change scenarios that resulted in a dry and a wet climate in Sindh. We used a three-stage process to select the climate change scenarios. In the first stage, we screened for Global Climate Models (GCM) models that seemed to adequately model the climate of Sindh. 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 Sindh poorly (Li et al., 2017), and downscaling the projections for future scenarios appeared to give unreasonable results. We therefore applied the approach to five sets of GCM outputs that appeared to give reasonable projections. (These steps are described more fully in Appendix B.) These five sets were chosen to give 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
- 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:

$$ETa\ (month,\ scenario) = ETa\ (month,\ historical) * ETo\ (month,\ scenario) / ETo\ (month,\ historical) \quad \text{(Equation 3)}$$

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 Sindh 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. 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 144 mm, and the projected annual totals vary from 131 (using miroc-esm) to 215 mm (using fgoals-s2). The seasonal distribution of the projected rainfall also varies with the scenario. For example, gfdl results in a projected Rabi rainfall almost double that of the historical period; the actual Rabi rainfall is low, however, at 21 mm in the historical period and 35 mm in the scenario.

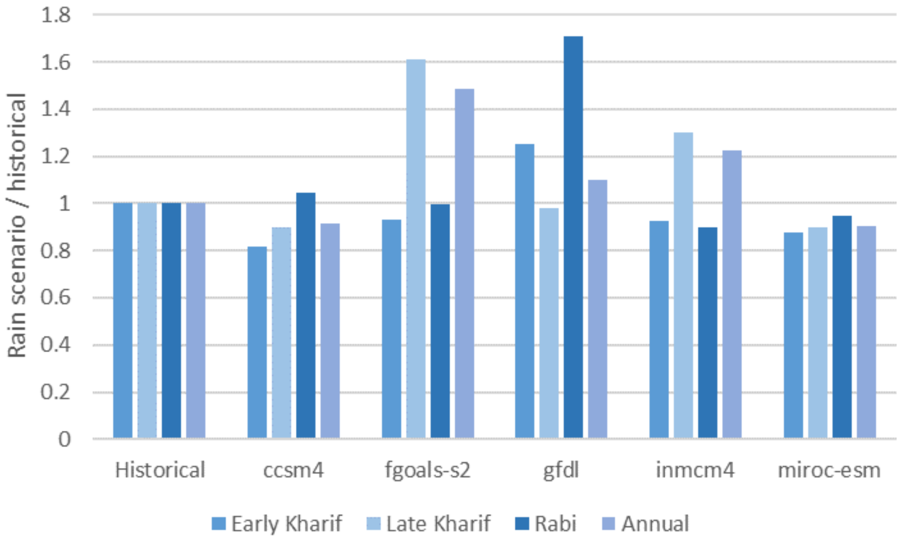


Figure 5 Average rainfall of the canal commands, averaged for Sindh province, for the historical period of 1981–2013, and that projected for the five selected climate change scenarios in 2046–2075 as a ratio of the rainfall in the historical period

The ratios of potential evapotranspiration of scenarios to that in the historical periods were calculated in the same manner as that for rainfall (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 2007 mm (inmcm4) to 2086 mm (gfdl).

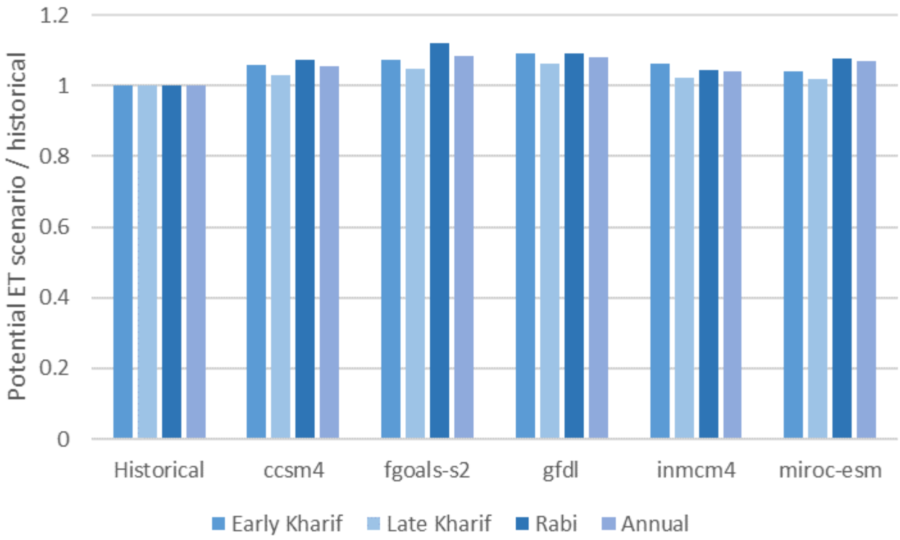


Figure 6 Average potential evapotranspiration of the canal commands, averaged for Sindh province, for the historical period of 1981–2013, and that projected for the five selected climate change scenarios in 2046–2075 as a ratio of the potential evapotranspiration in the historical period

It was shown 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 Sindh, 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 (miroc-esm model, ‘dry’ scenario).

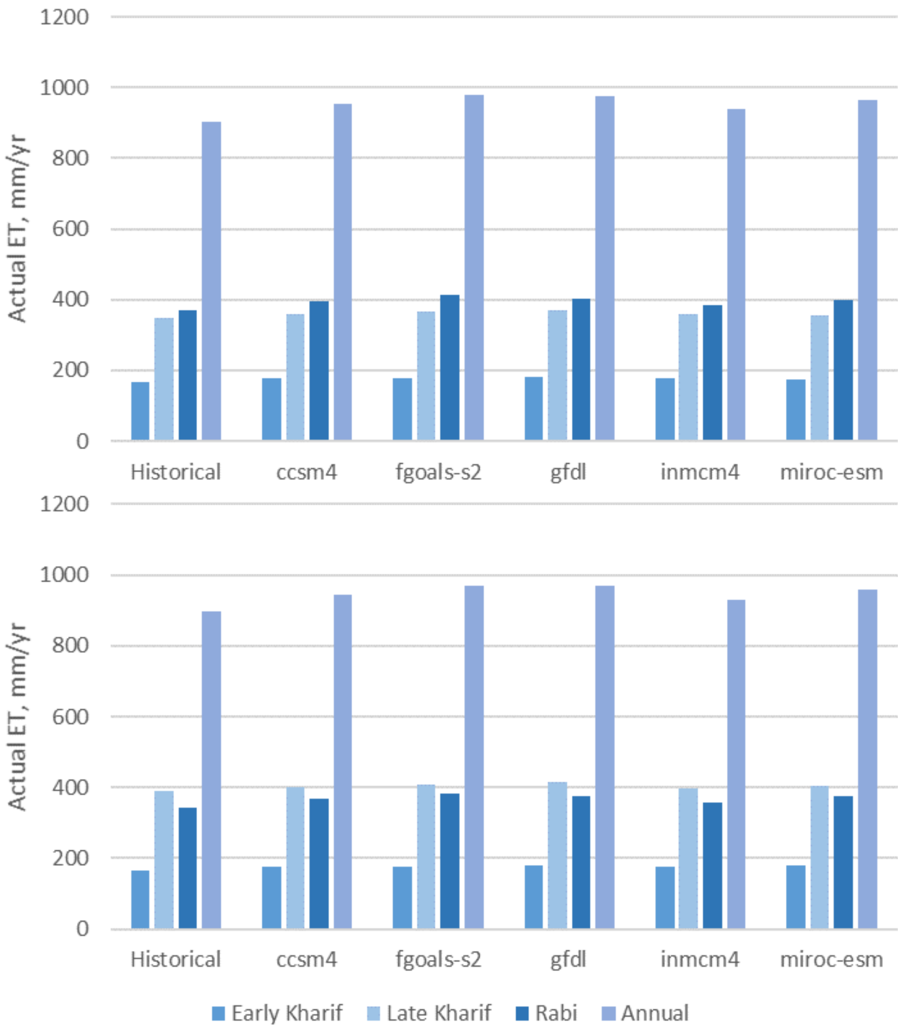


Figure 7 Average actual evapotranspiration of the canal commands, averaged for Sindh province, for the historical period of 1981–2013, and that projected for the five selected climate change scenarios in 2046–2075 as a ratio of the potential evapotranspiration in the historical period. The CMRSET based 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 discussed in Section 2.2 and as shown in Figure 4, groundwater is not much used, and year-to-year groundwater levels have generally varied little over the historical period. Thus, the change in the annual groundwater storage is likely to be insignificant over the long term. As discussed in Section 2.1 with respect to soil water storage, there is likely to be a change in seasonal groundwater 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 – that is, the groundwater level will fall during the Rabi (dry) season, but rise again during the Kahrif (wet) season. The error introduced with this assumption will be seen in the difference or balance term in Equation 2, which will be affected by an approximately equal and opposite amount in the two seasons. However, as we will show, we are mainly concerned with how the balance term changes with scenarios (of climate change and so on); the relative change to the difference or balance term is likely to be not much affected by the assumption that the change in groundwater storage is zero.

### 2.3.6 Specific water balance assessment scenarios

We examined 26 scenarios, comprising 13 based on the ETLook actual evapotranspiration assessment and 13 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 three assess the impact of the Karachi supply – current, 2025 and 2050, as described in the previous section. The next 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 26 scenarios is shown in Table 3. For each of the 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 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), were divided by the canal command areas to give the results in depth of water.

For presentation, results were aggregated to the whole of Sindh province (plus the two canal commands in Balochistan fed from the Guddu barrage in Sindh), and to annual, early Kharif, late Kharif, and Rabi seasons.

Table 3 Details of the 26 water balance assessment scenarios. The final two columns give the description used in this report to identify each scenario

| Sindh climate | Indus inflows | Dam storage | Karachi supply | ETLook 2007 *ETa* | CMRSET 2000-2013 *ETa* |
|---|---|---|---|---|---|
| Historical | Historical | Current | Current | Current ETLook | Current CMRSET |
| Historical | Historical | Current | 2025 | Karachi 2025 | |
| Historical | Historical | Current | 2050 | Karachi 2050 | |
| Historical | Historical | Future | Current | Dam sedimentation 2050 | |
| Historical | Historical | No Dams | Current | No Dam | |
| Future, dry (miroc) | Future, low inflows | Future | Current | Low flow, dry Sindh | |
| Future, dry (miroc) | Future, high inflows | Future | Current | High flow, dry Sindh | Climate change + sediment |
| Future, wet (fgoals) | Future, low inflows | Future | Current | Low flow, wet Sindh | |
| Future, wet (fgoals) | Future, high inflows | Future | Current | High flow, wet Sindh | |
| Future, dry (miroc) | Future, low inflows | Current | Current | Low flow, dry Sindh | |
| Future, dry (miroc) | Future, high inflows | Current | Current | High flow, dry Sindh | Climate change only |
| Future, wet (fgoals) | Future, low inflows | Current | Current | Low flow, wet Sindh | |
| Future, wet (fgoals) | Future, high inflows | Current | Current | High flow, wet Sindh | |

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 Sindh generally are adjusted to use the available canal water supplies. The groundwater is not much used, and year-to-year groundwater levels have generally varied little over the historical period. We assume that future cropping in Sindh will follow this pattern. Under this assumption, crop areas will 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 exploratory future cropping scenarios (Table 4) 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 4 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 a 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:

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

in which $I_{cw,scen}$ and $I_{cw,base}$ are the canal deliveries in a scenario and in the current conditions 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 Sindh 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 Sindh. (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 – i.e. the root zone.) Azad et al. (2003) quote a value for Sindh 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 30–40%, implying an irrigation efficiency of 60–70 %. Yu et al. (2013, their Table 5.1) give watercourse (i.e. river), canal and field efficiencies for each province of Pakistan; the figures imply a canal-to-rootzone efficiency of 68% for Sindh.

We made an approximate estimate of irrigation efficiency by comparing the change in cropped areas with the change in canal water deliveries (described in Appendix C); the implied irrigation efficiency is around 57%. This estimation method applies to the whole system, and implicitly incorporates re-use of water lost from the irrigation system. Re-use includes use of groundwater into which water lost from fields and canals has infiltrated; and use downstream of any water lost from fields and canals which returns to the river and/or canal system. We used a figure of 57% for the irrigation efficiency, consistent with our approximate estimate and in the middle of the figures suggested by Bhutta and Smedema (2007), Hussain et al. (2011) and Yu et al (2013). (Note that the relationship between change in crop areas and canal deliveries described in Appendix C could be used directly to estimate changes in crop area with changing canal deliveries; however it cannot be used directly to estimate the impact of changes in rainfall and potential evapotranspiration due to climate change. We therefore use the indirect method via the irrigation efficiency.)

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 increases, 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 Sindh province (plus the Pat Feeder and Desert canals of Balochistan), given as equivalent depth in mm/year or mm/cropping season. The results are given as annual water balances for the Kharif, early Kharif, late Kharif and Rabi seasons. After a brief description of the rainfall, actual evapotranspiration and canal delivery results, we 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 under 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 – specifically, scenarios 1 and 14 in Table 3 – however 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 14 scenarios (ie ETLook scenarios 1 to 13, plus CMRSET scenario 14). For example, ETLook scenarios 1 to 5 and CMRSET scenario 14 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. (Refer to Appendix A for interpretation of box and whisker plots used in this section.) The median annual rainfall from 1990 to 2013, averaged across the canal commands of Sindh (plus Pat and Desert canal commands in Balochistan), was 167 mm, with the wettest year of 482 mm in 1994 and the driest of 72 mm in 1999. (The whole period from 1999 to 2002 was exceptionally dry, with an average annual rainfall of 85 mm.) The median annual rainfall in the wet scenario increased to 223 mm, with a corresponding wettest year of 747 mm, and decreased to 166 mm in the dry scenario with a corresponding wettest year of 456 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 Sindh (plus Pat and Desert canal commands in Balochistan), was 925 mm using the ETLook method. For ETLook, the maximum year was 996 and the minimum was 816. The median annual actual evapotranspiration in the wet scenario increased to 1001 mm, with a corresponding maximum year of 1078 mm, and to 993 mm in the dry scenario with a corresponding maximum year of 1069 mm. Using the CMRSET method, the medians were 906 for the current scenario, 982 for the wet scenario and 982 for the dry scenario. In each case, the difference between ETLook and CMRSET was 19 mm.

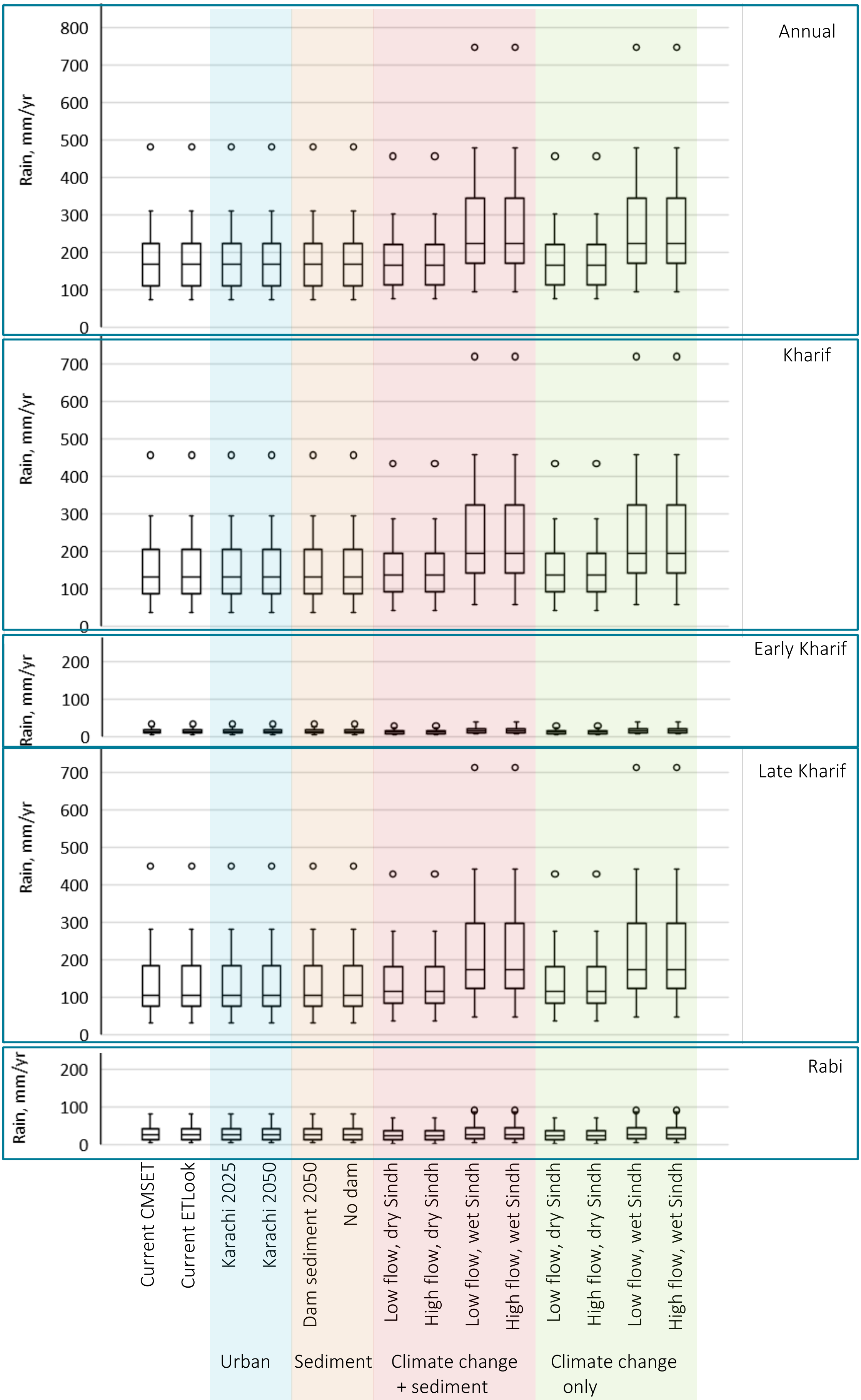


Figure 8 Rainfall in the scenarios; annual (top), Kharif (2nd plot), early Kharif (middle), late Kharif (4th plot), Rabi (bottom). The coloured panels show groups of similar scenarios

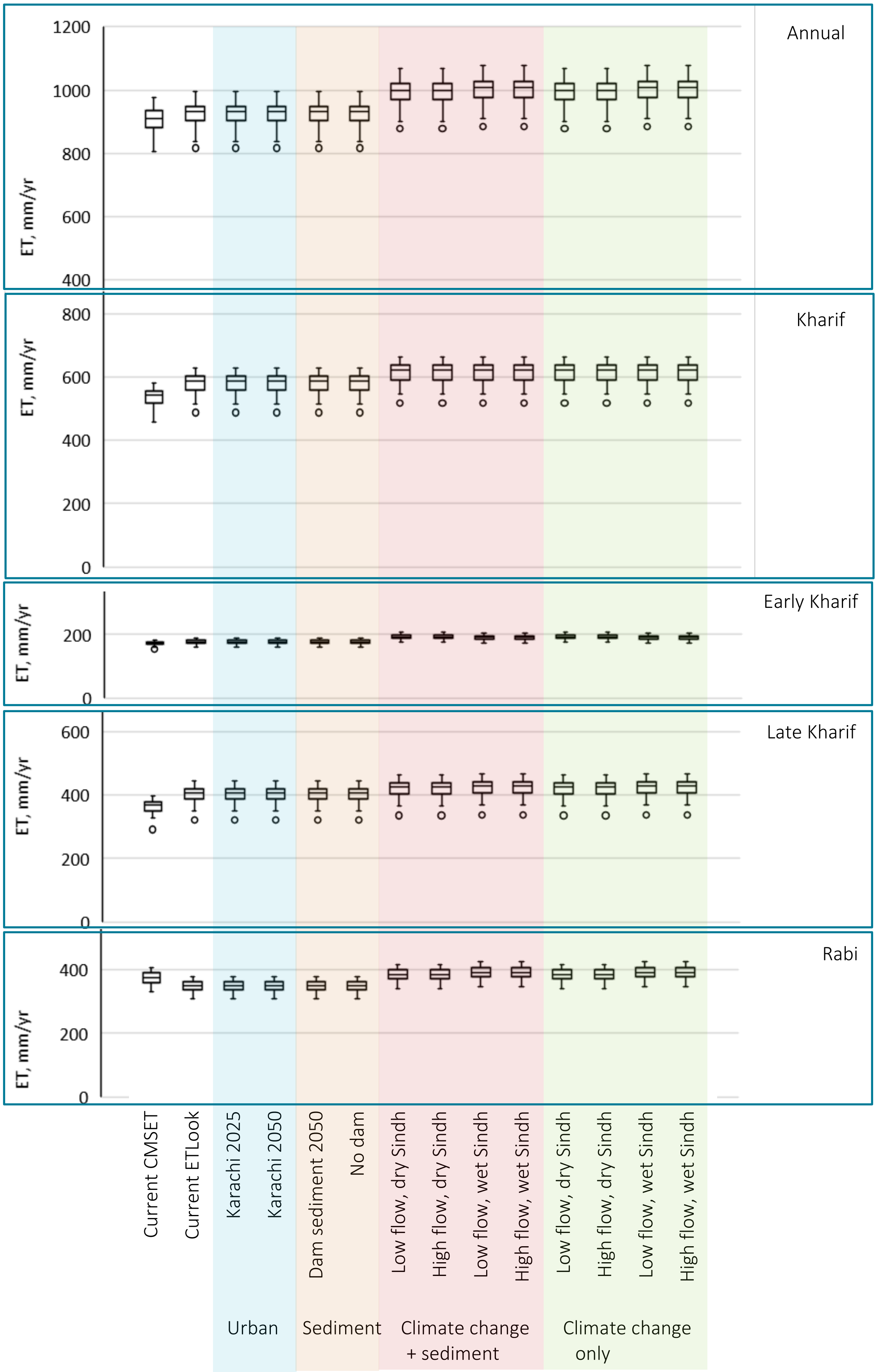


Figure 9 Actual evapotranspiration in the scenarios ; annual (top), Kharif (2nd plot), early Kharif (middle), late Kharif (4th plot), Rabi (bottom). The coloured panels show groups of similar scenarios. Note that the scale for the annual plot (top) does not start at zero

## 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 base case. 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 766 mm (low inflows with sedimentation, scenarios 6 and 8) to 890 mm (high inflows with no sedimentation, scenarios 11 and 13).

The Karachi 2025 and Karachi 2050 water supply scenarios reduce the canal deliveries slightly, annually and in all seasons (as shown by the light blue panel in Figure 10). The effect is confined to the Kalri canal command, but is sufficiently large to be observed at the province level. Note that the volume delivered to Kalri canal in total is not changed in the scenario; what changes is the amount of the total delivery that is available for delivery to irrigated agriculture after some is removed for Karachi.

Sedimentation of the storages, or the loss of dams altogether, results in annual total deliveries somewhat lower than the corresponding no-sedimentation scenario (as shown by the light brown panel in Figure 10). However, the canal deliveries from sedimented storages (or no dams) are somewhat higher in Kharif (and in both early and late Kharif), but much lower in Rabi. The higher canal deliveries in Kharif result from the increased sedimentation reducing storage, and hence less of the Kharif flows can be captured and stored; more therefore flow on past the dams. Conversely, in Rabi, less water is stored in the dams to augment Rabi flows and canal deliveries.

The climate change impacts 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).

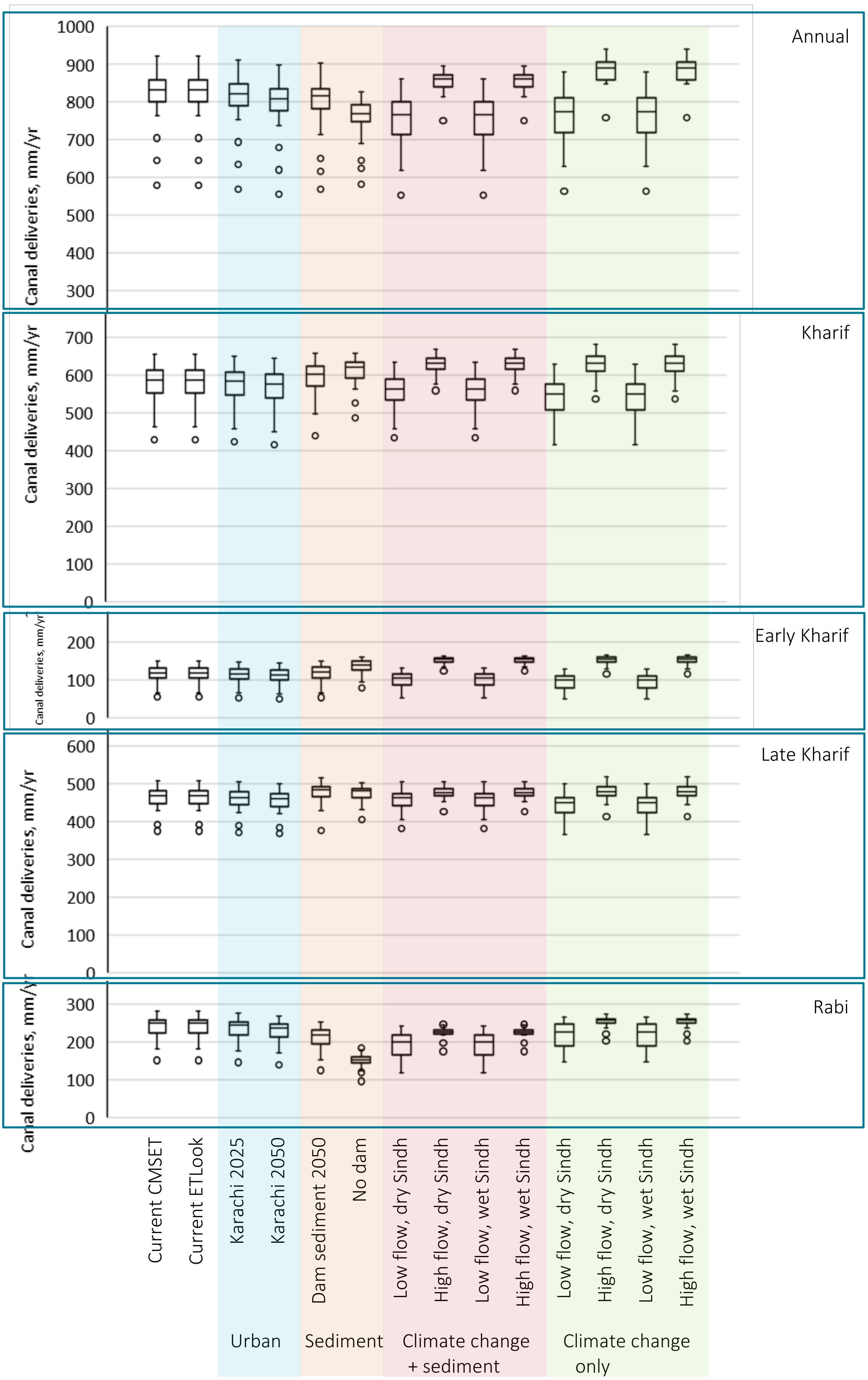


Figure 10 Canal deliveries in the scenarios ; annual (top), Kharif (2nd plot), early Kharif (middle), late Kharif (4th plot), Rabi (bottom). The coloured panels show groups of similar scenarios. Note that the scale for the annual plot (top) does not start at zero

## 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 greater urban water supply to Karachi in the Karachi 2025 and Karachi 2050 scenarios results in a negative change in the balance term annually and in all seasons. The sedimentation and no dam scenarios show 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 less dam storage to fill, hence reducing Kharif flows. The climate change impacts (both the climate change in Sindh 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. 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.

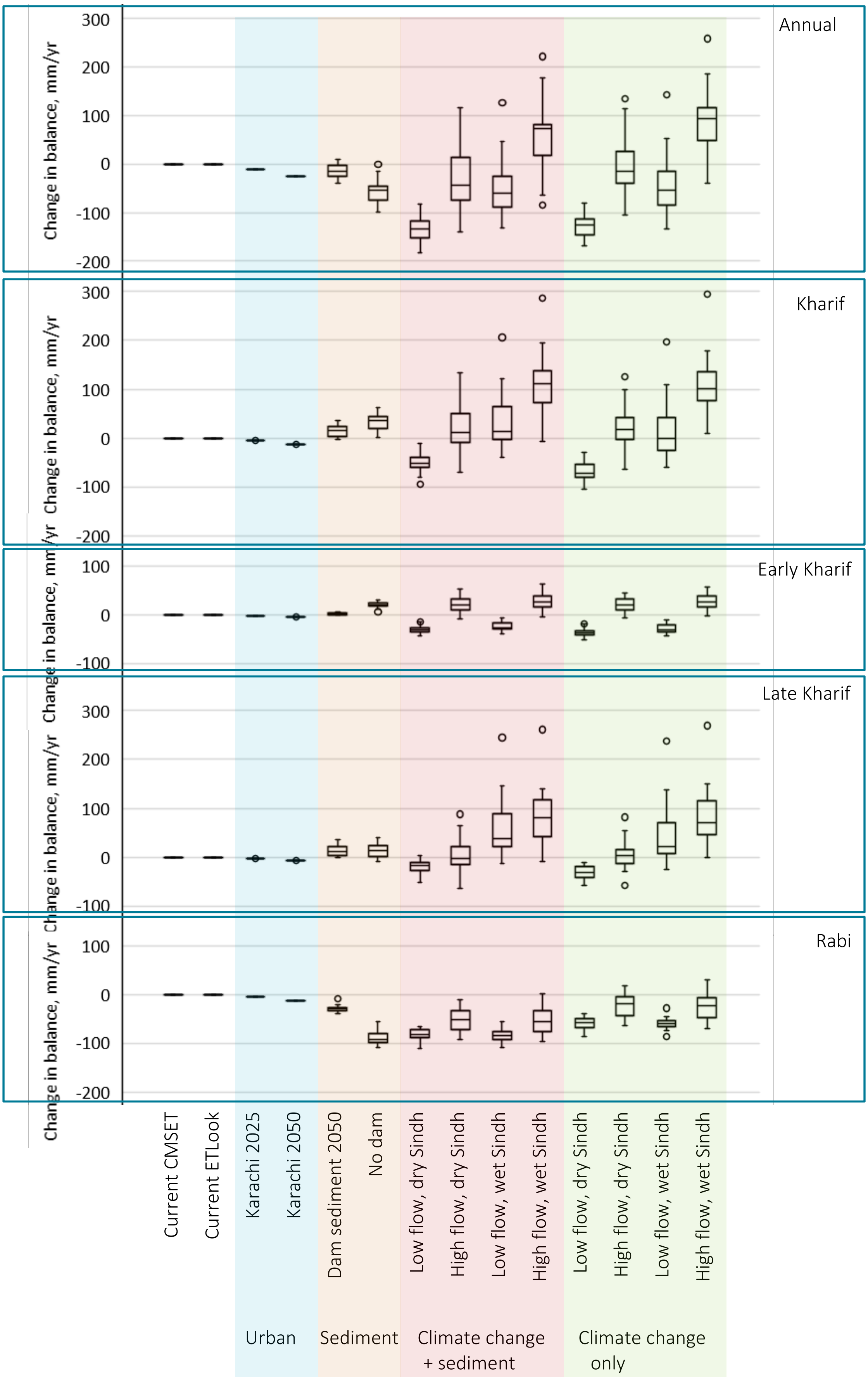


Figure 11 The change in the balance term, B (equation (2), in the scenarios ; annual (top), Kharif (2nd plot), early Kharif (middle), late Kharif (4th plot), Rabi (bottom). The coloured panels show groups of similar scenarios

## 3.5 Magnitude of different scenarios components

The scenarios were developed in a way that allowed separation of the individual effects of increased urban water supply to Karachi, dam sedimentation, climate change in Sindh, 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 urban water supply effect, the scenario impact is simply the change in balance in the scenario minus the base case, or in other words the scenarios (Karachi 2025 – Current ETLook, or Karachi 2050 - current) in Table 3 and in Figure 8 to Figure 11.
- 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 Sindh, 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 Sindh, 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 flows on canal deliveries is generally the largest magnitude impact, followed by the no dams scenario, then the sedimentation scenarios, then the climate change in Sindh scenarios, and lastly the increased urban water supply scenarios. While this is the general picture, in some seasons the order of the magnitude of some effects is reversed.

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.

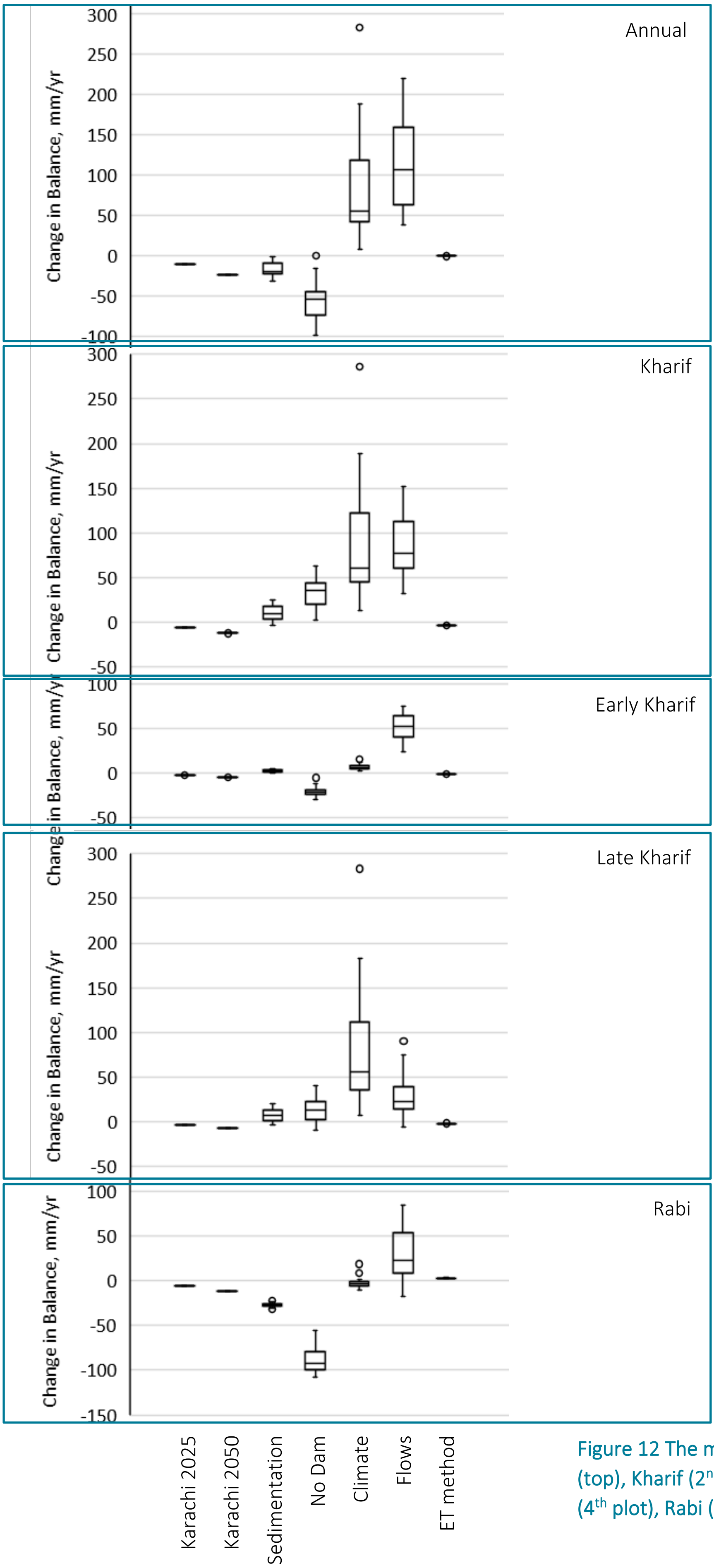


Figure 12 The magnitude of scenario impacts ; annual (top), Kharif (2nd plot), early Kharif (middle), late Kharif (4th plot), Rabi (bottom)

## 3.6 Changing crop areas

As discussed in Section 2.3.7, the crop areas in Sindh have historically adjusted to use the available canal deliveries. 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. We emphasise that this is an approximate calculation. 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 250 000 hectares. (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 170 000 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 746 000, 568 000 and 444 000 hectares, or in total 1 757 000 hectares. With other Kharif crops, the total Kharif area in 2013-14 was around 2 300 000 hectares.

In the Rabi season, the lesser canal deliveries plus decreased rain and increased evapotranspiration requirement in some scenarios generally lead to a reduction in area of crops that can be planted, generally of up to about 230 000 hectares, though more in the case of the no dam scenario. In the companion report on river flows and canal deliveries, it was shown that the no dam scenario leads to about a 35% reduction in canal deliveries 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 100 000 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 1 130 000, 298 000 and 444 000 hectares, or in total 1 872 000 hectares. With other Rabi crops, the total Rabi area in 2013-14 was around 2 300 000 hectares, similar to the total area of Kharif crops. Some crops such as sugarcane, fodder and tree crops grow in both seasons. The change in areas required in the no dam case is about 55% of the area of the wheat crop or 94% of fodder in 2013-14, and is greater than the area of the sugarcane in that year.

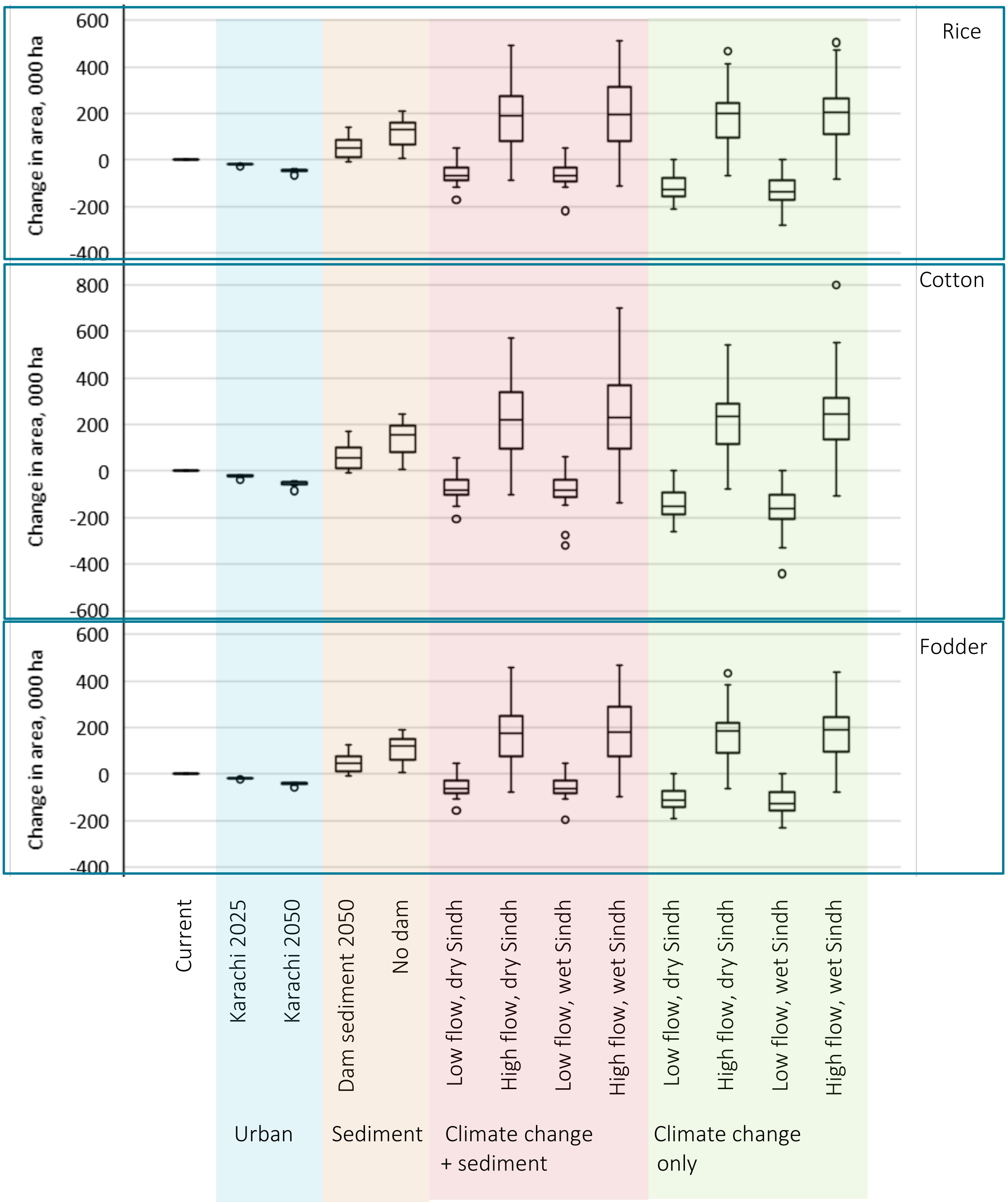


Figure 13 Range of change in areas of Kharif rice, cotton and fodder crops under the 12 exploratory future scenarios. The coloured panels show groups of similar scenarios

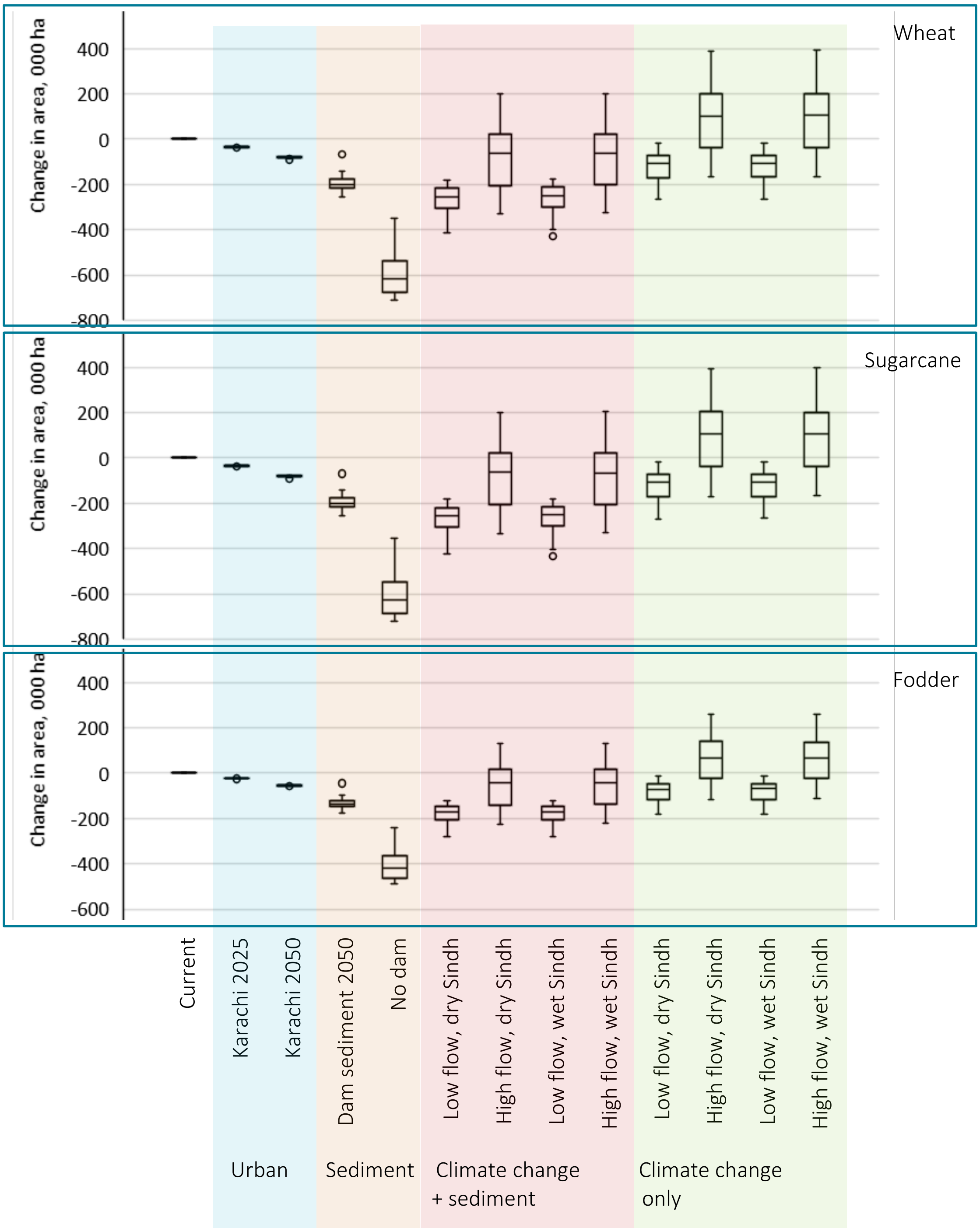


Figure 14 Range of change in area of Rabi wheat, sugarcane and fodder crops under the 12 exploratory future scenarios. The coloured panels show groups of similar scenarios

# 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 Sindh may increase or decrease due to climate change in the Upper Indus Basin, due to local rainfall in Sindh, due to sedimentation of dam storages, and due to a greater future supply of water to Karachi. The impacts of the various scenarios suggest that the area that may be planted to crops will change in the future, with increased areas and decreased areas both possible. 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 Urban water supply to Karachi

The two scenarios we examined were both based on all additional supplies to Karachi coming from the Indus via the Karli Canal and Kinjhar Lake. The scenarios incorporated a reduction in the proportion of water lost in conveyance, without which the water required at the diversion point would have been greater.

It should be noted that the scenarios described in the previous section included greater urban water supply to Karachi in one set of scenarios and climate change and sedimentation in another set of scenarios. We did not examine the joint impact of greater water supply to Karachi combined with climate change and sedimentation. The effects are additive: that is the approximately 3% decline in water availability for irrigation under the Karachi 2050 scenario can be added to the declines in the other scenarios.

However, other water sources may be envisaged. An obvious choice for Karachi is desalination from the sea. Another is high quality treatment and recycling. These choices would be expensive; however they would limit the volume of water required from the Indus, and thus retain water for use within the Sindh irrigation system.

## 4.2 Canal conveyance efficiency

As discussed in Section 2.3.7, we calculated the losses from fields, canals and other water conveyance infrastructure to be around 43%. Literature estimates vary from about 30–65% losses. Water will be lost primarily as evaporation from canals and shallow in-route storages (such as Kinjhar Lake in the Kalri canal system) and as seepage from the canals into the groundwater. Since the groundwater is saline in many places, much of the seepage cannot be reused (Ahmad et al., 2014). If these losses 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.

## 4.3 Crop productivity

Crop yields in Pakistan generally, and Sindh 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) and in particular by dealing with problems of waterlogging and shallow saline groundwater (van Steenbergen et al., 2015).

## 4.4 Crop choices

Pakistan generally, and Sindh in particular, 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).

## 4.5 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. Water storage maintenance and sedimentation control should therefore be a high priority (e.g. Roca, 2012).

## 4.6 New storages

As well as maintenance of the current storages, Rabi supplies into Sindh will be enhanced by building storages 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.

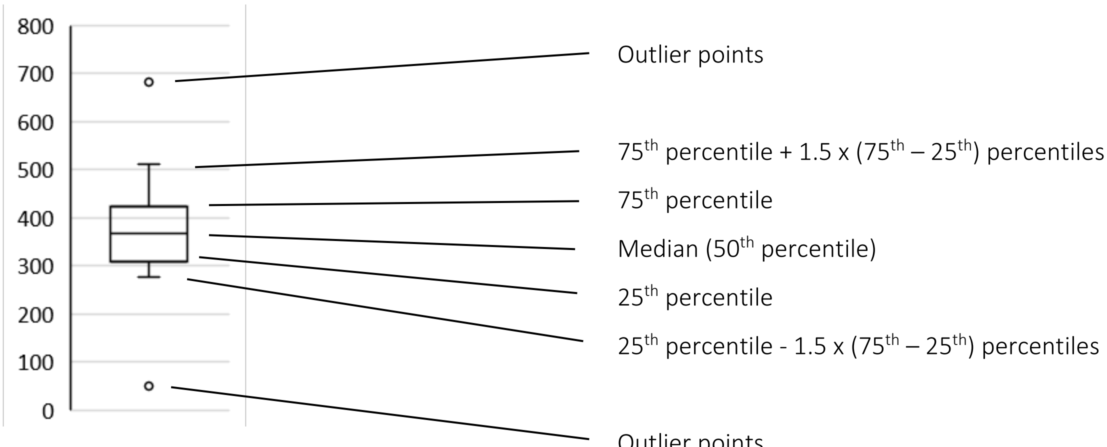


Figure A-1 Interpreting a box and whisker plot

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 from the CMIP5 global climate models were available at the time of the study. However, some of them appeared to give unreasonable rainfall results for Sindh. 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 of the resulting list of 11 GCMs were plotted for the northern, central and southern parts of Sindh, as shown in Figure B-1. Five GCMs were selected such that four covered the range of rainfall and evapotranspiration scaling factors, and one (ccsm4, indicated by yellow in Figure B-1) was close to the median rainfall and evapotranspiration scaling factors.

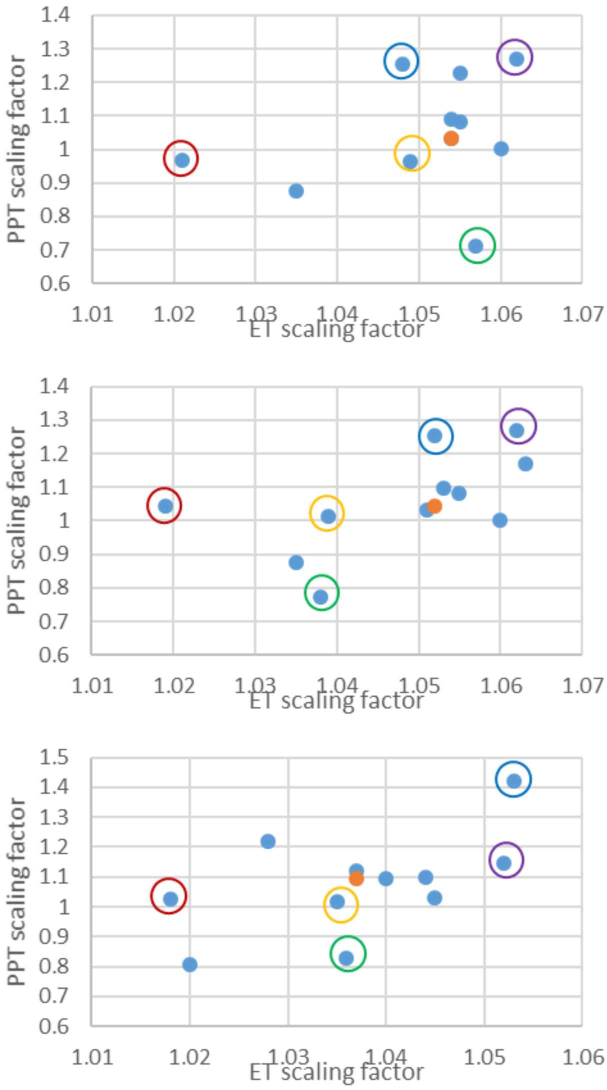


Figure B-1 Rainfall and evapotranspiration scaling factors for northern (top), central (middle) and southern (bottom) Sindh for the 11 selected GCMs indicated by blue points. The coloured circles indicate the GCMs noted in Table B-1. The orange point is the median value of the scaling factors (which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

# Appendix C Change in historical canal deliveries and cropped areas in Sindh – an approximate estimate of irrigation efficiencies

We can make an approximate estimate of the implied irrigation efficiencies by comparing the historical changes in crop areas with the volumes of water delivered via the canals. We start by noting that the area weighted average crop water requirement, as calculated using a crop coefficient model, is calculated as 1011 mm for 2013-14. This is very close to 1 m which over an area of 1000 km2 gives 1 bcm (billion cubic metres) of water. An irrigation efficiency of 1, with all water sourced from canals, would imply a change of about 1000 km2, or 100 000 ha for a change in supply of 1 bcm. However, that simple approximation ignores the contribution of rain. Rainfall in the canal commands of Sindh has historically averaged 144 mm/year (Section 2.3.1). Including the contribution from rainfall, the change in area for a supply change of 1 bcm would be about 117 000 ha. A value of less than 1 would imply a change of less than 117 000 ha for the same change in supply.

The time-series annual total area of crops collated by Kirby and Ahmad (2016) are plotted together with the Sindh canal deliveries (Figure C-1(left)) and re-plotted as a scatterplot (Figure C-1(right)).

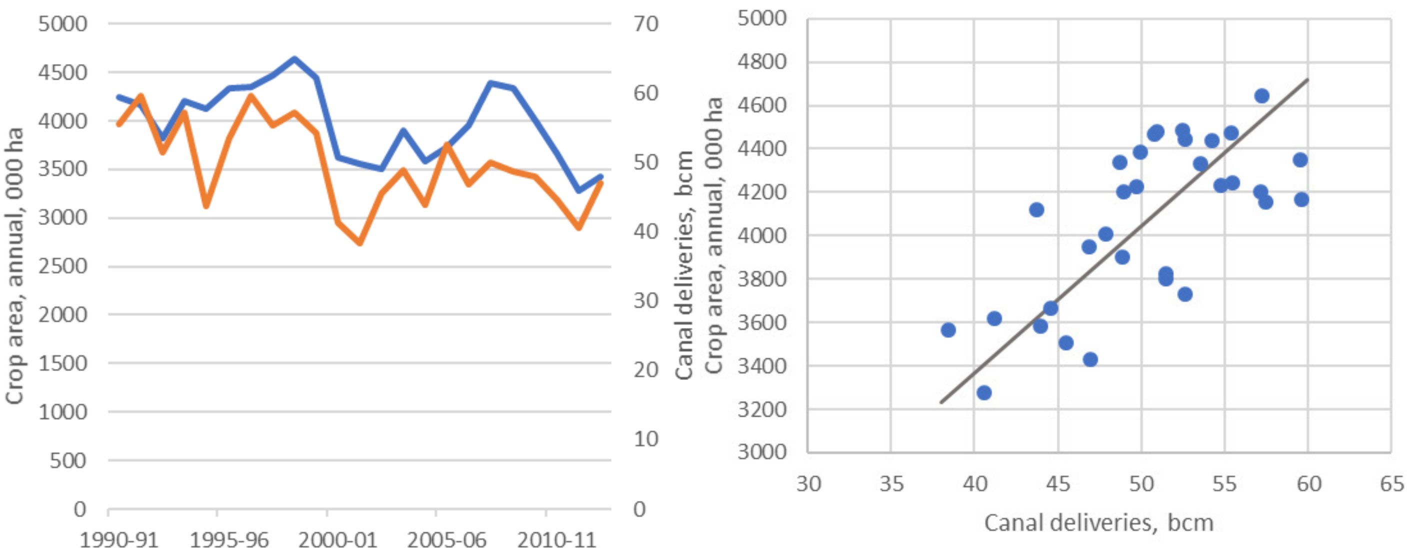


Figure C-1 (Left) Historical total area of all crops in Sindh province (blue line, left axis) and canal deliveries (orange line, right axis). (Right) Annual crop areas and canal deliveries re-plotted as a scatterplot. The reduced major axis regression line is shown.

The correlation between canal deliveries and crop area shown in Figure C-1 (right) is 0.69. A reduced major axis regression line[3] fitted to the scatterplot has a slope of 67 000 ha/bcm, which implies an irrigation efficiency of about 57% (ie 0.57 = 67 000 / 117 000).

[3] In the analysis above, we assume that there is a functional relationship between the canal deliveries and the resulting crop areas, and we seek the slope of the functional relationship. Rather than the more common y-on-x regression, we use a reduced major axis regression, which is one of several preferred methods for assessing a functional relationship between two variables (Webster, 1997).

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